Radiofrequency electromagnetic fields (300 Hz - 300 GHz)

Gezondheidsraad
Health Council of the Netherlands

To the Minister of Health, Welfare and Sport
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In 1975 the Health Council of the Netherlands made recommendations with respect to exposure to radiofrequency electromagnetic fields. These have been outdated by the scientific developments since then. The President of the Health Council therefore initiated a committee on February 15, 1995, that he charged with making an inventory of the state of science in this area and with drafting new recommendations for maximum acceptable exposure to the fields in question. After consultation of the Standing Committee on Radiation Hygiene, I hereby present you with the result of the discussions of the committee as laid down in this advisory report entitled *Radiofrequency electromagnetic fields (300 Hz - 300 GHz)*.

There are two points to which I would like to draw your attention.

The recommendations of the committee - to which I subscribe - are based on thermal effects for frequencies over 10 MHz. In the literature, non-thermal effects, such as direct damage to DNA, have been reported. However, the committee considers the results of these studies not reliable enough to be used in setting exposure limits. This is in line with current thinking in the international scientific community. Currently, studies are being undertaken into these effects and their health impact. If the results of these studies give rise to this, the Health Council will reconsider its present recommendations.

The committee points at a discrepancy between its recommendations and those of the committee that drafted the Health Council report *Optical Radiation* (report nr 1993/09). That committee recommended exposure limits for the frequency range adjacent to the range considered in the present report (the boundary is at 300 GHz) that are a factor 10 higher than the limits now proposed. Since also several organisations in the USA propose exposure limits for the frequency range over 300 GHz that are a factor 10 lower

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than those from the report *Optical Radiation*, this matter needs futher study. I intend to have such study performed in the near future.

The Vice-president of the Health Council of the Netherlands,

(signed)
professor JA Knottnerus

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Health Council of the Netherlands: Radiofrequency Radiation Committee

to:

The Minister of Health, Welfare and Sport

The Minister of Housing, Physical Planning and Environment

The Minister of Social Affairs and Employment

The Minister of Transport, Public Works and Water Management

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Contents

Executive summary

People are increasingly being exposed to electromagnetic fields in the radiofrequency range, defined in the framework of this report as the frequency range from 300 hertz (Hz) to 300 gigahertz (GHz = 10^9 Hz). Typical sources are radio- and television broadcast transmitters, portable telecommunication devices and radar equipment. Under certain conditions, such exposure may lead to adverse health effects. Exposure limits will minimize the risk of such effects. In this report a committee of the Health Council of the Netherlands recommends exposure limits for various exposure conditions. The report is an update and revision of a report on this subject published by the Health Council in 1975.

Frequency ranges

The effects of exposure to electromagnetic fields differ, depending on the frequency of the fields.

In the lower frequency range of 300 Hz to 1 megahertz (MHz = 10^6 Hz) currents are induced in the body that may influence biological systems. They may, for instance, interfere with the normal information processing capabilities of the central nervous system. This may become apparent in nerve and muscle stimulation and involuntary movements. The relevant dosimetric quantity in this frequency range is the current density, expressed in ampere per square meter (A/m^2) or milliampere per square meter ($mA/m^2 = 10^{-3}$ A/m^2).

In the intermediate frequency range of 100 kilohertz (kHz = 10^3 Hz) to 10 GHz, the absorption of electromagnetic energy leads to the generation of heat and heat tolerance is the limiting factor. The appropriate dosimetric quantity is the specific absorption rate (SAR), the absorbed energy per unit mass, expressed in watt per kilogram (W/kg). The transition from current density to SAR being the relevant dosimetric quantity is very gradual. Therefore in the frequency range of 100 kHz to 10 MHz both quantities apply.

In the upper frequency range of 10 - 300 GHz the energy from the electromagnetic fields is increasingly being dissipated at the body surface, resulting in heating of superficial layers, mainly the skin. This heating is directly related to the power density of the incident fields. Therefore the power density is considered to be the relevant dosimetric quantity in this frequency range. It is expressed in units of watts per square meter (W/m^2).

Basic restrictions

According to the Committee, certain levels of current density, SAR and power density should not be exceeded in order to prevent adverse health effects. In line with common practice these health-based recommended exposure limits are termed basic restrictions in this report.

In establishing such basic restrictions the Committee makes a distinction between workers and the general public. Workers are defined as those adult individuals that may be exposed in the course of their professional duties to EM fields and that are trained for awareness of the risks associated with such exposure and for taking precautions. Therefore, within the framework of this report, not all working people fall within the definition of workers. Workers generally form a homogeneous group of healthy people, while the general public also consists of elderly, young, sick, and weak people in which the homeostatic, temperature-controlling mechanisms might be compromised. Therefore the basic restrictions proposed in this report for the general public are lower than those for workers.

In table 1 the basic restrictions proposed by the Committee are summarized.

Derived exposure levels

The Committee recognizes that in practice measuring SAR or induced current in human beings is not feasible. It therefore proposes to use more readily measurable quantities, the unperturbed electric and magnetic field strength. The limits for these parameters are derived from the basic restrictions.

Table 1 Basic restrictions.

frequency range	current density (mA/m^2)		SAR (W/kg) [a]		power density (W/m^2) [b]	
	workers	general public	workers	general public	workers	general public
300 Hz - 1 kHz	10	2				
1 - 100 kHz	f / 100 [c]	f / 500 [c]				
100 kHz - 10 MHz	f / 100 [c]	f / 500 [c]	0.4	0.08		
10 MHz - 10 GHz			0.4	0.08		
10 - 300 GHz					100	$6.727 \times f^{0.473}$ [d]

[a] averaging time = 6 min

[b] averaging time = $68 / f^{1.05}$ min (frequency f in GHz)

[c] frequency f in Hz

[d] frequency f in GHz

In determining the exposure limits for the electric fields, the Committee also took into account possible indirect effects. These may result from contact currents when touching large ungrounded metal objects that have been charged by the electric field.

The Committee proposes the limit values for the electric and magnetic field strengths given in tables 2 and 3.

Partial body exposure

The Committee considers it justified to allow a higher absorption of energy when, instead of the whole body, only parts of it are exposed. For the head, neck and trunk a maximum SAR of 10 W/kg averaged over 10 gram tissue is recommended and for the limbs 20 W/kg averaged over 100 gram tissue. These values apply to workers and SAR maxima for the general public are 2 and 4 W/kg, respectively. A value of 2 W/kg averaged over 10 gram tissue is indicated for exposure of a fetus. The averaging time of 6 min also applies to partial body exposures.

Short exposures

When the exposure is only of short duration, i.e., less than 6 minutes, higher SAR values can be allowed, as long as the SAR averaged over each 6-min interval does not exceed the exposure limits.

Multiple frequencies

Commonly exposure will be to multiple frequencies. The Committee recommends in such cases to add the power densities or the squares of the electric and magnetic fields

Table 2 Proposed maximum electric field strengths.

frequency	electric field strength (volt per meter, V/m)			
	workers		general public	
	no indirect effects	indirect effects possible		
300 Hz - 2.04 kHz	1250 / f	500 / f	250 / f	(f in kHz)
2.04 kHz - 2.58 kHz	614	500 / f	250 / f	(f in kHz)
2.58 kHz - 2.88 kHz	614	194	250 / f	(f in kHz)
2.88 kHz - 1 MHz	614	194	87	
1 MHz - 10 MHz	614 / f	194 / $f^{0.5}$	87 / $f^{0.5}$	(f in MHz)
10 MHz - 400 MHz	61	61	28	
400 MHz - 2 GHz	118 $\times f^{0.72}$	118 $\times f^{0.72}$	53 $\times f^{0.72}$	(f in GHz)
2 GHz - 10 GHz	194	194	87	
10 GHz - 300 GHz	194	194	78 $\times f^{0.16}$	(f in GHz)

strengths obtained for each frequency, expressed as fractions of the respective limit values. These added values should not exceed unity.

Pulsed fields

The Committee concludes that the effectiveness of pulsed electromagnetic fields is comparable to that of continuous fields. It therefore proposes for exposure to pulsed radiation to use the same guidelines as for continuous radiation.

Table 3 Proposed maximum magnetic flux densities and magnetic field strengths.

frequency	magnetic flux density (microtesla, µT)		magnetic field strength (ampere per meter, A/m)		
	workers	general public	workers	general public	
300 Hz - 1.0 kHz	25 / f	5 / f	20 / f	4 / f	(f in kHz)
1.0 kHz - 80 kHz	25	5	20	4	
80 kHz - 180 kHz	2.0 / f	5	1.6 / f	4	(f in MHz)
180 kHz - 10 MHz	2.0 / f	0.92 / f	1.6 / f	0.73 / f	(f in MHz)
10 MHz - 400 MHz	0.2	0.09	0.16	0.07	
400 MHz - 2 GHz	0.39 $\times f^{0.73}$	0.17 $\times f^{0.73}$	0.31 $\times f^{0.72}$	0.14 $\times f^{0.74}$	(f in GHz)
2 GHz - 10 GHz	0.65	0.29	0.52	0.23	
10 GHz - 300 GHz	0.65	0.26 $\times f^{0.16}$	0.52	0.21 $\times f^{0.16}$	(f in GHz)

Contact currents

The Committee proposes to set maximum values to contact currents, in order to protect against electric shocks, discomfort and burns. Contact currents should not exceed 1.0 mA for frequencies between 300 Hz and 2.5 kHz, $0.4 \times f$ mA (frequency f in kHz) between 2.5 and 100 kHz and 40 mA between 100 kHz and 10 MHz. These values pertain to workers. Those for the general public are a factor 2 lower.

The use of portable telephones and other specific exposure situations

Having proposed these health-based exposure limits, the Committee considers the consequences of these proposals for some specific, often encountered exposure situations: the use of portable telephones, industrial sealing devices and equipment used in physical therapy.

The Committee concludes that the available scientific data do not indicate that the absorption of electromagnetic energy emitted by present-day portable radiotelecommunication devices such as hand-held telephones poses a health hazard, provided that these devices are operated in a normal way. The Committee stresses that this conclusion is based on only very limited data. It recommends to obtain more data on SAR levels in the head resulting from exposure to electromagnetic fields emitted by hand-held telephones and that several types of telephones from every system available in the Netherlands (digital and analog) be tested. The Committee considers for the time being determination of SAR values in the head by means of measurements in phantoms the most reliable method. It feels that the SAR levels in the head are not described accurately enough by the computational models that have been developed for this purpose. It therefore advises to optimise these models.

Electromagnetic interference by electromagnetic fields generated by hand-held telephones may indirectly result in threats to health if vital medical equipment is disturbed. The Committee therefore endorses recent proposals made by the telecommunication industry in the Netherlands for regulation of the use of hand-held telephones in the direct vicinity of sensitive medical equipment.

The Committee also points at the possibility of interference with the functioning of pacemakers. Although such interference is not necessarily life-threatening, it can be annoying or frightening to the patient. The Committee endorses the recent recommendations of Wireless Technology Research on this matter. For patients wearing an implanted pacemaker this means that it is recommended that hand-held telephones should be worn at a distance of at least 15 cm from the pacemaker, unless it is known that the pacemaker is adequately protected against electromagnetic interference or the telephone is completely switched off.

Available data indicate that the exposure limits recommended in this report are sometimes considerably exceeded in the direct vicinity of industrial and paramedical equipment operating with radiofrequency electromagnetic fields, *e.g.*, sealing machines and certain equipment used in physical therapy. This is reason for the Committee to recommend that adequate measurements be performed to determine the electromagnetic field strengths near such devices. If exposure limits are exceeded, proper mitigation measures should be taken.

Chapter 1

Introduction

In present day society, man is increasingly exposed to non-ionizing electromagnetic radiation. These are generated by radio and television broadcast stations, portable telephones and other telecommunication devices, by various household, medical and industrial appliances and by military and civil radar equipment. In this report a committee of the Health Council of the Netherlands discusses exposure to these electromagnetic radiation and possible adverse health effects resulting from such exposure. On the basis of this information the Committee proposes health-based exposure limits.

1.1 Earlier Health Council reports

In 1992 the Health Council issued a report on the possible adverse health effects of exposure to non-ionising electromagnetic fields* in the frequency range of 0-300 Hz**, the extremely low frequency or ELF range, focusing on 50 Hz fields generated by power lines (GR92). The latest Health Council report on radiofrequency radiation and microwaves dates from 1975 (GR75). Based on the ongoing scientific research and the

* An electromagnetic source generates electric and magnetic fields. At sufficient distance from the source, depending on the wavelength, the electric and magnetic fields are coupled and can be considered as radiation. The Committee elaborates on this in more detail in chapter 2.

** Time-varying electromagnetic fields periodically change polarity from positive to negative. The rate at which this occurs is the frequency, the SI-unit of which is hertz (1 Hz = 1 cycle per second). Explanation of the units is given in the list at the end of this report.

altered views with regard to the effects of radiofrequency (RF) radiation on living beings, various national and international organizations have recommended exposure limits that deviate from the ones proposed by the Health Council in 1975. These developments, as well as an increase in the number of radiation-generating sources, justify the present revision of those recommendations.

In 1975 the Health Council report covered the range of frequencies between 300 MHz and 300 GHz (1 MHz = 10^6 Hz and 1 GHz = 10^9 Hz). Many sources, however, emit radiation with frequencies below 300 MHz. The present report covers the frequency range from 300 Hz to 300 GHz. The lower limit is selected in order to link up with the 1992 Health Council report on extremely low frequencies (covering the range 0 - 300 Hz), while the upper limit is the generally accepted lower frequency limit of the infrared range.

The health effects of non-ionizing electromagnetic radiation with frequencies of 300 GHz and higher are dealt with in the Health Council reports ‘Optical radiation’ (GR93), ‘UV radiation. Human exposure to ultraviolet radiation’ (GR86) and ‘UV radiation from sunlight’ (GR94).

1.2 The Committee and its charge

On February 15, 1995, the President of the Health Council initiated the Radiofrequency Radiation Committee, designated throughout this report as ‘the Committee’. Its composition is shown in annex A. The Committee’s charge was to answer the following questions with respect to (exposure to) radiofrequency radiation:

1. What guidelines can be given for health-based limits of exposure to RF radiation, that correspond as much as possible to international standards and guidelines? In its answer to this question, the Committee will also have to provide answers to the following questions:

a. Is it necessary to make a distinction, with respect to basic restrictions, between high and low frequencies; if so, is 10 MHz an acceptable value for discrimination between these two frequency ranges?
b. Must a distinction be made between workers and the general population with respect to health based exposure limits, or is it more desirable to make a distinction between certain areas with respect to the degree of control of exposure, or is it more useful to make a distinction between children and adults, based on body size?
c. Which safety factor has to be chosen in the limitation of the maximum absorption of energy?
d. To what extent can a higher absorption of energy be allowed when, instead of prolonged total-body exposure, only parts of the body are exposed or exposure is only of short duration?
e. What is the consequence for the exposure limits if the RF radiation is pulsed or modulated?

2 Which are the consequences of implementation of the guidelines to be proposed, for working with RF radiation or for the use of specific applications, *e.g.* wireless telecommunication devices and sealing equipment?

1.3 Structure of this report

In chapter 2 the Committee presents a short introduction into the physical background of non-ionising electromagnetic radiation, an overview of possible biological mechanisms involved in the interaction between such radiation and living beings and a short overview of the most relevant experimental data. In chapter 3 a summary of the most recent exposure guidelines proposed by various bodies is given. In chapter 4 the Committee draws its conclusions from the available scientific data and presents its own recommendations with respect to exposure limits. In several annexes, the Committee elaborates on subjects that it considers important background information.

Chapter 2

General

2.1 Definitions, sources

An electromagnetic (EM) source generates electric and magnetic fields. Except for static fields, these exhibit wave-shaped variations with time (comparable with the ripples on a watersurface upon touching). At sufficient distance from the source, depending upon wavelength, the electric and magnetic fields are coupled and perpendicular. They can than be considered electromagnetic radiation (see 2.1.2).

2.1.1 Frequencies

Electric and magnetic fields and EM radiation are characterized by their frequency (f, SI-unit Hz) or their wavelength (λ, SI-unit m). These two quantities are interrelated by the velocity of the electromagnetic waves in the propagating medium. In vacuum the relation is:

$$f = c / \lambda$$

where $c = 3 \times 10^8$ m/s, the velocity of light in vacuum. In table 4, the EM fields are classified according to frequency and wavelength.

Table 4 Designations of the various frequency ranges.

designation	frequency range	wavelength range
Static	0 Hz	∞
Sub-ELF (sub extremely low frequency)	0 - 30 Hz	∞ - 10,000 km
ELF (extremely low frequency)	30 - 300 Hz	10,000 - 1000 km
VF (voice frequency)	300 - 3000 Hz	1000 - 100 km
VLF (very low frequency)	3 - 30 kHz	100 - 10 km
LF (low frequency) or long waves	30 - 300 kHz	10 - 1 km
MF (medium frequency) or medium waves	300 - 3000 kHz	1000 - 100 m
HF (high frequency) or short waves	3 - 30 MHz	100 - 10 m
VHF (very high frequency)	30 - 300 MHz	10 - 1 m
UHF (ultrahigh frequency)	300 - 3000 MHz	100 - 10 cm
SHF (superhigh frequency)	3 - 30 GHz	10 - 1 cm
EHF (extremely high frequency)	30 - 300 GHz	10 - 1 mm

2.1.2 *Fields and radiation*

In the interaction of EM fields with biological structures, the following quantities are important in the framework of this report:

E : electric field strength (in units of volt per meter, V/m),
H : magnetic field strength (in units of ampere per meter, A/m),
B : magnetic flux density (in units of tesla, T).
J_e : electric current density (in units of ampere per square meter, A/m^2),
W : energy (in units of joule, J)
P : power (in units of watt, W)
S : power density (in units of watt per square meter, W/m^2)

The magnetic field strength and fluxdensity are interchangable quantities, related according to $B = \mu H$, where μ is the magnetic permeability of the medium. For most non-metallic materials μ equals μ_0, the magnetic permeability of air: $\mu_0 = 1.257 \times 10^{-6}$ henry per meter (H/m).

Another important factor in the interaction between EM radiation and an object is its distance from the source. An important distinction to be made is that between the area in the direct vicinity of the source, the so-called near-field, and that further away,

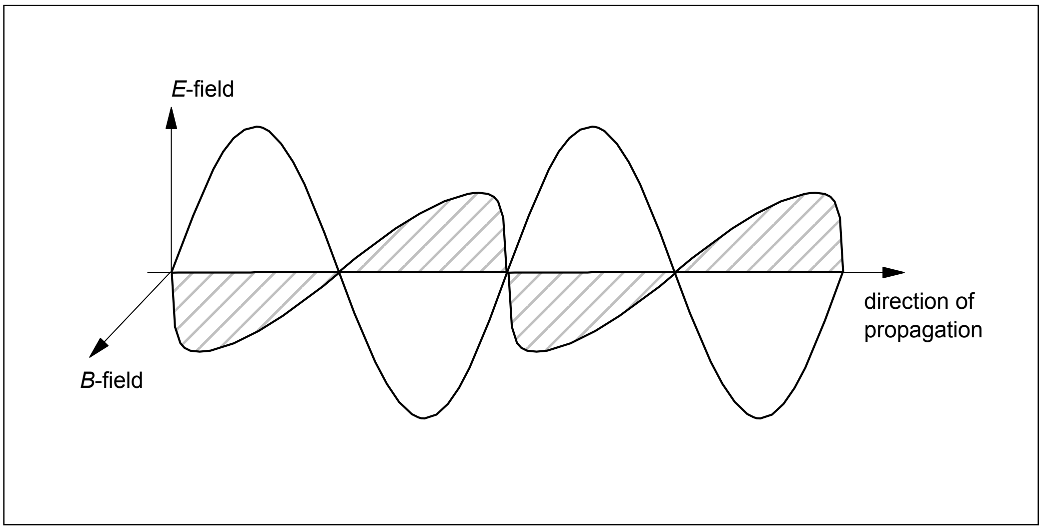

Figure 1 Schematic representation of an electromagnetic wave.

the far-field. In the far-field the magnetic and electric field components are fully coupled and perpendicular to each other and to the direction of energy propagation (see figure 1). This energy propagation is termed radiation and the far-field is sometimes referred to as the radiating far-field. The amplitudes of the electric and magnetic fields in the far-field decrease inversely with distance from the source. In the near-field this coupling is only weak and the electric and magnetic field strengths on the average fall off faster than with the inverse of the distance. Field strengths in the near-field are difficult to calculate because of the complex field behaviour. As a consequence, these field strengths usually have to be obtained from measurements. (The Committee deals with the measuring of electric and magnetic fields in section 2.2.) There is no unequivocal the boundary between the near-field and the far-field. If L is the maximum dimension of the source and λ is the wavelength, generally accepted approximations are $2L^2/\lambda$ in the case that L is larger than λ and $\lambda/2\pi$ in case L is smaller than λ.

In order to capture all electric and magnetic fields both in the near- and far-field in one generic term, the Committee speaks in this report only of EM fields.

2.1.3 Interaction with exposed objects

Under the influence of an externally applied EM field, atoms, molecules and ions in tissue may follow the time variations of the electric field, for instance because of the presence of internal electric dipoles. This results in conversion of part of the energy of the EM field into heat. The conductivity σ (SI-unit siemens per meter, S/m) is the electromagnetic property of the tissue that can be considered as the macroscopic measure of this conversion. To quantify the thermal absorption in tissue, the specific energy absorption rate (SAR) is introduced, the absorbed energy per unit mass.

The SAR is defined as the time derivative of the incremental energy, dW, absorbed by, or dissipated in, an incremental mass, dm, contained in a volume element, dV, of a given density, ρ (in kg/m^3) (IEEE92):

$$\text{SAR} = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) \text{ (in W/kg)}$$

For sinusoidal EM fields, the SAR is related to the internal electric field according to:

$$\text{SAR} = \frac{\sigma\,(E_{rms})^2}{\rho} \quad \text{(in W/kg)}$$

where E_{rms} is the root mean square (rms) value* of the internal electric field . Although this absorption rate is given in terms of the electric field only, both the electric field and the magnetic field play a role in the interaction with an organism.

In the upper part of the frequency range considered – in the GHz range – objects can be considered as being in the far-field, where the electric and magnetic field vectors are coupled and the interaction of an EM field and an object can be thought of as that of an electromagnetic wave incident upon the object. However, when the frequency is low enough (the wavelength being an order of magnitude larger than the dimensions of the organism), for humans approximately below 10 MHz, the change of the magnetic field vector due to the presence of the organism can be neglected and the electromagnetic interaction is mainly determined by the electric currents generated in the organism by the oscillating electric fields.

2.1.4 Sources

Many sources generate EM fields. Some of these are natural sources such as the sun and other stars, others are artificial ones. In the frequency range of 300 Hz - 300 GHz considered in this report, extraterrestrial radiation levels from natural (cosmic) background are negligibly small (WHO93).

The most common artificial sources can be classified in sources emitting the energy into free space:

- radio and television stations
- telecommunication transmitters

* The rms value is a calculated mean or effective value of a time-varying function. For an electric field with field strength $E(t)$ and periodicity T (= 1/frequency) it is calculated according to:
$E_{rms} = [\,(1/T)\,\int_t^{t+T} E(t)^2\,dt\,]^{0,5}$

- radar
- surveillance devices

and sources where the energy remains within an enclosed domain:
- industrial heating devices
- household heating devices
- (para)medical applications.

In annex B the Committee gives a classification of sources of EM fields and of environments where EM fields are present.

2.2 Measuring and calculating EM fields

Whether or not the intensity of an EM field may have an adverse effect on health is largely determined by the induced electric current or the SAR. However, these quantities cannot be readily and noninvasively measured directly in the human body. Information on field strengths and induced currents in the body can only be derived from measurements on quantities such as the external electric or magnetic field strength, or, especially at frequencies over 200 MHz, the electromagnetic flux density (NCRP81).

Several points need consideration for the correct evaluation and interpretation of measurements.

First, it is obvious that the parameters have to be measured with adequate equipment. There is a large variation in sensitivity and tolerance; the choice of non-optimal equipment may have a negative influence on the accuracy of the measurements.

Furthermore, there will always be an inaccuracy in the measurements, resulting from the given tolerance in the readings and some systematic (but minimizable) instrumentation faults. Anisotropic probes, *i.e.*, probes that do not have a spherical sensitivity characteristic, are inherently associated with an isotropic error (the top/side ratio), an error caused by the ellipse ratio (the effect of turning the probe on its axis) and a frequency-related sensitivity. Typical values for the combined uncertainty associated with these factors are ± 1.8 to ± 4.1 dB* for the power reading and of ± 0.8 to ± 2.0 dB for the voltage or current reading. An uncertainty of ± 0.8 dB can be

* In measurement technology it is common practice to express differences and errors in decibel, dB. The dB scale is proportional to the logarithm of the ratio of two values of the same physical quantity. To convert the errors to a linear scale, the mean measured values have to be divided by the dB factor to obtain one limit and multiplied by it to obtain the other limit. This means that if, *e.g.*, a power reading of 1 W/m^2 is associated with an error of ± 0.8 dB, the error range is between 0.8 and 1.25 W/m^2.

obtained for the power reading by always moving and turning the probe for maximum readout and by accurate calibration. When such good measurement practice is not applied, the uncertainty can be as high as ± 4.8 dB.

Finally, the local field strengths or power densities can be influenced by the presence of an object or person (NCRP81). This works two ways. Measurements in free space can be disturbed by the presence of persons nearby, for instance those performing the measurements. Also, the field strengths and currents in a person at the location where these parameters are measured in free space will be different from those actually measured. This is a problem that is more difficult to overcome and for which measurements in life-size phantoms are needed.

With respect to measurements of EM fields, the Committee recommends to follow the guidelines of the NCRP* (NCRP93).

2.3 Calculation of the SAR inside a human body

In order to obtain some quantitative insight into the absorption of an EM field by a human body, model calculations have been performed for the Committee, using an advanced numerical threedimensional model. These calculations are given in annex C. The results show that calculations performed with the numerical 3-D model yield outcomes that are in line with results obtained with simple mathematical models using spheres and ellipsoids to correlate the internal SAR with external EM field intensities.

2.4 Exposure levels

Humans can be exposed to EM fields from a variety of sources (see 2.1.4). Exposure depends strongly on the type and geometry of the source, the frequency of the EM field generated, the distance from the source and local conditions such as shielding. Because so many factors are involved, it is not possible to give a full description of the exposure of the population in the Netherlands, nor of populations anywhere else. Some examples of typical exposure situations, however, are given in annex D. In a report recently issued by the Ministry of Social Affairs and Employment an inventory has been made of the exposure of workers to EM fields (Kle95).

2.5 Biological mechanisms

The effects of EM fields on biological structures can be distinguished in thermal and non-thermal effects. The thermal effects are well documented and are associated with

* The National Council on Radiation Measurement and Protection in the USA.

heating of the structure resulting from dissipation of energy from the EM field as described in section 2.1. Non-thermal effects are mainly associated with induced electric currents in the biological structure. In this section the biological mechanisms influenced by these different types of effects will be discussed.

2.5.1 Non-thermal effects

Effects of electric currents

All animal and human cells have an electric potential difference across their cell membrane, resulting from the difference in the concentrations of ions and charged macromolecules, such as proteins, in the intra- and extracellular space. This potential difference is most pronounced in electrically excitable cells: nerve cells and muscle cells. The difference in ion concentrations is maintained by ion pumps and ion channels that result in active and passive transport of ions, respectively. External stimuli (*e.g.* an electric current) may alter the ion transport across the cellular membrane and as a result of that the potential difference over the membrane. This results in depolarization or hyperpolarization, depending on the direction in which the scales tip. In nerve cells, changes in potential during physiological stimulation are several tens of millivolts per cell. Following the stimulus, the resting potential is restored by active and passive transport of ions across the cellular membrane.

Supranormal stimuli, such as strong electric currents, may lead to temporary altered functions of the nervous system, that especially become apparent in the motor system (*e.g.*, by nerve and muscle stimulation and involuntary movements). With sustained very strong stimulation tetanus and muscle damage will occur. If this involves the heart muscle, it may lead to cardiac arrest. In table 5 an overview is given of the general biological effects evoked by different current densities. The threshold current densities for neuronal and muscular stimulation increase progressively at frequencies below several Hz and above 1 kHz (Ber88).

Table 5 Effects in the human body evoked by different current densities in the frequency range of 3 - 300 Hz (WHO87).

current density (mA/m^2)	effect
< 1	no effects demonstrated
1 - 10	minor physiological effects
10 - 100	clear physiological effects
100 - 1000	possible adverse health effects
> 1000	acute danger resulting from ventricular fibrillation

EM field-induced currents in humans

For EM fields below about 10 MHz, *i.e.*, with wavelengths larger than 30 m, the human body is small compared with the wavelength of the fields. As indicated in 2.1.3, at these frequencies little of the energy of the electric or magnetic field is absorbed by tissues, and biological effects, *e.g.* the stimulation of nerves or muscles, result from currents that are induced by the fields. The field strength necessary for stimulation of

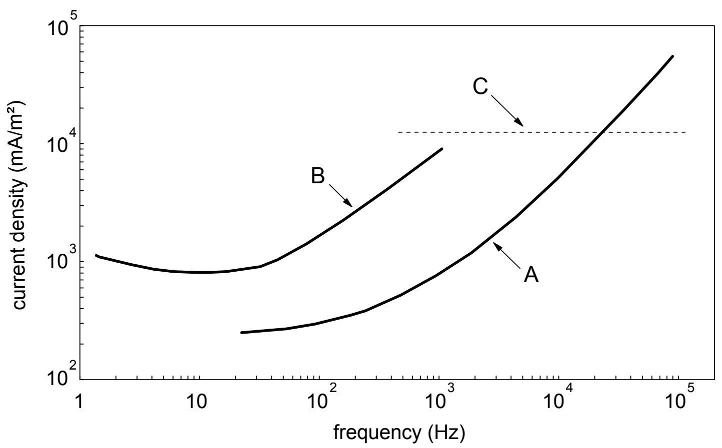

Figure 2 Threshold current densities for effects on excitable cells. Curve A: envelope of thresholds for stimulation of various cells under various conditions; curve B: threshold for stimulation of extra-systole (heart muscle); curve C: current density approximately corresponding to a SAR of 1 W/kg in muscle tissue. (Modified from Ber85, Ber86 and WHO93.)

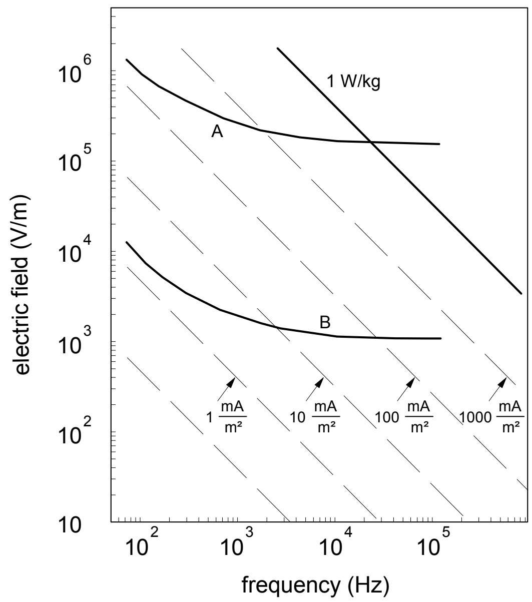

Figure 3 Unperturbed electric field strength, as a function of frequency, that induces the indicated current density (mA/m^2) in the head or cardiac region of a person exposed with the long axis of the body parallel to the orientation of the E-field. In other parts of the body the current densities are larger at the same external field strengths. Curve A: threshold value for the stimulation of various cells under various conditions; curve B: limit value curve with a safety margin of about 100 from potentially hazardous levels in curve A. (Modified from Ber85 and WHO93.)

nerves or muscles depends on the frequency. Current density values resulting in stimulation effects increase approximately linearly with frequency above 1 kHz (see figure 2). At 10 kHz the threshold of current density for relevant effects on excitable tissues is about ten times higher than with frequencies below 1 kHz (see figures 3 and 4). Above 100 kHz the current density thresholds for stimulation of excitable tissues are higher than those required to produce energy dissipation rates of about 1 W/kg. At such rates of interaction, thermal effects become important.

External field strength compared with internal natural fields in humans

Internal electric fields or current densities induced by man-made fields normally are much weaker than the internal natural fields in humans*. Data on internal fields strengths resulting from external fields are not readily available for the frequency range considered in this report, 300 Hz to 300 GHz. Determination of the internal fields is

* The electric potential across the cell membrane, which is typically between 10 and 100 mV, corresponds to a static electric field of 2×10^6 to 20×10^6 V/m.

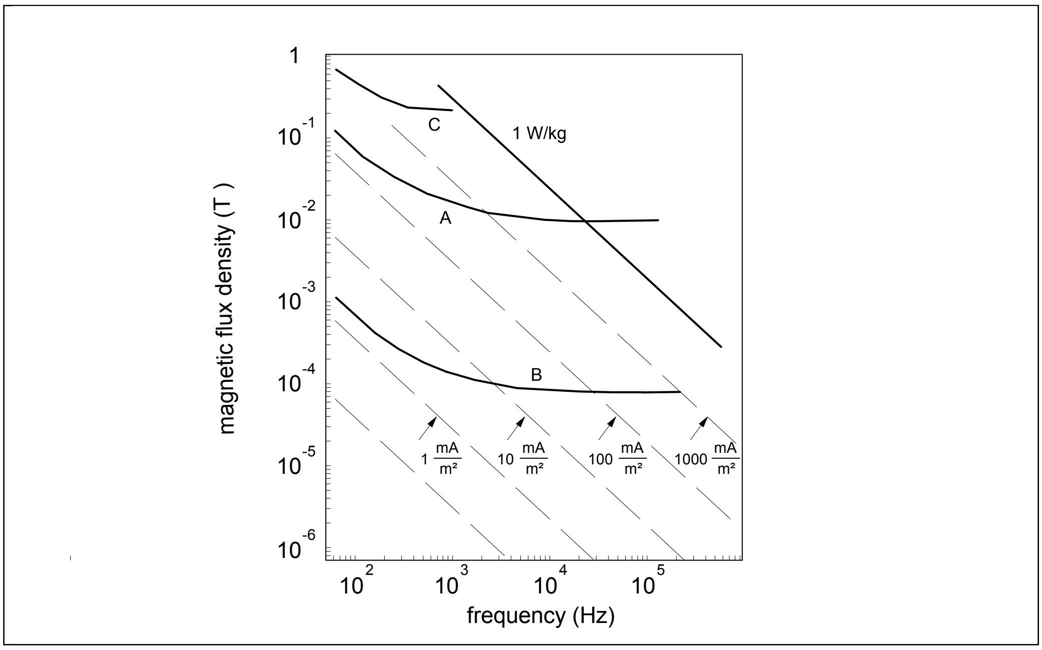

Figure 4 The magnetic fluxdensity as a function of frequency for inducing current densities to the peripheral regions of the head or the heart. For larger effective current loops (*e.g.* for the trunk) the induced current densities may be larger at the same external magnetic flux density. Curve A: threshold for stimulatory effects in nerve or muscle tissue; curve B: limit value curve with a safety margin of about 100 from the potentially hazardous levels in curve A; curve C: threshold for effects on heart muscle. (Modified from Ber85 and WHO93.)

hampered by the strong frequency dependence of penetration of EM fields in biological tissue in combination with the complex composition of biological structures.

Other non-thermal effects

Some experimental results obtained from exposure to EM fields have been interpreted as indicating that effects occur with field strengths well below the stimulation threshold for excitable tissues and without significant changes in temperature. This concerns behavioural changes and changes in EEG patterns in continuous-wave or frequency-modulated fields, altered efflux of calcium ions from brain tissue exposed *in vitro* to extremely low frequency-modulated waves, and changes in embryo development (see section 2.6.5). Several theoretical models have been proposed to explain these observations, but thus far none of these has been validated. Moreover, convincing experimental evidence from independent studies supporting these data is lacking.

2.5.2 *Thermal effects*

Dosimetric quantities

With increasing frequency there is a gradual shift from induction of currents to deposition of energy by the EM fields. In the frequency range from 100 kHz to a few hundred MHz, the human body becomes a much more effective absorber of EM fields due to resonance between the EM field and the body. This occurs when the wavelength approaches the body dimensions. Above approximately 100 kHz the power density needed to induce current densities high enough to stimulate excitable tissues becomes higher than that required to produce energy deposition rates of about 1 W/kg. However, with frequencies between 100 kHz and 10 MHz it is possible to stimulate excitable tissue with short pulses without detectable heating. Therefore, between 100 kHz and 10 MHz both induced current density and SAR should be considered as relevant dosimetric quantities. With frequencies above 10 MHz the SAR is the relevant dosimetric quantity for establishing exposure effects. Over 10 GHz absorption is increasingly superficial and the heating is related directly to the power density of the incident fields. Therefore the incident power density of the field is the appropriate measure of exposure.

The absorbed energy of a specific field strength at a specific frequency depends on a number of factors, such as the polarization of the field, the size of the person, whether he is sitting or standing and whether he is in good contact with the ground. Any selection of a lower frequency cut-off value for thermal effects is arbitrary (see section 4.2).

Resonance

Several frequency ranges for thermal effects can be identified, on the basis of absorption characteristics of the human body. In fact, all organisms exhibit a resonance behaviour, marked by a significant increase in absorbed energy when the incident wavelength is in the range of the body dimensions – the smaller the body, the higher the resonant frequency. According to the same principle, resonance can also occur in specific body parts.

For exposure of the human body in the sub-resonance range, frequencies less than 30 MHz, where the length of the body is much less than the incident wavelength, the average SAR is characterized by a dependence on the square of the frequency.

In the resonance frequency range (30 - 300 MHz), the average SAR in a person reaches its maximum. For an adult standing in free space, resonance occurs at a

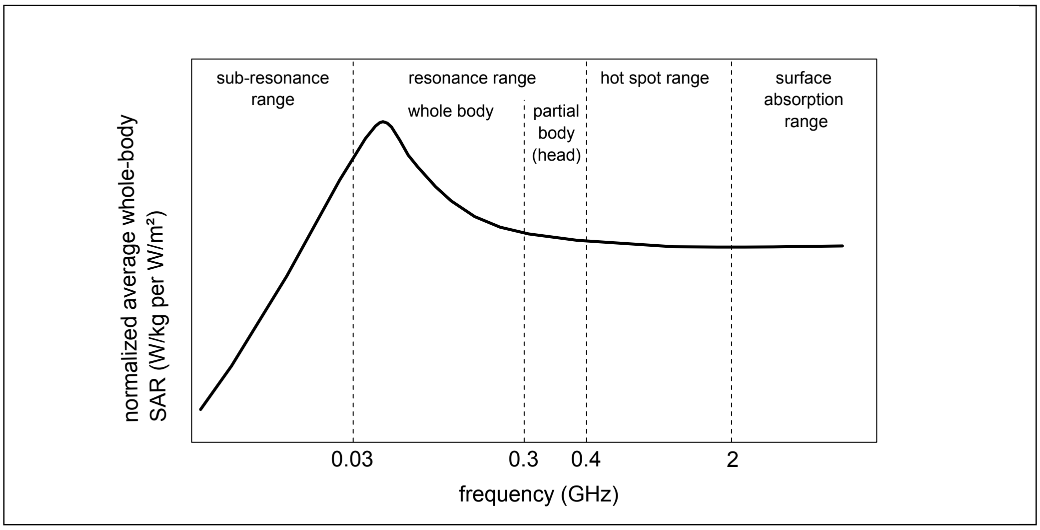

Figure 5 Illustration of normalized average whole-body SAR with frequency and related absorption characteristics in adult humans. (Source: WHO93, modified.)

frequency of approximately 70 - 80 MHz when the electric field is aligned vertically*. If the person is grounded, this frequency is halved. The resonance frequency increases for smaller body lengths: for an ungrounded 5-year-old child it is approximately 160 MHz. As the frequency increases, partial body resonance in the legs, arms or head may occur as the wavelength of the EM field comes into the range of the dimensions of the particular body part, *e.g.* for the head at about 300 - 400 MHz.

At frequencies in the range of approximately 0.4 - 2 GHz locally increased energy deposition may result. This frequency range is often referred to as the 'hot spot' range.

As the frequency increases, the depth of penetration decreases and the energy absorption occurs increasingly superficial: the surface absorption range, extending from about 2 GHz to 300 GHz.

A schematic illustration of the frequency dependence of the SAR is shown in figure 5.

Heating

Energy deposition by EM fields in the 10 MHz - 300 GHz range results in heating. The human body can detect heat such as that caused by exposure to EM fields through different mechanisms. Cutaneous perception may be an indicator for exposure at frequencies of several GHz and more. In the surface absorption range, with

* The wavelength in tissue depends on the permittivity of the tissue. (The permittivity is a property that represents the influence of a medium on the electric flux density.) The internal wavelength is always shorter than the external incident wavelength.

wavelengths similar to, or smaller than the thickness of skin, most of the energy is absorbed in the outer tissue layers containing thermal sensors. In the sub-resonance, resonance and ‘hot spot’ frequency range the energy will penetrate deeper into the body. The internal organs do not have thermal sensors and therefore cannot sense heat in the same way as does the skin. Only when temperatures are high enough, pain may be experienced. Thermal damage can already occur, however, at power density levels that do not cause sensation of pain (Jus88).

A moderate increase in the internal temperature due to external stimuli is compensated by a variety of mechanisms (*e.g.* sweating or changes in skin blood flow). An increase in temperature that is too high (over approximately 41 °C in humans) cannot be adequately compensated for and leads to irreversible structural changes in important cellular proteins. Overheating (‘burning’) causes cell death as a result of denaturation of proteins and evaporation of water. In principle this process is irreversible, although in the long run local regeneration (wound healing) may occur. This is not the case, however, in brain and muscle tissue. Also, certain organs have a poor blood supply and are therefore easily overheated. This pertains especially to the testes, where excessive heat may inhibit spermatogenesis, and to the eye lens, where excessive heating may cause cataract.

The compensating mechanisms mentioned will need some time to come into effect and to measurably exert their influence. A measure for this effect is the thermal equilibrium time, defined as the time for a temperature rise of the body to decay by 50% after removal of the extraneous heat source (NRPB93). Thermal equilibrium in humans exposed at rest is estimated to be attained in about 1 hour (NRPB93). The Committee considers 6 min a reasonable estimate for the thermal equilibrium time. With such decay half-time the temperature rise will be reduced to about 0.001 of its original value after 1 h (= 10 half-times). The Committee will use 6 min in its recommendations as an averaging time for SAR determination.

2.5.3 *Indirect effects: contact currents*

In case of EM-field exposure at frequencies below 100 MHz, currents can be induced in humans upon physical contact with large ungrounded metallic objects. From 300 Hz to approximately 100 kHz, such currents may result in the stimulation of electrically excitable tissues (nerves and muscles) above the threshold for perception of pain. At frequencies between approximately 100 kHz and 100 MHz, contact currents of sufficiently high density may cause burns when they enter through a small cross-section of the body, such as a finger (Ber88, WHO93).

2.6 Experimental studies on the biological effects of EM fields

There is abundant literature on the biological effects of exposure to EM fields. However, indications for harmful effects on humans are relatively scarce, since most studies have been performed on animals. In recent years, there is increasing literature (see, *e.g.*, ICN96, WHO93) reporting the absence of effects, and the possibility of publication bias in the older literature is probably higher than in more recent literature.

The Committee chose not to review each single publication available, but to rely on several recent reviews on the effects of EM fields (Her93, ICN96, NCRP86, Sau91, WHO93), supplemented with recent publications collected through the MEDLINE literature database up to April 1996. The following sections present a short overview of the effects involved. The publications reported are indicative for the lower thresholds of power density or SAR resulting in measurable effects. All data pertain to animal studies, unless specified otherwise.

2.6.1 General comments

Most research dealing with effects of EM fields has been performed in the MHz and GHz range. Relatively few investigations have been carried out in the kHz range. For example, the WHO report on EM fields lists only 6 experiments in the kHz range *versus* approximately 200 in the MHz and GHz range (WHO93).

In general, the experimental data indicate that the effects of EM fields occur at lower power densities when the object is exposed to pulsed EM fields compared with exposure to continuous fields. When available, the Committee reports thresholds for pulsed or continuous EM fields separately. If no differentiation is made, only data on effects due to continuous EM fields were available.

The literature on biological effects of radiofrequency carrier waves that are amplitude-modulated at extremely low frequencies is reported separately in section 2.6.5.

2.6.2 Effects at the cellular level

DNA damage

The data suggest that the only exposures that are potentially mutagenic are those at high power densities, which result in a substantial increase in temperature. When temperatures remain within physiological limits, neither acute nor long-term exposure results in an increase in chromosome aberration frequency (WHO93).

Recent reports suggest that low level, acute exposure to radiofrequency EM fields may increase single and double DNA strand breaks in brain cells (Lai95, Lai96). However, given the weight of evidence against a direct effect of EM fields on DNA and the fact that these studies appear to carry some experimental flaws, the experiments need to be replicated before they can be used in assessing health risks (ICN96).

Carcinogenesis

Results of cancer-related studies are contradictory and in most cases difficult to interpret. Long-term exposure to continuous wave EM fields at 2450 MHz, leading to SARs of 2-3 W/kg, has been reported to enhance the development of chemically induced tumors in mice (Szm82, Szm88). However, several shortcomings in these studies, such as the use of inadequate control groups, preclude drawing firm conclusions (WHO93).

Effects on membranes

The NCRP concluded in its review of effects on macromolecular and cellular systems that for continuous waves at frequencies above 5 MHz, if an effect occurs at all, it is associated with elevated temperatures (NCRP86). In a more recent review Cleary noted that there is strong evidence from a number of *in vitro* experiments for the involvement of non-thermal interactions as well as heating (Cle89). Effects that may be attributed to specific interactions include altered transport of potassium and sodium ions across erythrocyte plasma membranes, changes in calcium ion fluxes across membranes and decreased activity of specific enzymes (WHO93). Table 8 of WHO93 contains contradictory findings and indicates that the exact membrane temperature is the crucial factor in the probability that an effect occurs (Lib84). The lower threshold for effects is a SAR of around 2-3 W/kg and is associated with an increased Na^+ efflux in human erythrocytes (Fis82).

2.6.3 *Interactions at the organ level*

Auditory effects

The induction of auditory effects during exposure to pulsed EM fields has been thoroughly investigated. For frequencies between 200 MHz and 6.5 GHz exposure to pulsed fields is perceived by some people as audible clicks, chirping or buzzing sounds, depending on the pulsing regime and the power density. The auditory effect results from the induction of thermoelastic waves in the head due to a temperature increase as low as 5×10^{-6} °C. The threshold for this effect is related to the energy density per pulse for pulses shorter than 30 μs and to the peak power for pulses up to 500 μs. In humans, a threshold value for the energy density of 16 mJ/kg per pulse was found (Guy75). In animal studies, reported thresholds vary from 0.9-1.8 mJ/kg per pulse of 30 μs (corresponding to SARs of 30-60 W/kg) for rats to 10-16 mJ/kg per pulse of 30 μs (corresponding to SARs of 300-500 W/kg) for cats (Cho85, Guy75).

For exposure of the ear to continuous waves no effect other than heat sensation has been reported.

Eye

Due to the poor ability of the eye to remove heat, exposure to EM fields can easily induce a significant temperature rise. Induction of cataracts by exposure to EM fields has been studied extensively. Different exposure conditions can affect the type of opacity formed. Below 1.5 GHz, the dimensions of the orbit-eye combination are too small to result in local field concentration. Above 10 GHz, penetration decreases and power absorption becomes restricted to superficial tissue (NCRP86). A threshold power density of approximately 1.5 kW/m^2 (corresponding to a SAR of 100 W/kg) was observed for the development of cataract in rabbits exposed for 1 hour to continuous EM fields (WHO93). However, in primates no cataracts were observed with exposure to power densities as high as 5 kW/m^2 (WHO93).

After exposure of monkeys to pulsed EM fields Kues and co-workers found in histological evaluation of the irises an increased vascular leakage at a SAR of 2.6 W/kg (Kue88). Enhanced vascular leakage was reported in monkey eyes pre-treated with the eye pressure reducing drug timolol maleate at power densities as low as 10 W/m^2, corresponding to a SAR of 0.26 W/kg (Mon88).

Teratogenic effects

The literature shows that exposure to EM fields at power density levels high enough to induce a significant increase of the maternal body temperature is required for teratogenic effects to occur (WHO93). Among the effects reported are reduced fetal mass, specific abnormalities (especially exencephaly), increased embryo and fetal losses and enhanced effect of chemical teratogens. Threshold SARs for the induction of these effects with continuous EM fields are in the range of 4-7 W/kg for mice and rats (Jen84a, Jen84b, Mar86). Lary and Conover concluded that heat causes birth defects and prenatal mortality when the temperature of the pregnant female animal exceeds 40 °C (Lar87).

In one study teratogenic effects are described in rats after exposure of dams from day 0 to 20 of gestation to 27.12 MHz continuous fields, resulting in a whole body SAR of only 0.1 mW/kg (Tof86). However, these results are difficult to reconcile with those of other studies employing the same frequency, demonstrating that embryotoxic and teratogenic effects were directly related to the temperature of the dams during EM field exposure, once a threshold (41.5 °C for 40 min) was exceeded, and to the duration of the increased temperature (Bro88, Lar82). This dose-effect relationship is well known from direct exposure of humans to heat (Ple81, War86).

Testes

Effects of exposure to radiofrequency EM fields on male fertility are mainly caused by heat. A problem with most experimental studies is that the animals need to be anaesthetized, which alters their response to thermal loading. Under these conditions of impaired thermoregulation, a threshold value of 30 W/kg has been reported for a reduction in the number of primary spermatocytes and spermatids after exposure to continuous EM fields for 30 min (Kow83, Sau81).

Exposure to pulsed EM fields yielded a threshold of 8-10 W/kg for these effects (Leb87).

Cutaneous perception

In general there is a delay in response from the onset of exposure to EM fields to the sensation of warmth or pain (Sau91, WHO93). This delay is variable, from fractions of a second to many seconds. Both perception and delay are strongly depending on frequency, power density, duration of exposure, dimension of the exposed area and location of the exposed part of the body. In humans, pain thresholds are about two orders of magnitude above the perception threshold. Reported perception thresholds in humans range from external power densities of 130 - 600 W/m^2 for both pulsed and continuous fields. Cutaneous perception depends on the frequency of the incident EM field. For frequencies in the GHz range exposure to EM fields will be perceived by heat sensation in the skin, whereas for frequencies in the resonance region internal organs may suffer thermal damage without any sensation of warmth or pain during the exposure. Thus, cutaneous perception of EM energy is not a reliable sensory response for the full frequency range considered in this report.

2.6.4 *Interactions at the systemic level*

Induced-current effects

At frequencies below 100 kHz results of experimental animal studies and theoretical modelling have been used to identify frequency-dependent stimulation thresholds as a function of electric and magnetic fields. Figures 2, 3 and 4 show some of these thresholds.

Cardiovascular system

Responses of the intact cardiovascular system to exposure to EM fields are consistent with those associated with conventional heating. The effects reported depend on power density and environmental conditions.

In several studies, the effect of exposure to EM fields in magnetic resonance systems has been investigated in human volunteers. Conflicting results are reported. Exposure times of 17 to 30 min at low SARs (0.8 - 3 W/kg) were associated with an increase in heart rate of up to 45% and an increase in body temperature of 0.7 °C (Aba89, Kid85), while at higher SARs of 2.7 - 4.0 W/kg only minimal changes in heart rate and body temperature were found (Sch85, She89). However, these studies were performed on a limited number of subjects who were aware of being exposed to EM fields, which might have influenced the heart rate. There were no controls. Therefore it is difficult to interpret these studies.

The lowest reported threshold value for a change in heart rate in rats due to exposure to continuous fields is a SAR of 2.3 W/kg (McR88). Heart weight was not affected by long-term exposure (several hours per day for 6 months) at a SAR of 2.5 W/kg (D'An80).

No cardiovascular responses have been found for short or long-term exposure to pulsed or modulated EM fields.

Nervous system

Most experiments have been performed on the brain. Among the effects reported are altered EEG response, changes in permeability of the blood-brain barrier, increased Ca^{++} efflux, and different responses to drugs.

In numerous studies the experimental conditions were not optimal and effects of electrode currents, low temperature and low oxygen tension cannot be excluded (Lid84, NCRP86). Such studies are not suitable for determining exposure limits.

For exposure to continuous wave EM fields the lowest threshold reported is around 2 W/kg; it is associated with increased permeability of the blood-brain barrier (Alb77). Baranski and Edelwejn report potentiation of the effects of neuroactive drugs by continuous wave exposure at a SAR of 1.2 W/kg (Bar74).

For exposure to pulsed EM fields the lowest threshold value is reported by Lai and co-workers: after 45 minutes of exposure to 2450 MHz given in 2 μs pulses at 500 Hz resulting in a SAR of 0.45 W/kg, choline uptake in rats decreased (Lai89).

Changes in EEG pattern have been found in rabbits after long-term exposure to amplitude-modulated EM fields with a SAR as low as 0.001 W/kg (Tak79). However, this was a small preliminary study with only four animals, in which the EEG pattern might have been influenced by the application of anaesthesia. The research has not been continued since and the result remains unconfirmed. Consequently, it is difficult to value these results and this study is also not suitable for determining exposure limits.

Hematological effects

In a large number of studies hematological effects in animals exposed to EM fields were investigated. Such effects have only been found when a significant rise of the body temperature was induced (Sau91, WHO93). Smialowicz reviewed earlier studies and did not find any consistent effect of exposure to EM fields on peripheral blood cells in developing rats (Smi84).

Immunologic effects

Exposure to EM fields has been reported to affect various components of the immune system. Stimulatory as well as inhibitory responses have been reported, but they were mostly transient in nature and could usually be attributed to thermal stress. Common effects are depression of natural killer cell activity and increased lymphocyte responsiveness. Similar effects are found after conventional heat application. For exposure to continuous wave EM fields the threshold for these effects is in the range of 2-5 W/kg (Lib79, Pri72).

Long-term (25 months) exposure of rats to pulsed EM fields with SARs up to 0.4 W/kg did not result in any immunological effects (Guy85b).

Endocrine effects

The endocrine response to exposure to EM fields appears to be similar to the response to other external stress-inducing factors such as noise or heat: corticosterone levels in the blood increase and thyroxin levels decrease. Lu and co-workers reported in rats a decrease in corticosterone levels after continuous wave exposure to 0.2 W/kg, while in the same experiment an increased corticosterone level was observed when the exposure level was increased to 8.2 W/kg (Lu81).

In primates (Rhesus monkeys) a threshold of 3-4 W/kg was found for these effects with pulsed EM fields (Lot82, Lot83).

Thermoregulatory responses

Exposure of human volunteers to SARs of up to 4 W/kg for 20-30 minutes resulted in increases of the body temperature of 0.1-0.5 °C (Gor86, Kid85, Sch85, She87, She88, She89). Environmental conditions have a strong impact on the threshold values for thermoregulatory response.

Thermoregulatory responses to continuous wave EM field exposure have been reported to occur at SARs as low as 0.3 W/kg for rats, mice and monkeys (Ada82, Lot88, Ste79).

Temperature-dependent behavioural effects

Hot working environments are known to increase accident rates and reduce task performance in humans (Bel67). This phenomenon has not been assessed in relation to exposure to EM fields, however.

For animals, the threshold SAR for affecting the ability to learn new tasks is lower than that at which the proper performing of known tasks is disrupted, 0.7 W/kg and 2.3 W/kg, respectively (DeL84, D'An86b, Mit77). A threshold of 0.1 W/kg was reported for a decrease in the ability to learn certain operant tasks (D'An86a). However, these findings could not be reproduced (DeW87).

From these studies, the threshold for effects with exposure to pulsed fields appears to be in the same range as that with continuous wave fields.

It is not clear whether during the experiments on behaviour the influence of auditory effects (see 2.6.3) can be excluded.

2.6.5 Biological effects of ELF amplitude modulated EM fields

A substantial research effort is directed to possible effects of ELF EM fields on biological systems. A discussion of these studies is outside the scope of the present report. However, several of these studies have been carried out where radiofrequency EM fields, amplitude modulated at ELF frequencies, have been used to increase the penetration of the ELF signals into the tissues. The most widely known are the experiments in which the Ca^{++} efflux from chicken brain tissue was studied (*e.g.* Bla85, Bla89). Also other tissues were studied using *in vitro* and *in vivo* experiments in several species.

The question now arises whether the reported effects of these ELF amplitude modulated EM fields are only due to the ELF modulation or whether there is also a contribution of the radiofrequency EM fields. Several observations argue against the latter possibility:

- the effects of exposure to ELF fields only and to ELF amplitude modulated EM fields are similar
- in experiments that showed effects of ELF amplitude modulated EM fields, no effect of the radiofrequency EM fields alone was found
- in most of the experiments the tissue was exposed to very low power densities of 7.5 to 147 W/m^2 or SARs of 0.3×10^{-3} to 5.3×10^{-3} W/kg (assuming a factor of 0.36×10^{-4} for the conversion of W/m^2 to W/kg; Bla89).

Also, the following comment can be made. Considering the field intensity as the exposure metric, in several experiments, an ELF field intensity 'window' has been found. In such a window, a response is observed in a specific intensity range, while at higher and lower intensities the response is weak or even absent. In some experiments even more than one window was observed. In itself, window-effects are not new in biology. They can be the result of competing processes such as cell growth and temperature. Multiple window-effects over a range of a single variable, however, cannot be simply explained. Several hypotheses have been put forward but remain as yet unproven (Bla89, Pos88).

In short, there is no scientific consensus about the observations that have been reported in these experiments with ELF amplitude modulated EM fields and about their interpretation. The Committee therefore considers these studies not suitable for use in determining exposure limits.

2.6.6 Conclusions

In vitro studies are important to determine the mechanisms of interaction between EM fields and biological systems and to identify appropriate biological endpoints and exposure conditions to be tested in whole animals. They cannot, however, solely serve as a basis for health risk assessment in humans. Animal studies are necessary to study the integrated response of the whole biological system to exposure to external factors, such as EM fields. The extrapolation of results from animal studies to humans has to be done with great care. It requires an understanding of the underlying mechanisms in the different species involved.

Assessment of the health risk of exposure to EM fields has to be done within the context of the ability of the human body to deal with thermal stress under regular circumstances. In normal environments the thermoregulation system of healthy individuals is able to remove heat at rates of 3 to 6 W/kg for extended periods of time. In everyday life, the healthy body deals without problems with thermal loads varying from 1 to 10 W/kg induced by resting metabolism or muscular activity (Duk80, Gor84).

The animal studies indicate that most effects of exposure to continuous wave EM fields are only observed at power densities capable of causing a significant increase in tissue temperature. There is a wide range of threshold SAR values for the various effects. The lower threshold SAR is in the order of 2-3 W/kg and at the higher end values up to 100 W/kg have been reported. Threshold SARs for behavioural and thermoregulatory effects are lower, ranging from 0.3 to 0.7 W/kg, but these findings cannot be easily extrapolated to humans, who have additional thermoregulatory mechanisms compared to the animals studied.

Experiments with human volunteers showed that exposure to SARs of approximately 4 W/kg during 20-30 minutes is required for a small increase in body temperature. With exposure to pulsed EM fields, effects were generally noted at slightly lower power densities than with exposure to continuous wave fields.

2.7 Epidemiological studies

Almost all epidemiological studies of the effects of exposure to EM fields performed so far are case-control studies, a type of study that is disease-oriented. A group of patients is selected according to certain criteria and a group of controls is composed that matches as far as possible the group of patients regarding a number of relevant characteristics. Next, the factors to which patients and controls were exposed in the past are identified. The finding that a certain exposure is more frequent among patients than among controls could indicate a possible causal association.

In the risk assessment of exposure to environmental factors, in principle epidemiological data are preferred. There are numerous problems, however, that can decrease the validity or value (not to be confused with the statistical reliability) of the results of epidemiological studies. These problems can only be accounted for in part. In case of the health effects of exposure to EM fields, a number of factors can be identified that have a negative bearing on the reliability of the results (Den92, WHO93):

- Frequently the results are based on exposure characteristics, for instance a job description or living at a certain distance from a source of EM fields, and not on actual exposure measurements at the site of the receptor. Hence, the possibility of exposure misclassification cannot be excluded.

- It is difficult to establish the exposure to EM fields in individuals over a meaningful period of time.
- Control of confounding is very difficult. Some major confounders are simultaneous exposure to ELF EM fields or exposure to other physical or chemical agents.

A detailed review of the epidemiological literature is given by Dennis and co-workers (Den92), by the WHO (WHO93) and, most recently, by Goldsmith (Gol95). The studies mentioned in these reviews will be shortly outlined. In addition, some recent studies are discussed.

2.7.1 General health

In the late sixties some investigators in the former USSR described a number of non-specific health complaints relating to long-term exposure to EM fields, occurring in industry workers occupationally exposed to microwaves. A large number of complaints were reported, such as headache, sleep disturbances, tiredness, loss of sexual potency, pains in the chest and feelings of non-well being. Also, some changes in blood cell concentrations and blood chemistry were reported. In general, these studies were lacking a proper experimental design. Therefore it is not possible to draw any conclusions from them regarding a possible association between exposure to EM fields and health effects.

Two properly designed studies performed in the seventies in eastern Europe are worth mentioning. Siekierzynski studied exposure of Polish men to pulsed EM fields generated by radar equipment (Sie74). He did not find any difference in functional disturbances between a group that had been exposed for one to ten years to power densities of 2 - 60 W/m^2 and a non-exposed group (power densities less than 2 W/m^2). Djordjevic did not find any negative effect on the health status of Yugoslav radar personnel in relation to a five to ten years exposure to pulsed radar fields at power densities up to 50 W/m^2 (Djo79).

Lilienfield and co-workers studied the personnel of the American embassy in Moscow, which was exposed in the period 1953 - 1976 to very low levels of RF radiation between 0.6 and 9.5 GHz with power densities up to 0.15 W/m^2. The study included 4827 exposed individuals and a control group of 7561 individuals. The exposure time was 9 to 18 hours a day for an average period of 8 months. No differences in health status or effect on life span or cause of death could be linked with exposure to EM fields (Lil78).

Robinette and associates studied a group of 40,000 American naval personnel. One group of 20,000 was occupationally exposed to pulsed EM fields at frequencies between 0.2 - 5 GHz generated by radar equipment during the Korean War. The exposure level, which was estimated on the basis of job description and power of the equipment, was occasionally in excess of 100 W/m^2. The exposure level of the control group was less than 10 W/m^2. The average duration of exposure was two years. The more exposed group was split in a subgroup with an expected 'moderate' exposure and one with an expected 'high' exposure. No significant differences in overall mortality or morbidity were seen between the two subgroups and the controls (Rob80).

In a recent small study (17 exposed *vs.* 12 controls), Nilsson and co-workers performed extensive neurological, psychometric and neuropsychiatric examinations on radar mechanics who had been exposed to pulsed EM fields at levels in excess of 10 W/m^2. No indications for effects on the central nervous system were found, except that the frequency of occurrence of an increase in a protein band with an isoelectric point of 4.5 in the cerebrospinal fluid was higher in the exposed group. However, the significance of this finding for the health status is unclear (Nil89).

Workers exposed to EM fields from heat sealing and plastic welding machines, which operate in the frequency range 20-100 MHz, are possibly the most highly occupationally exposed group. Employees working on these machines who had been exposed at levels of 100-250 W/m^2 and even higher, showed increased rates of paraesthesia in the hands (numbness, impaired two-point discrimination), neurasthenia (nervous disability characterized by lassitude, headache, backache and indigestion) and irritative eye symptoms. The eye complaints were sometimes aggravated by the fumes of the heated plastic material (Kol88).

Since the lens of the eye is particularly sensitive to heat, some epidemiological studies have focused on lens opacities and cataracts. In most studies no differences were found between exposed and non-exposed (mostly military) personnel. Investigations of long-term effects in elderly workers are lacking. In confirmed cases of cataracts, exposure to EM fields was estimated to exceed 1 kW/m^2 (Den92). In animal experiments, cataracts were observed in rabbits after exposure at 2450 MHz up to 1.5 kW/m^2, but not in primates after exposure to 5 kW/m^2 (see 2.6.3).

2.7.2 *Reproduction and birth outcome*

In the seventies a few studies have been carried out on possible adverse reproductive outcome in relation to exposure of the father to EM fields from radar. Results of a study in which a correlation was found between exposure to EM fields and Down's syndrome (Sig65), were not confirmed in later studies (Bur77, Coh77).

No differences in pregnancy outcome in 305 female welders were found compared with the Swedish general population. The exposure levels of the female welders exceeded 250 W/m^2 (Kol88).

Epidemiological studies among female physical therapists have indicated that exposure to EM fields may have reproductive effects. A case-control study in Sweden by Källen reported that physical therapists who gave birth to children with malformations had been exposed to higher levels of ultrasound and stronger EM fields from short-wave equipment than other physical therapists (Käl82). Larsen observed with Danish female physical therapists a statistically significant gender shift in the offspring in favour of girls (80% girls *vs*. 20% boys) which may be associated with exposure to EM fields during the first month of pregnancy (Lar91). These findings could not be confirmed by a study in Switzerland, however. This study also failed to show that the prevalence of low birth weight is related to the exposure (Gub94).

Ouellet-Hellstrom and Stewart concluded from a case-control study that pregnancies of physical therapists in the USA were more likely to result in miscarriage when the mothers reported the use of microwave diathermy units (915 MHz and 2,450 MHz) 6 months prior to the pregnancy or during the first trimester (Oue93). The odds ratio increased with increasing levels of exposure, even after control for prior fetal loss. Although the trend was significant, the odds ratio at the highest exposure level was not. Whether the excess risk is associated directly with the use of microwave diathermy or with 'something closely related to its use' has yet to be determined. The risk of miscarriage was not associated with use of short-wave diathermy equipment, operating at 27 MHz (Oue93). Since the exposure data obtained in this study were based on self-reported use of microwave and short-wave diathermy, recall bias will be present. Furthermore, the observations cannot be reconciled with the physical argument that the highest exposure to a pregnant uterus in the first trimester will most likely be from exposure to short-wave and not from microwave diathermy (Hoc95).

2.7.3 Cancer

In the earlier mentioned study of 40,000 American naval personnel the 'moderate' and 'high' exposed groups appeared to have higher mortality rates from cancers of the digestive tract, respiratory tract and the lymphatic and hematopoietic systems than the control group, but these mortality rates were not statistically significant (Rob80).

In a small study among long-term EM field-exposed military personnel the reported frequency of exposure was higher among 14 cases of polycytemia than in 17 age-matched controls (Fri81). Since the exposure data were obtained by interview, it is possible that recall bias confounded the results.

In a retrospective cohort study of Polish military personnel exposed to EM fields, an increased cancer incidence was found. The exposure was described as 4 to 8 hours per day at levels below 2 W/m^2 with several minutes in the range 2-10 W/m^2, but sometimes even 100-200 W/m^2. An increased incidence was observed for lymphomas and leukemia, but confounding by other harmful and possible carcinogenic factors cannot be excluded (Szm88). No causal relationship has been established (Szm96).

Thomas and co-workers studied the risk of brain tumors in men in electrical and electronic jobs, with special attention to possible exposure to EM fields (Tho87). The occupations considered involved exposure to radiofrequency EM fields but also to ELF fields, soldering fumes and solvents. An excess brain tumor risk of 2.3 (95% confidence interval 1.3 - 4.2) was found to be related to an electrical or electronic job, but could not be explained by exposure to microwave and radiofrequency EM fields.

Studies of non-occupationally exposed people are rare. In 1982, Lester and Moore claimed a correlation between increased cancer mortality and possible exposure to radar from airport bases (Les82). Many confounding factors such as age structure, social class and urbanization may have played a role. The finding could not be confirmed in a later study (Pol85).

Recently, in Hawaii a cluster of children with acute leukemia was detected in the vicinity of a military installation with low-frequency radio towers transmitting at 23.4 kHz. In a case-control study with 12 cases and 48 matched controls the odds ratio for having lived within 2.6 miles of the radio towers before diagnosis of leukemia was 2.0. However, this result is not statistically significant (Mas94).

Milham studied amateur radio operators, using records of licensed amateurs living on the west coast of the USA, and derived standardized mortality ratios (SMRs) for comparison with USA population-based mortality rates. The SMR for all causes of death was lower for the radio amateurs, but for some types of leukemias significantly raised SMRs were observed, especially for acute myeloid leukemia and related neoplasms of the lymphoid tissues and multiple myeloma. A problem with this study is again the lack of data on exposure and exposure conditions. A relevant observation is that 30-40% of the radio amateurs had electrical or electronics occupations, with exposure to ELF fields and chemicals such as metal fumes, solvents and PCBs acting as confounding factors (Mil85).

2.7.4 *Conclusion*

The Committee concludes that the epidemiological studies indicate that general health effects due to exposure to EM fields are not to be expected at the levels to which people are normally exposed.

The conflicting results on the effects of exposure on birth outcome in female physical therapists make further studies necessary before any firm conclusions can be drawn on this issue. Special attention must be given at adequate exposure dosimetry, since in the present studies the exact exposure is not known.

The epidemiological studies do not provide evidence that EM fields *per se* have a carcinogenic effect. Some studies suggest a higher cancer risk for occupations where combined exposure to EM fields and chemical agents may occur. However, due to the design of these studies many confounding factors are involved. Therefore it is difficult to say whether EM fields play a role. This question should be further evaluated in appropriate epidemiological studies.

2.8 Specific groups at risk

An important step in establishing exposure limits is to define the population to be protected. A commonly used distinction is that between the general public and the occupationally exposed population, because of several differences in exposure status and susceptibility between these groups. Some of these differences are summarized in table 6.

Table 6 Differences between the occupationally exposed population and the general public.

occupationally exposed	general public
exposure levels higher	exposure levels lower
exposure potentially 40 h/week	exposure potentially continuous, lifetime
‘healthy workers’ no children and elderly	broadly variable health status all ages
often controlled conditions • exposure surveillance • special medical attention	uncontrolled conditions • exposure level unknown • no special medical attention
precautions against RF burns and shocks	no precautions
awareness of potential risk	generally no awareness; involuntary risk

Among both the occupationally and non-occupationally exposed populations there can be people who are more susceptible than average to exposure to EM fields. This susceptibility can be divided into two categories: susceptibility due to a disturbed thermoregulatory function and susceptibility due to implanted medical devices. A summary is presented in table 7.

Table 7 Causative factors for a higher susceptibility to possible adverse effects of exposure to radiofrequency EM fields (Ber92, Hoc91, NRPB93, WHO93).

disturbed thermoregulation	implanted medical devices
age (young children and elderly)	cardiac pacemaker
obesity	orthopedic devices
fever	cochlear implants
diabetes	cardiac valves
cardiovascular disease	transcutaneous drug delivery systems
hormonal dysfunction	
cerebral dysfunction	
medication	
pregnancy	

2.8.1 Disturbed thermoregulation

Because heating is the major effect of exposure at frequencies above 10 MHz, restrictions on whole-body heat loads are proposed to avoid adverse health effects. It is well-known that some people are less tolerant to heat than others and therefore more susceptible to thermal stress imposed by exposure to EM fields. One factor of importance is age: the thermoregulatory system of infants is under-developed and in the elderly no longer fully competent. Also, obesity and cardiovascular diseases, such as hypertension, decrease the ability to adapt to an increased heat load.

A rise in body temperature due to fever or a hormonal (hyperthyroidism) or cerebral (hypothalamic lesion) dysfunction will decrease the ability to adapt to thermal stress induced by exposure to EM fields. Also various drugs, such as some diuretics, vasodilators, tranquilizers and sedatives, decrease heat tolerance.

Thermal stress is known to be teratogenic in experimental animals, including primates. Central nervous system and facial defects in children are linked with severe hyperthermia *in utero* during the first trimester of pregnancy (Mil92, Ple81). The embryo and fetus may be at risk for heating induced by EM fields because of less effective cooling mechanisms. It has been shown that fetal temperature rises more than that of the mother during severe thermal stress (You90).

It is important to note that the impact of a compromised thermoregulatory function in humans in combination with a whole-body heat load from EM fields is still speculative. Only a few studies describe the response of people who are less tolerant to heat or have impaired thermoregulation to exposure to EM fields (Bud85, She87, She89). These data pertain to patients undergoing magnetic resonance diagnostic procedures at whole-body SARs of around 0.4 W/kg, recording variable increases in body temperature. However, it is not clear whether this response can be fully ascribed to the exposure to EM fields. The stress induced by being confined to the rather narrow cylinder of the MRI equipment may well influence the body temperature.

Also a high environmental temperature or heavy physical strain may have a negative influence on thermoregulation.

2.8.2 *Implanted medical devices*

Metallic implants exposed to EM fields increase local energy absorption by enhancing the local electric field. As a result the surrounding tissue may be heated. Especially orthopedic metallic devices, such as wires, plates, rods and joint replacements, may be of interest. But also other devices need consideration, such as metal cardiac valves and transdermal drug delivery systems containing metal parts, such as implanted insulin infusion systems. Concern about dental restorations is not necessary: the cooling in the mouth is efficient and teeth are heat-resistant (Hoc91). The exposure limits for the general public are considered to prevent also the occurrence of untowards effects of heating of tissue around metal implants.

For other implanted medical devices such as cardiac pacemakers and cochlear implants, electromagnetic interference (EMI) is of main interest. EM fields may directly interfere with the pulse generator of a cardiac pacemaker, or indirectly through the lead system that can act as an antenna. Shielding and filtering can largely prevent EMI, but sufficiently strong interfering signals may still result in malfunctioning of the pacemaker. Interference with cochlear implants occurs through the direct reception of radio signals. Sources in the workplace from which interference has been reported include electric arc welding equipment, transmitting towers and antennas, dielectric and induction heaters and diathermy devices (Hoc91).

Recently, concern has been raised about mobile cellular telephones and their potential risk to pacemaker patients. Mobile cellular telephones may be an important source of EM fields due to their widespread use and their potential proximity to the implanted cardiac pacemaker, for example when carried in the breast pocket of a jacket.

In annex E the Committee provides background information on EMI of cardiac pacemakers and present relevant standards. A comprehensive evaluation of research into the effects of EM fields generated by portable telephones on pacemaker function has recently been published by Wireless Technology Research (WTR), an independent organization created to develop and implement research designed to address potential public health risks from wireless communication technologies. The conclusion of this study is that several types of cardiac pacemakers are susceptible to EM fields (Car96). This may even be the case for field strengths lower than exposure limits based on thermal effects, that have been proposed by several organizations and that will be dealt with in chapter 3 of this report.

The Committee therefore subscribes the recommendations of WTR (see annex E) that special precautions be taken to prevent EMI of EM fields on cardiac pacemakers. People wearing an implanted pacemaker should not carry a portable telephone that is in stand-by mode in close proximity to the device, but maintain a minimum distance of 15 cm. Furthermore pacemaker manufacturers should be encouraged to develop models that are adequately protected from EMI by wireless communication devices.

2.8.3 Electromagnetic interference with other medical equipment

Electromagnetic interference by EM fields from portable telecommunication devices may disrupt the proper functioning of vital medical equipment, *e.g.*, cardiac surveillance equipment in intensive-care units (VIF95). This may indirectly result in threats to the health of patients. The Committee therefore endorses recent proposals made by the telecommunication industry for the restriction of the use of hand-held telephones in the vicinity of sensitive medical equipment (VIF95).

Chapter **3**

Basic restrictions: current guidelines

Data on effects on humans is very limited. Most data has been obtained with animal experiments. However, in most of these experiments only specific frequencies have been employed. In order to allow a better assessment of the health risk from exposure to EM fields, a larger spectrum of exposure conditions should be studied.

Extrapolation of animal bioeffect data to human exposure situations is complicated by the differences in electromagnetic parameters between humans and animals, differences in mechanisms regulating body temperature and differences in body dimensions. These result in a different dependence of the effects considered on the wavelength and intensity of the EM fields, hampering the drawing of quantitative conclusions for humans from animal experiments. However, many animal studies are highly relevant for the understanding of the putative mechanisms by which EM fields could interact with animals and humans at the molecular and cellular level.

In chapter 2 the Committee indicated that different dosimetric quantities are important at different frequency ranges. Certain levels of these quantities should not be exceeded in order to limit the risk of adverse health effects. In line with common practice these health-based recommended exposure limits are termed basic restrictions in this report. In the present chapter the basic restrictions proposed by various national and international organizations are summarized.

3.1 Currents

As outlined in section 2.5.1, the most important effects in biological tissues in the frequency range of 300 Hz - 10 MHz are caused by electric currents that are induced in the body by EM fields, or by contact currents. In order to avoid effects that may adversely affect health, such as interference with the function of nerves and of nerve cells, the currents in the body should not exceed certain limits. It is generally accepted that in the lower frequency range, 300 Hz to 1 kHz, current densities of 10 mA/m^2 or lower do not lead to adverse health effects. Above 1 kHz this limit value increases linearly (see 2.5.1) and can be described by $f/100$, where f is the frequency in Hz (CEN95a, NRPB93).

3.2 SAR

Generation of heat is considered to be the most relevant effect of exposure to EM fields in the frequency range of 100 kHz - 10 GHz (see section 2.5.2), although some of the proposed standards also use it as the basic restriction in the lower frequency range. It is assumed that in humans exposure to a whole body average SAR of 2-4 W/kg during minimally 20 to 30 minutes leads to a total body warming of 0.1-0.5 °C (NRPB93, WHO93). A sustained 1 °C temperature rise in core body temperature is generally accepted to be the maximum tolerable (IEEE92, NRPB93). A sustained further raised temperature may lead to adverse health effects. The Committee agrees to this.

The animal experiments lead to the conclusion that under otherwise normal environmental conditions adverse health effects generally do not occur when the SAR is less than approximately 4 W/kg.

Based on either one of these arguments, all guidelines proposing organizations feel that exposure to EM fields should not lead to a whole-body SAR of more than 4 W/kg.

Safety factors

When the presently available data is used to estimate exposure levels for which it is assumed that the chance for deleterious effects on human health will be negligible, the uncertainties and variability in exposure conditions, the only limited knowledge about the response of humans to exposure to EM fields and the variations in susceptibility of human beings have to be taken into account. In the extrapolation of animal data to humans, the differences between the species, as mentioned before, have to be accounted for. To these purposes, safety factors (SF) are often applied to the exposure levels at which the occurrence of effects is presumed to be negligible.

The value of the SF basically depends upon a judgement of the uncertainty in the available data. In the case of the choice of an SF for the SAR, external and internal factors that influence the regulation of the body temperature are taken into account, besides, in case the proposal is based on animal data, the interspecies variation. For instance, variables considered by IRPA/INIRC* in the development of SFs were (IRPA88):

- differences in absorption of energy of EM fields by humans of various size, with special regard to children
- the lack of knowledge of the relationship between peak SAR of pulsed fields and biological effects
- differences in environmental conditions; a high ambient temperature, high humidity and low air movement lower the maximum tolerable thermal stress; exposure limits should also be protective under these adverse conditions
- reflection, focusing and scattering of the incident fields causing enhanced absorption of energy.

In addition to this, other factors may be considered in deriving an appropriate SF for EM field exposure, *e.g.*, the presumed disturbed thermoregulation in the frail elderly, people with certain diseases, pregnant women, etc. Also, differences in activity patterns (*e.g.,* during physical exercise) between exposed individuals may be relevant. The influence of other factors on the risk is uncertain and therefore difficult to account for. Such factors include possible altered response of humans taking medication, possible combined effects of EM fields with chemical or other physical agents in the environment, possible effects of modulated fields on the central nervous system.

IEEE** states that with the selection of the SAR limit of 4 W/kg ‘worst-case’ conditions were taken into account that, collectively, provide a greater degree of safety than that implied by the explicit SF of 10 (IEEE92). Furthermore IEEE states that the impact of exposure to 0.4 W/kg is practically indistinguishable from that of normal ambient temperature variations, exposure to the sun, exercise, etc.

3.3 Recommendations by various organizations

In this section, the Committee gives a short overview of the basic restrictions proposed in the different guidelines and indicates their rationale and, if applicable, those for the applied SFs. In several cases, different recommendations are given for ‘workers’ and

* The International Non-ionizing Radiation Committee of the International Radiation Protection Association. Since 1992 it operates as an independent organization under the name International Commission on Non-ionizing Radiation Protection (ICNIRP).

** The Institute of Electrical and Electronics Engineers in the USA.

‘public’, for adults and children or for ‘controlled’ and ‘uncontrolled’ environments. (Controlled environments being defined as areas where people may be exposed while being aware of such exposure, either because it is part of their professional duties or because the possibility of exposure is clearly indicated by posted signs.) The philosophies underlying such distinctions will be briefly outlined in section 4.1.

Health Council

In the 1975 report of the Health Council of the Netherlands, no subdivision was made in the frequency range considered of 300 MHz to 300 GHz (GR75). The concept of SAR was not yet developed, exposure limits were given in terms of power density and were based on thermal effects. The Council recommended a maximum power density of 100 W/m^2, averaged over 1 second and for at most 5 h per day, for ‘microwave workers’. A value of 10 W/m^2 for continuous exposure was proposed for all others. No rationale for the implicit SF of 10 was provided.

ANSI

On the basis of an extensive review of the literature the American National Standards Institute (ANSI) concluded in 1982 that acute exposure, less than 1 hour, at a whole body average SAR of less than 4 W/kg is not associated with adverse health effects (ANSI82). This conclusion is based on disruption of behaviour with acute exposures in experimental animals. For a number of reasons, related to safety and biological uncertainty, a tenfold reduction in the permissible whole body average SAR was proposed, leading to a maximum SAR value of 0.4 W/kg for continuous exposure. In a 1992 update of these guidelines an extra safety factor of 5 was introduced for exposure in uncontrolled environments for certain frequency ranges, *e.g.,* resonance frequencies (IEEE92). This results in a maximum permissible SAR of 0.08 W/kg. These recommendations pertain to the frequency range of 100 kHz - 6 GHz.

The basic restriction in the range of 6 - 300 GHz is a power density of 10 mW/cm^2 (= 100 W/m^2), both for controlled and uncontrolled environments. An additional requirement in the frequency range 100 kHz - 300 GHz is a maximum body-to-ground current of 100 mA for controlled and 45 mA for uncontrolled environments.

For the lower frequency range, 3 - 100 kHz, the effects of induced and contact currents were taken into account. A complex and extended rationale is provided (IEEE92).

IRPA/INIRC and WHO

Also IRPA/INIRC has chosen the whole body average SAR of 4 W/kg, based on thermal considerations, as the basic quantity for establishing exposure limits in the frequency range of 10 MHz - 300 GHz (IRPA88). An additional criterion is a maximum body-to-ground current of 200 mA. For occupational exposure an SF of 10 is applied to the value of 4 W/kg, resulting in whole-body-average-SAR limit of 0.4 W/kg. As rationale for the SF a number of specific reasons is listed that have been indicated in section 3.2. For exposure of the general population an additional SF of 5 is used, resulting in a limit for the whole-body average SAR of 0.08 W/kg (IRPA88).

At frequencies below 10 MHz IRPA/INIRC bases its recommendations on a maximum body-to-ground current of 200 mA. A difference of a factor 5 between workers and the general population is introduced for the derived maximum permissible electric and magnetic field strengths.

The recommendations of IRPA/INIRC have been integrally adopted by the World Health Organization (WHO93).

ICNIRP* recently issued a statement on health issues associated with the use of portable telephones (ICN96). In this paper, ICNIRP proposes partial body SAR limits of 10 W/kg for workers and 2 W/kg for the general public.

NRPB

The National Radiological Protection Board of the United Kingdom (NRPB) states that a short-term rise in body temperature of 1 °C is acceptable from a health point of view and that the temperature should not exceed 38 °C over prolonged periods (NRPB93). It is stated that exposure to a SAR of 1 W/kg for about 1 h, or to a SAR of 4 W/kg for a short period will result in a temperature increase of less than 1 °C in a lightly clothed person. NRPB proposes a SAR of 0.4 W/kg as basic restriction for the frequency range between 100 kHz and 10 GHz, but does not provide a rationale for the magnitude of the safety margin. No distinction is made between workers and general population. However, in the values for the electric and magnetic field strengths that are derived from the SAR, relaxation of the limits values by a factor of 1.2 to 1.4 is allowed in the resonant frequency range if no children are exposed.

The basic restriction for the frequency range of 10 - 300 GHz is a power density of 100 W/m^2.

* The International Commission on Non-ionizing Radiation Protection, since 1992 the independent continuation of the International Non-ionizing Radiation Committee of IRPA.

In the lower frequency range, current density in the body is the limiting factor. It should not exceed 10 mA/m^2 between 300 Hz and 1 kHz, and *f*/100 mA/m^2 (*f* in Hz) between 1 kHz and 100 kHz.

CENELEC

The European Committee for Electrotechnical Standardization (CENELEC) has recently issued two prestandards for the exposure to low- and high-frequency electromagnetic fields (CEN95a, CEN95b).

In the frequency range of 1 MHz to a few GHz, CENELEC holds a SAR of 4 W/kg the threshold for effects considered detrimental for health. For workers an SF of 10 is applied, resulting in a maximum allowed SAR of 0.4 W/kg. For the public an additional SF of 5 is introduced, resulting in a SAR of 0.08 W/kg. Additionally, for the frequency range of 10 - 100 MHz a maximum current of 100 mA (workers) or 45 mA (public) through any limb is allowed.

In the upper frequency range, up to 300 GHz, the specific absorption is the principal basic restriction. For workers the limit is set at 10 mJ/kg and for the general public at 2 mJ/kg.

In the lower frequency range, up to a few MHz, current density is the basic restriction. Up to 1 kHz the maximum value is 10 mA/m^2, and at higher frequencies it increases linearly according to *f*/100 mA/m^2 (*f* in Hz). These values are for workers and include an SF of 10; for the public an additional SF of 2.5 is proposed. CENELEC provides no rationales for its choices of the SF.

3.4 Current situation in the Netherlands

In the Netherlands no standards regulating maximum exposure to radiofrequency radiation are in effect. In the leaflet ‘Rules for radiofrequency radiation near broadcast stations’ the Chief Public Health Inspector for Environmental Hygiene uses the 1988 IRPA/INIRC guidelines (VROM90).

Chapter **4**

Conclusions and proposed health-based exposure limits

4.1 Thermal and non-thermal effects

The demonstrated effects of EM fields on humans and animals can be distinguished in the induction of currents in the body, the principal effect encountered in the lower frequency range, and the generation of heat resulting from the absorption of electromagnetic energy, the predominant effect in the higher frequency range. Some experimental studies suggest that biological effects may result from other non-thermal mechanisms than induced currents. However, these studies generally suffer from various inadequacies, such as improper design and inappropriate analysis of the experimental data. Moreover, the results could not be reproduced in independent studies. Also, these observations, as far as they are found with *in vitro* studies, are difficult to extrapolate to adverse effects for an entire organism and no biological mechanisms for such effects can be readily put forward. Therefore, in proposing exposure guidelines for the frequency range of 10 MHz and higher, the Committee cannot take putative biological effects resulting from non-thermal mechanisms into consideration.

4.2 Distinction between population groups or areas

All organizations that have proposed guidelines feel that exposure limits should not apply to all people in every situation. There are two different approaches to this issue. The first is that a distinction is made between workers and the general public. The second approach is to make a distinction between restricted and unrestricted areas. For some parameters a distinction is made by some organizations between adults and children, if differences in sensitivity between these groups are important.

The Committee feels that there are good reasons for a two-tier exposure proposition and prefers the distinction between workers and general public. The rationale is that workers generally form a homogeneous group of healthy people, while the general public also consists of elderly, young, sick, and weak people in which the homeostatic, temperature-controlling mechanisms might be compromised. Other arguments are uncertainties about long-term effects due to a lack of data, the absence of direct medical and general supervision for the public with respect to exposure to EM fields and the fact that workers are exposed only during working hours, while the general public can be exposed continuously.

The Committee defines 'workers' in the framework of this report as those adult individuals who may be exposed in the course of their professional duties to EM fields **and** who are trained for awareness of the risks associated with such exposure and for taking precautions. This means that not all employees of a company where exposure to EM fields is possible are workers according to this definition. The essential factor is whether the employees are trained as described.

4.3 Derivation of guidelines: basic restrictions

In the previous chapter, the Committee described that ANSI, NRPB, INIRC/IRPA and CENELEC all proposed to adopt an energy deposition corresponding to an average whole body SAR of 4 W/kg as the maximum tolerable. The Committee agrees with this approach, but feels that the rationale for selecting this criterion as the basic restriction for setting guidelines is not well-explained by each of the organizations mentioned. According to the Committee, the most relevant rationale is based on experimental data obtained with volunteers, where it was demonstrated that exposure during more than 20 min to a SAR of 4 W/kg results in a rise in the body temperature of approximately 1 °C. Although the human body can tolerate such temperature rise, it is uncertain whether a long lasting elevation of the body temperature increases the risk of adverse effects. In order to prevent such increased risk, the Committee feels that a safety factor should be applied to the 4 W/kg value. It suggests a factor of 10, in line with the approach of ANSI, NRPB, INIRC/IRPA and CENELEC. This results in a basic restriction of a SAR of 0.4 W/kg. For the reasons mentioned in the previous section the Committee makes a difference between workers and general public and introduces an extra SF of 5 for the public, resulting in a maximum SAR of 0.08 W/kg. The averaging time for the determination of the whole-body SAR should be 6 min (see 2.5.2).

In the lower frequency range, biological effects result from induced current rather than from generation of heat. Therefore the current density should be restricted. The Committee follows the recommendations of NRPB, but, instead of making a difference between adults and children, differentiates between workers and general public. The values proposed by NRPB for adults are applied to workers and the values for the general public are set a factor 5 lower.

There is no sharply defined transition between frequencies where the induced current and where the SAR is the most relevant dosimetric quantity. Therefore the Committee suggests to use both current density and SAR basic restrictions over the frequency range of 100 kHz - 10 MHz.

In the frequency range of 10 GHz and higher, surface absorption dominates and the SAR is a less useful parameter. The Committee proposes to use the incident power density, that is directly proportional to the surface absorption, as basic quantity in this frequency range. A value of 100 W/m^2 is proposed for workers. This is in line with the recommendation of ANSI (IEEE92) and NRPB (NRPB93). It should be noted that in the Health Council report 'Optical radiation' (GR93) the recommendation for the infrared range of 300 GHz and up was 1000 W/m^2. This value is based upon experimental data and ANSI curves dating from 1973 (ANSI73). The 1993 Health Council report adopted the values proposed in an earlier report (GR78). However, since 1973, ANSI has introduced a safety factor of 10 for the 1000 W/m^2 value, resulting in the recommendation of 100 W/m^2. The Committee follows this approach, which is consistent with that used by the SAR, where also a safety factor of 10 is introduced to the value that is considered to be the final health-based exposure limit. Along the same line of reasoning an extra safety factor of 5 is introduced for the power density for the general public, resulting in a limit value of 20 W/m^2.

However, since the deposition of energy becomes increasingly superficial in the upper GHz range and temperature regulation gradually shifts from internal to external mechanisms, the distinction between workers and general public is less relevant in this range. Therefore the basic restrictions for workers and general public can be identical at 300 GHz. The Committee proposes a transition range between 10 GHz and 300 GHz.

The Committee indicated already that for the determination of SAR values an averaging time of 6 min is appropriate. When the effects of exposure are quasi-optical, as is the case in the upper frequency range considered, and the absorption of energy becomes increasingly superficial, the averaging time has to be reduced. In accordance with the recommendation of NRPB, the Committee proposes an averaging time of 6 min for exposure to EM fields with frequencies up to 10 GHz, and a linear decrease of the averaging time to 10 sec at 300 GHz. This corresponds to the following relation between frequency and averaging time for frequencies between 10 and 300 GHz:

Table 8 Basic restrictions.

frequency range	current density (mA/m^2)		SAR (W/kg) [a]		power density (W/m^2) [b]	
	workers	general public	workers	general public	workers	general public
300 Hz - 1 kHz	10	2				
1kHz - 100 kHz	f / 100 [c]	f / 500 [c]				
100 kHz - 10 MHz	f / 100 [c]	f / 500 [c]	0.4	0.08		
10 MHz - 10 GHz			0.4	0.08		
10 GHz - 300 GHz					100	$6.727 \times f^{0.473}$ [d]

[a] averaging time = 6 min

[b] averaging time = $68 / f^{1.05}$ min (frequency f in GHz)

[c] frequency f in Hz

[d] frequency f in GHz

$$t_{avg} = 68 / f^{1.05} \ (f \text{ in GHz}).$$

These averaging times are applicable to the power density, that is the preferred dosimetric parameter in the 10 - 300 GHz range.

The basic restrictions proposed by the Committee are summarized in table 8.

4.4 Derived quantities: exposure limits

The basic restrictions are given in quantities that cannot be readily determined in living organisms. In practice it is more convenient to have limit values for parameters that can be measured in a technically straightforward way. Therefore, limit values are preferentially given for the electric and magnetic field strengths and current densities at the location of the object. All standard-setting bodies have proposed so-called derived exposure limits for these parameters. In most cases rather simple models were used to calculate these values from the SAR. The Committee considers the use of these models acceptable, but recommends that calculations with presently available more sophisticated models be performed.

The values for the derived exposure limits proposed by the various organizations are all based on the same, or almost the same basic restrictions (see chapter 3). Nevertheless they show small differences as a consequence of the model used. The Committee decided that the selection of limit values for the electric and magnetic field strengths should be governed by three criteria. First, they should provide an envelope around the experimental data (NRPB93, Gar95). Second, they should not be unnecessarily restrictive. Third, they should be protective against indirect effects.

Indirect effects are defined in this respect as sensations of perception or pain resulting from contact currents when touching large metallic objects that act as conductor in an electric field. The Committee used the indirect effects reported by Deno (Den74) and Guy (Guy85a) in the establishment of exposure limits.

4.4.1 *Electric field limits*

The starting points for the curves in the lower frequency range are the values for 50 Hz proposed by IRPA/INIRC (IRPA90) and adopted by the Health Council committee 'ELF electromagnetic fields' (GR92): 5 kV/m for exposure of the general public and 10 kV/m for exposure of workers. Extrapolation to higher frequencies is done according to the frequency-dependence of the induced current density (table 8), that is the basic restriction in this frequency range. The resulting curve for workers, that describes E-fields a factor 2 higher that those for the general public, is considered to apply to situations where indirect effects may be possible. If this is not the case, E-field limits that are a factor 5 higher than those for the general public may apply to workers.

In the intermediate frequency range from approximately 2 kHz to 1 MHz, the Committee down-extrapolates the curves proposed by IRPA/INIRC (IRPA88) to frequencies lower than 0.1 MHz up to the point where they intersect the curves established for the lower frequencies.

In the resonance range, defined as 10 MHz to 400 MHz, the Committee adopts the recommendations of IRPA/INIRC (IRPA88). The values for the general public are a factor $\sqrt{5}$ lower than those for workers, since the basic restrictions SAR and power density are a factor 5 lower for the general public, and the E-field strengths are quadratically related to both SAR and power density.

In the GHz range the basic restriction is a maximum power density of 100 W/m^2 for workers. This means that the curves of the derived E-fields rise steeper between 400 MHz and 2 GHz than those proposed by IRPA/INIRC, that are based upon a power density of 50 W/m^2. The difference between limits for the general public and workers gradually decreases to zero at 300 GHz.

In figure 6 and table 9 the E-field limits proposed by the Committee are summarized.

4.4.2 *Magnetic fields limits*

In the lower frequency range the Committee again uses as starting point the 50 Hz values proposed by a Health Council committee in 1992 (GR92), that were adopted from IRPA/INIRC (IRPA90). These values, 0.5 mT for workers and 0.1 mT for the general public, are extrapolated to higher frequencies, while fulfilling the current

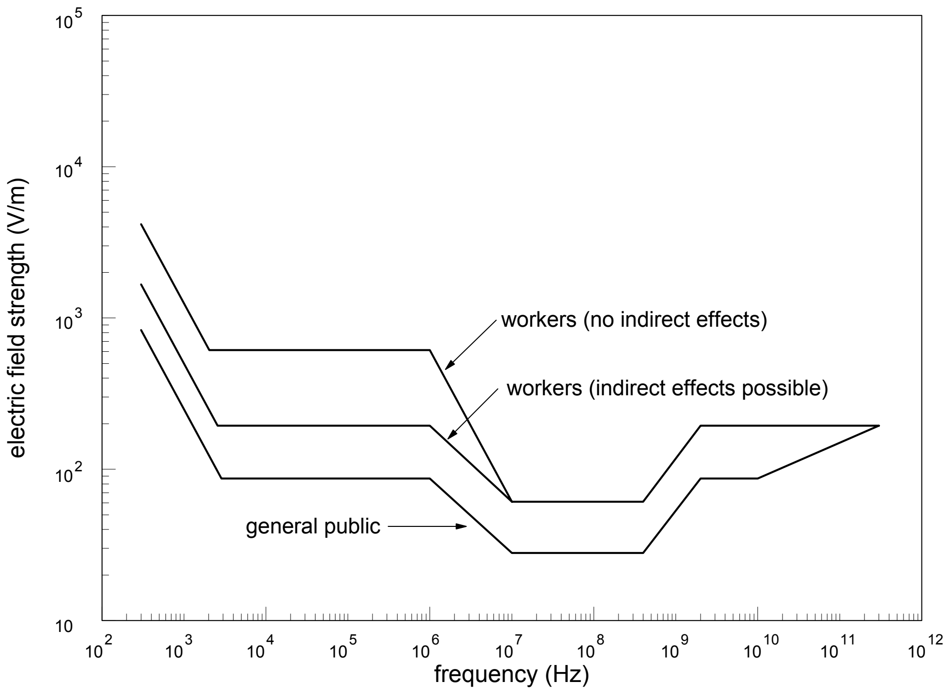

Figure 6 Proposed maximum electric field strengths.

Table 9 Proposed maximum electric field strengths.

frequency	electric field strength (V/m)			
	workers		general public	
	no indirect effects	indirect effects possible		
300 Hz - 2.04 kHz	1250 / f	500 / f	250 / f	(f in kHz)
2.04 kHz - 2.58 kHz	614	500 / f	250 / f	(f in kHz)
2.58 kHz - 2.88 kHz	614	194	250 / f	(f in kHz)
2.88 kHz - 1 MHz	614	194	87	
1 MHz - 10 MHz	614 / f	194 / $f^{0.5}$	87 / $f^{0.5}$	(f in MHz)
10 MHz - 400 MHz	61	61	28	
400 MHz - 2 GHz	$118 \times f^{0.72}$	$118 \times f^{0.72}$	$53 \times f^{0.72}$	(f in GHz)
2 GHz - 10 GHz	194	194	87	
10 GHz - 300 GHz	194	194	$78 \times f^{0.16}$	(f in GHz)

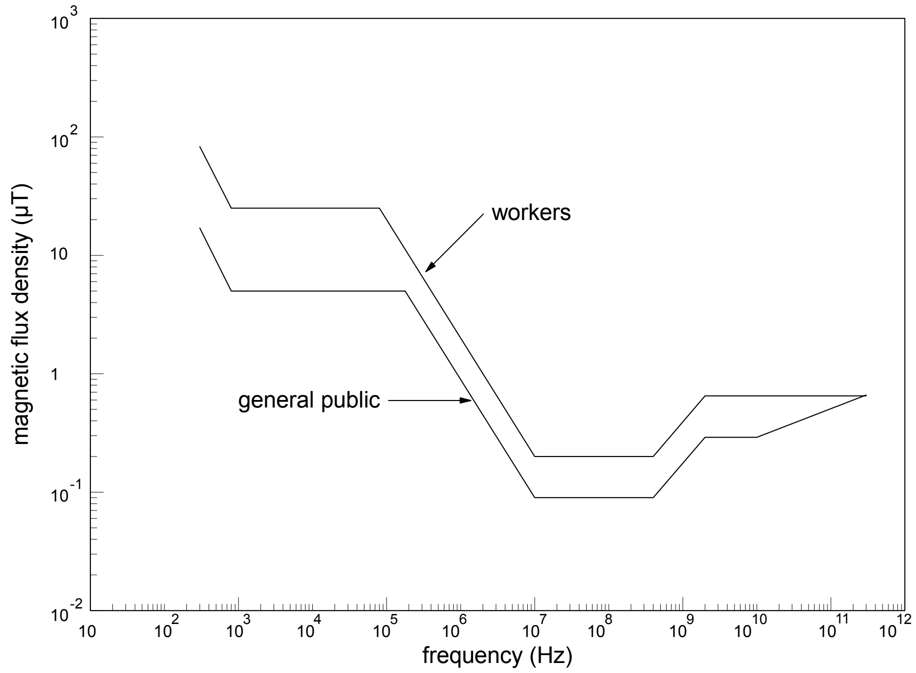

Figure 7 Proposed maximum magnetic flux density levels.

Table 10 Proposed maximum magnetic flux densities and magnetic field strengths.

frequency	magnetic flux density (μT)		magnetic field strength (A/m)		
	workers	general public	workers	general public	
300 Hz - 1.0 kHz	25 / f	5 / f	20 / f	4 / f	(f in kHz)
1.0 kHz - 80 kHz	25	5	20	4	
80 kHz - 180 kHz	2.0 / f	5	1.6 / f	4	(f in MHz)
180 kHz - 10 MHz	2.0 / f	0.92 / f	1.6 / f	0.73 / f	(f in MHz)
10 MHz - 400 MHz	0.2	0.09	0.16	0.07	
400 MHz - 2 GHz	$0.39 \times f^{0.73}$	$0.17 \times f^{0.73}$	$0.31 \times f^{0.72}$	$0.14 \times f^{0.74}$	(f in GHz)
2 GHz - 10 GHz	0.65	0.29	0.52	0.23	
10 GHz - 300 GHz	0.65	$0.26 \times f^{0.16}$	0.52	$0.21 \times f^{0.16}$	(f in GHz)

density basic restrictions given in table 8. The model used is an ellipsoid with axes of 0.4 m and 0.2 m as described by Reilly (Rei92) and a conductivity σ of 0.2 S/m, an average value for muscle tissue.

For the intermediate frequency range, the Committee adopts the values proposed for workers by IRPA/INIRC (IRPA88) in the range of 100 kHz - 400 MHz and down-extrapolates this curve to intersect with the one calculated for the lower frequencies. The values for the general public are a factor √5 lower.

In the upper frequency range, the same rationale as with the electric fields is followed. The basic power density restriction is 100 W/m^2 for workers and the B-field values are calculated accordingly. The difference between workers and public gradually diminishes between 10 GHz and 300 GHz.

In figure 7 and table 10 the B- and corresponding H-field limits proposed by the Committee are summarized.

The Committee stresses that the proposed exposure limits can and should not be considered as strict limits between 'safe' and 'unsafe' levels. They should rather be seen, in line with the approach adopted by NRPB, as levels the exceeding of which requires attention and measures.

4.5 Partial body exposure

General exposure limits are given in the various guidelines for whole-body SAR. NRPB, ANSI and CENELEC also propose partial body limits for various tissue volumes. In general, SAR limit values for the extremities are higher than those for the rest of the body.

The Committee basically follows the recommendations of NRPB, but makes a distinction between workers and public, analogous to the approach for whole-body exposure. The NRPB rationale, that is adopted by the Committee, is to prevent localized temperatures higher than approximately 38 °C in the head or the developing embryo or fetus, 39 °C in the neck and trunk, and 40 °C in the extremities. These conditions will be satisfied if the SAR levels as shown in table 11 are not exceeded. The averaging time is 6 min in all cases.

Table 11 Maximum SAR values in W/kg for partial body exposure.

	head, neck , trunk, fetus[a] averaged over 10 g tissue		limbs averaged over 100 g tissue	
frequency	workers	general public	workers	general public
100 kHz - 10 GHz	10	2	20	4

[a] for the fetus only the value for the general public applies

These recommendations are in line with the proposal of ICNIRP for (near-field) exposure of the head by EM fields emitted by radiotelephones (ICN96). ICNIRP also proposes 10 W/kg for workers and 2 W/kg for the general public.

4.6 Exposures of short duration

The Committee considers all exposures lasting shorter than 6 minutes, the time taken as thermal equilibrium time (see 2.5.2), as exposures of short duration. With such short exposures, temperature controlling mechanisms in the body are not yet effective and there is a linear relationship between energy deposition and temperature increase. SAR values higher than the limits of 0.4 W/kg for workers and 0.08 W/kg for the general public are allowed, as long as the SAR averaged over each 6-min interval does conform to these limits.

4.7 Exposure to multiple frequencies

In most real-life situations exposure to EM fields involves more than one frequency. In order to calculate exposure limits for this kind of combined exposure, the Committee follows the approach of IRPA/INIRC to simply add the power densities or the squares of the electric and magnetic fields strengths, expressed as fractions of the respective limits. The result should not exceed unity. In formula:

$$\sum_{i}\left(\frac{E_i}{L_{E,i}}\right) \leq 1 \quad \text{and} \quad \sum_{i}\left(\frac{H_i}{L_{H,i}}\right) \leq 1 \quad \text{for all frequencies} \leq 10\ \text{MHz}$$

and

$$\sum_{i}\left(\frac{E_i}{L_{E,i}}\right)^2 \leq 1 \quad \text{and} \quad \sum_{i}\left(\frac{H_i}{L_{H,i}}\right)^2 \leq 1 \quad \text{for all frequencies} > 10\ \text{MHz}$$

where E_i is the electric field component from the i-th source, H_i is the magnetic field component from the i-th source and $L_{E,i}$ and $L_{H,i}$ are the corresponding electric and magnetic field limits.

The formulas for frequencies less then or equal to 10 MHz follow from considerations of induced current density, while those for frequencies exceeding 10 MHz follow from SAR considerations. In case some frequencies are below and other above 10 MHz, one should take the most stringent criterion, *i.e.*, the formulas for frequencies less than or equal to 10 MHz should then be applied to all frequencies.

4.8 Pulsed EM fields

The biological effectiveness of pulsed EM fields depends on the average energy per pulse. Both ANSI, IRPA/INIRC and CENELEC provide limits for maximum exposure. The formulas to establish these maxima are quite different, however. ANSI bases its limits on prevention of auditory effects. The Committee does not consider auditory perception of EM fields to be an adverse health effect and therefore does not follow this approach, but only considers non-auditory effects.

In section 2.6.6 it was mentioned that with pulsed irradiation effects were noted at slightly lower power densities than with continuous irradiation. However, the Committee feels that this difference falls within the biological variation in sensitivity and is therefore covered by the applied safety factors. It consequently recommends for exposure to pulsed radiation the same guidelines as for continuous radiation.

4.9 Contact currents

The Committee recommends to set limits to contact currents, in order to protect against electric shocks, discomfort and burns. It again makes a distinction between workers and general public. However, because of the availability of adequate experimental data, a safety factor of only 2 is deemed necessary for the general public. The recommendations are based upon experimental data summarized in WHO93. The values for workers are chosen to prevent pain upon finger contact in adults. With the safety factor of 2 the lower limit is sufficiently protective against even touch perception in children.

The recommendations of the Committee are shown in table 12.

Table 12 Proposed maximum values for contact currents.

	contact current (mA)		
frequency	workers	general public	
300 Hz - 2.5 kHz	1	0.5	
2.5 kHz - 100 kHz	$0.4 \times f$	$0.2 \times f$	(f in kHz)
100 kHz - 10 MHz	40	20	

4.10 Specific applications

4.10.1 Portable telephones

Dosimetry

In order to prevent negative health effects, the EM fields emitted by hand-held telecommunication devices, such as portable telephones and walkie-talkies, need to be restricted in such a way that the energy absorption in the body complies with the guidelines recommended by the Committee. During normal operation of these devices mainly the human head is exposed, therefore the partial body SAR limits (section 4.5) apply. Since the head is in the near-field region of the antenna, it is not possible to derive exposure limits for either the electric or magnetic field. The limits proposed in section 4.4 may not be used, since these are obtained by assuming far-field conditions and whole-body irradiation.

Several numerical and experimental methods have been proposed to determine the SAR in the head (And95, Dim94, Gan95, Mei95, Zwa92a). These studies have shown that the position of the telephone has a considerable influence on the SAR distribution in the head. The presence of the hand and the position of the antenna are also important. The SAR distribution may vary considerably with the design of the telephone. Although the numerical methods are becoming increasingly sophisticated, the Committee feels that they are not yet accurate enough to be used for the calculation of the SAR values inside the head. A major problem is the modelling of the EM fields emitted by the telephone. Numerical simulations should be further developed, but until they can be considered adequate, SAR values should be calculated from measurements of the field strengths generated by the actual telephones in an artificial head.

GSM hand-held telephones

Measurements have been performed on various types of hand-held telephones. For instance, Meier *et al.* tested 9 different GSM telephones, radiating at 900 MHz (Mei95). They measured the strength of the E-field throughout a realistic head phantom and calculated the SAR distribution from those data. The measurements were performed with the telephones in normal operating position, *i.e.*, with the antenna slightly tilted to the back of the head. Focusing or reflecting effects were not observed in this situation. The energy deposition always decreased with increasing distance from the source. SAR values were calculated normalized to 1 W continuous output power. However, GSM telephones operate with a maximum output of 2 W, and actual radiotransmission takes place during only 1/8th of the time (the principle of time-sharing is applied, where the information of seven different users is relayed simultaneously in pulsed 577 μs 'packets'). The effective maximum output therefore is only 0.25 W. To obtain the actual SARs generated by the telephones, the reported values have to be devided by a factor 4 (Kus96). Following this procedure, maximum SARs of 0.03 - 0.7 W/kg averaged over 10 g tissue have been determined. In the worst-case position, with the feeding point of the antenna nearly touching the head above the ear, maximum SAR values of 0.1 - 1.3 W/kg were obtained. These values are well below the partial body exposure limits for the head of 2 W/kg proposed for the general public.

These are very limited data, however, and the Committee recommends that more measurements be performed.

Other hand-held telephones

The digital GSM system is only one of several systems in operation in the Netherlands at present, albeit the fastest growing. In June 1996 more than half of the mobile telephone users, approximately 435,000, subscribed to a GSM network provider (Oud96). The remainder of users of wireless telephones, approximately 300,000, subscribed to one of the analog systems. These operate at different frequencies: 150 MHz (ATF1), 450 MHz (ATF2) and 900 MHz (ATF3). The ATF3 network has the largest number of subscribers. The hand-helds using this system have a maximum output of 1 W. In contrast to the GSM telephones, the analog systems do not use pulsed radiation, but instead transmit continuous EM fields.

Anderson and Joyner measured E-fields in a phantom head induced by three different analog hand-held telephones and calculated SAR levels in the brain and eye (And95). The telephones transmitted at an output power of 0.6 W. Normalized to 1 W output power, maximum SARs in the eye were 0.01 to 0.35 W/kg and in the brain 0.2

to 1.38 W/kg. This means that exposure is well below the maximum SAR value of 10 W/kg recommended for workers and also below the maximum value of 2 W/kg recommended for the public. Temperature increases in both the eye and the brain associated with the indicated SARs were calculated to be less than 0.05 °C (And95).

Again, these are very limited data and the Committee recommends that more measurements be performed. Measurements should also be performed on devices using other analog and digital systems.

A recent report prepared for the Dutch Ministry of Social Affairs and Employment concluded that the field strength from portable telecommunication devices may exceed the limits and that using these devices might therefore pose certain health risks (Kle95). This conclusion was based, however, on calculations on EM fields generated by devices with a maximum output power of 17 W. Since the most commonly used hand-held telephones have a maximum output power of only 1 or 2 W, these conclusions cannot be extrapolated also pertain to the use of these devices. Furthermore, the conclusions were reached by applying far-field limits to near-field conditions. The Committee indicated before that this is an incorrect procedure and that instead reference should be made to SAR values.

Cordless telephones

Cordless telephones are being used in many households. They consist of a handset that has a wireless connection to a base unit which is plugged into the normal telephone outlet. These devices operate with a maximum output power of only 10 mW, which is why they have a reach of no more than approximately 150 m. With such low output power it is not possible that the exposure limits are exceeded. The same is true for the so-called Greenhopper telephones. They also operate with a maximum output power of 10 mW.

Automobile telephones

Car-mounted telephones are widely being used in the Netherlands. With these devices the antenna is located at the outside of the automobile. The maximum output power is higher than that of hand-helds: 6 W using the ATF3 network and 8 W with GSM. Exposure of the occupants of the vehicle generally is low. It strongly depends on the distance to the antenna and on shielding by the metal body of the vehicle. Balzano and co-workers measured E-field intensities and state that with transmissions in the VHF band (30-300 MHz) the E-field intensity in the car is less than 20 V/m (Bal86). Assuming far-field conditions to apply, comparison with table 9 shows that the limit values are not exceeded. Guy and Chou measured E-fields and determined SAR patterns in full-size human phantoms exposed inside and outside an automobile to 835 MHz fields emitted by a roof- or trunk-mounted antenna (Guy86). Localized maximum SAR values were 0.02 to 0.23 W/kg per watt output power outside the vehicle and 0.02 W/kg per watt inside. Converted to the 6 W maximum output power of an ATF3 car-telephone the SAR values are maximally 0.12 to 1.38 W/kg outside and 0.12 W/kg inside. These values are all well below the 2 W/kg limit for partial body exposure of the general public recommended by the Committee.

Epidemiology

In a recent study the overall mortality of cellular telephone users was investigated (Rot96). Within a group of more than 250,000 customers with an account of at least 3 years old, mortality of users of hand-held telephones was not significantly different from that of users of non-hand-held mobile telephones. The authors admit that this is only a very crude estimate, but they also conclude that these findings indicate that there is no large short-term effect on overall mortality of using hand-held telephones.

Conclusions

According to the Committee, the available data do not indicate that the use of wireless telephones may lead to adverse health effects. This is in agreement with the conclusions in a recent statement by ICNIRP concerning mobile telephones (ICN96). However, only very few measurement data have been published. Therefore, the Committee recommends that adequate measurements be performed on a sufficient number of different types of telephones of all systems available.

The Committee also recommends that computational methods be refined as to adequately describe the complex interactions between EM fields emitted by hand-held telephones and the human head. Until this has been accomplished, computational methods should not be used to determine compliance of hand-held telephones with the recommended health-based exposure limits, the partial-body maximum SAR values.

The Committee wishes to stress at this point that compliance with these maximum SAR values only pretends to exclude adverse direct health effects. In special cases, it may be possible that EM fields emitted by these telephones, even when they are low enough not to result in exceeding the recommended SAR values, may form an indirect health risk. This might be the case when interference with sensitive (medical) equipment, such as pacemakers, is possible, as indicated in sections 2.8.2 and 2.8.3.

4.10.2 RF industrial and paramedical equipment

In a recent survey (Kle95) it was shown that both in the Netherlands and in other countries field strengths at the operator position of equipment in use in industrial settings and in physical therapy and operating at radiofrequencies may sometimes considerably exceed exposure limits.

The Committee recommends that exposure levels at the operator position be measured for all equipment presently in use and that adequate precautionary measures be taken to prevent over-exposure of operators and others present near such equipment.

Rijswijk, 28 January 1997,
for the Committee
(signed)

dr E van Rongen,	dr EW Roubos,
scientific secretary	chairman

Glossary of unit symbols

A	ampere: unit of electric current
mA	milliampere = 10^{-3} A
A/m	ampere per meter: unit of magnetic field strength
A/m^2	ampere per meter square: unit of electric current density
°C	degree centigrade: unit of temperature
kg	kilogram: unit of weight
g	gram = 10^{-3} kg
H	henry: unit of inductance
H/m	henry per meter: unit of magnetic permeability
Hz	hertz: unit of frequency; 1 Hz equals 1 cycle per second
kHz	kilohertz = 10^{3} Hz
MHz	megahertz = 10^{6} Hz
GHz	gigahertz = 10^{9} Hz
J	joule: unit of energy
mJ	milli-joule = 10^{-3} J
J/s	joule per second: unit of power
m	meter: unit of length
mm	millimeter = 10^{-3} m
cm	centimeter = 10^{-2} m
km	kilometer = 10^{3} m
m/s	meter per second: unit of velocity
S	siemens: unit of conductance

S/m	siemens per meter: unit of conductivity
s	second: unit of time
µs	microsecond = 10^{-6} s
T	tesla: unit of magnetic flux density
V	volt: unit of voltage
mV	millivolt = 10^{-3} V
kV	kilovolt = 10^{3} V
V/m	volt per meter: unit of electric field strength
W	watt: unit of power
mW	milliwatt = 10^{-3} W
W/m^2	wat per meter square: unit of energy flux density (power density)
W/kg	watt per meter: unit for the specific absorption rate, SAR

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Annexes

Annex **A**

The Committee

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Annex **B**

Electromagnetic sources and environments

Technical developments have resulted in a vast number of different sources of EM fields. As a consequence, the ‘electromagnetic environment’ is usually very complex. A classification of exposures requires a complete inventory of sources and environments. In the framework of this report, such inventory is not possible, since the number of both sources and environments is very large.

The International Electrotechnical Committee (IEC) uses a qualification based on environments, a summary of which is given below (IEC91).

Sources

The following types of source are sufficient to characterize any environment:

- low-frequency sources
- high-frequency sources
- electrostatic discharge sources.

These sources may cause electromagnetic disturbances, resulting from a number of phenomena:

- conducted low-frequency phenomena:
  - harmonics and interharmonics (3 kHz): these result from non-linear sources, *e.g.* in household applications and traction systems
  - signaling voltages in power systems:
    100 Hz - 3 kHz: ripple control systems

3 kHz - 95 kHz: power-line carrier systems
95 kHz - 148.5 kHz: home signaling systems

- voltage fluctuations: these are mainly caused by heavy industrial loads such as those resulting from the operation of arc furnaces, welding machines, etc.
- voltage dips and interruptions: they can result from short-circuits, faults on medium and high-voltage lines and switching of heavy loads
- voltage unbalances: caused by a-symmetrical loads
- power-frequency variations: major perturbations in the network cause frequency reductions
- induced low-frequency voltages that can result from low frequency currents in nearby cables

▪ radiated low-frequency phenomena (50/60 Hz)
- magnetic fields, resulting mainly from power lines, in particular overhead lines, and as stray fields from transformers or other equipment
- electric fields; strong E-fields appear under high-voltage lines. E-fields from household equipment are generally very small

▪ conducted high-frequency (10 kHz-150 MHz) phenomena
- induced continuous wave voltages or currents
- unidirectional transients
- oscillatory transients

Several phenomena are responsible for the occurrence of these disturbances:
1 oscillatory surges of relatively high frequency
2 high-energy surges of various waveforms
3 very fast surges, *e.g.* electrostatic discharges

▪ radiated high-frequency phenomena
- magnetic fields
- electric fields
- electromagnetic fields:

1 oscillatory radiating sources: these emit at least 90% of the average power in a spectral interval [f_{min},f_{max}]; this class of sources contains all kinds of applications such as radio and television transmitters
2 pulsation sources produce fields that last not more than 200 ms and do not change polarity more than 10 times for their duration; these sources have an instantaneous risetime, which result in very complicated waveshapes
3 non-coherent radiating sources: the emission from such sources normally behaves like background noise because the sources appear shapeless and without structure.

▪ electrostatic discharge phenomena (ESD): these occur if two persons or objects approach each other and one of them is charged. Initially the ESD receptor is subjected to an electric field, and this is followed by a discharge with a transient current. This phenomenon strongly depends on ambient humidity, temperature, nature of surroundings, etc.

- nuclear electromagnetic pulse.

Environments

It is unlikely that all sources will be present in all environments. The environments have been classified as follows:

- residential, rural
- residential, urban
- commercial
- light industrial
- heavy industrial, power plant and switchyard
- traffic area
- dedicated telecommunications center
- hospital.

Annex **C**

Models and computations

Comparison of computation methods

During the past several years considerable effort has been put into the development of computational techniques for the description of the effects of an EM field incident upon an object. These can be divided in global techniques (*e.g.*, the development of wave functions and integral equations) and local techniques (finite-difference and finite-elements methods).

In this annex, the Committee briefly discusses two numerical techniques that can be used to solve complicated electromagnetic scattering problems. The first is the finite-difference time-domain (FD-TD) method (Yee66, Taf89). In this method the time and space derivatives in the Maxwell curl equations are approximated by centered finite differences. This leads to an explicit time stepping iterative algorithm. The second method is the integral comparison method, where the Maxwell differential equations are computed to integral equations over area of the object. These integral equations can be solved using an efficient iterative method (the WCG-FFT method; Zwa92b).

Next, the numerical approximations of the two methods for a three-dimensional scattering problem on a strongly inhomogeneous dielectric sphere are presented. This problem is comparable to the analysis of EM field distribution inside a human body. The main advantage of using the sphere as a test case is that the analytical solutions (Mie series) are at hand.

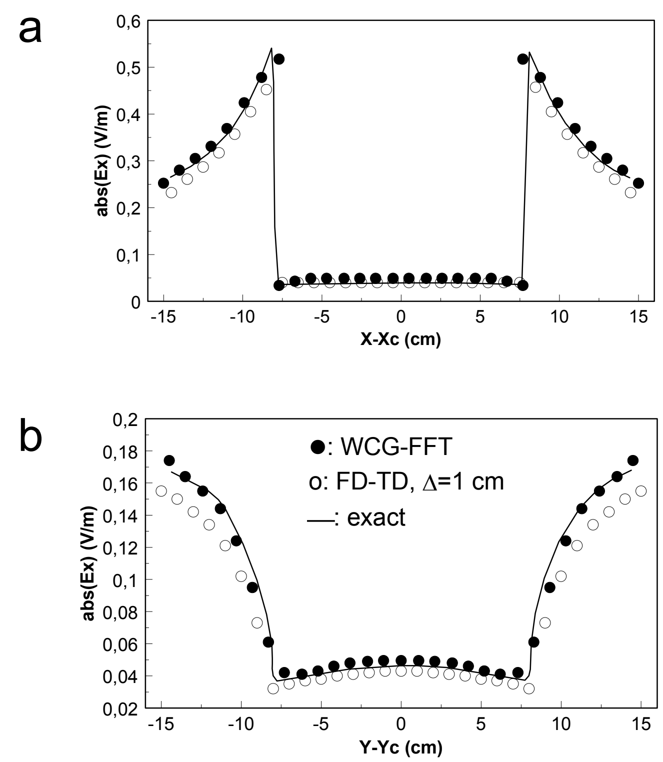

Figure 8 The electric field generated by a 300 MHz plane wave incident on a radially inhomogeneous lossy dielectric sphere with a total radius of 7.59 cm.

Scattering by a dielectric sphere

The test case considered, and for which analytical results are available, is a plane wave incident on a radially inhomogeneous lossy dielectric sphere. This sphere is characterized by an inner layer with radius r_1 = 2.59 cm, relative permittivity ε_r = 72 and conductivity σ = 0.9 S/m, and an outer layer with radius r_2 = 5.0 cm, relative permittivity ε_r = 7.5 and conductivity σ = 0.05 S/m. The electric field is polarized parallel to the x-axis and propagates along the negative z-axis. The center of the sphere is located in the origin. The frequency of the incident EM field is 300 MHz.

In the FD-TD method, the sphere was modelled in a FD space consisting of $50 \times 50 \times 50$ cells, corresponding with a discretization of 1/100 λ. The absorbing boundary condition was located at a distance of 10 cells from the object. Time integration was performed for 400 time-steps or 2 cycles of the incident wave, which corresponds to two front-to-back-to-front traverses of the wave through the

Table 13 The electromagnetic parameters and the mass-density used for computation of the SAR for different frequencies.

tissue	1 MHz	30 MHz	100 MHz	300 MHz	mass-density
muscle	ε_r* = 113	ε_r = 113	ε_r = 72	ε_r = 54	1.070 g/cm^3
	σ = 0.63 S/m	σ = 0.63 S/m	σ = 0.6 S/m	σ = 1.0 S/m	
fat	ε_r = 20	ε_r = 20	ε_r = 7.5	ε_r = 5.7	0.937 g/cm^3
	σ = 0.043 S/m	σ = 0.043 S/m	σ = 0.076 S/m	σ = 0.11 S/m	

* The permittivity ε represents the influence of a medium on the electric flux density, ε_r is the permittivity relative to that in vacuum.

Table 14 SAR values and total absorbed power (rms) calculated in the Jaap-phantom for different frequencies. The incident field is a uniform plane wave with an E-field strength of 1 V/m (= 0.707 V/m rms).

frequency (MHz)	maximum SAR (W/kg)	mean SAR over the entire body (W/kg)	total absorbed power (W)
1	8.0×10^{-7}	8.6×10^{-9}	7.4×10^{-7}
30	4.7×10^{-4}	5.2×10^{-6}	4.7×10^{-4}
100	6.5×10^{-4}	1.6×10^{-5}	1.4×10^{-3}
300	2.0×10^{-4}	6.4×10^{-6}	5.8×10^{-4}

Table 15 Maximum electric field strength of the incident uniform plane wave associated with different total-body average SAR values.

	maximum E-field (V/m, rms)		
frequency (MHz)	SAR = 0.08 W/kg	0.4 W/kg	4 W/kg
1	2,156	4,822	15,248
30	88	196	620
100	50	112	354
300	79	177	560

computational domain. In the WCG-FFT method a mesh size of 29 × 29 × 29 was used to discretize the sphere.

Figures 8a and 8b show the magnitude of the electric field inside the sphere in the x- and y-directions, respectively. Compared to the Mie-series solution (the continuous lines), the results obtained with the iterative WCG-FFT method (the closed circles) are more accurate than those obtained with the FD-TD method (the open circles). However, the overall performance of the FD-TD method is good.

Table 16 Maximum power densities of the incident uniform plane wave associated with different total-body average SAR values.

	power density (W/m^2, rms)		
frequency (MHz)	SAR = 0.08 W/kg	0.4 W/kg	4 W/kg
1	12,330	61,689	616,890
30	21	102	1,018
100	7	32	331
300	17	83	829

Calculation of the SAR inside a human body

In order to obtain some quantitative insight in the absorption of an EM field interacting with a human body, a numerical simulation of the full vectorial, three-dimensional, electromagnetic scattering problems has been carried out (Zwa92b).

The numerical model of the human body is generated from a CAT-scan of an actual person (Zwa92a) and is known as the Jaap-phantom. Using this model, the electromagnetic field distribution has been computed for four different frequencies: 1 MHz, 30 MHz, 100 MHz, and 300 MHz. The calculations have been carried out for uniform plane waves, polarized longitudinally to the Jaap-phantom and propagating from anterior to posterior. The dimensions of the Jaap-phantom are approximately 38 × 54 × 180 cm and for the calculations it has been discretized into 21 × 31 × 106 cubical subdomains. The phantom consists only of muscle and fat. By using the mass-density for these tissues, the computed weight of the Jaap-phantom is 90 kg.

It is known that the electromagnetic parameters of human tissue are strongly frequency-dependent. Hence, for each frequency different electromagnetic medium parameters have to be used. The parameters for fat and muscle are taken from (Joh72) and presented in table 13. No parameter data for 1 MHz were given, therefore the parameters pertaining to 30 MHz have been used for this frequency.

The computations have been performed for irradiation with an incident uniform plane wave with an E-field strength of 1 V/m. The computed values of the maximum SAR, the whole-body SAR and the total absorbed power are presented in table 14. From this table it is easily verified that the computed maximum SAR values exceed the respective mean SAR values by an order of magnitude or more.

The electric field strengths associated with different total-body average SAR values are presented in table 15.

The corresponding power densities of the incident electromagnetic field are obtained from

$$P = \frac{E^2_{\text{r.m.s.}}}{\sqrt{\mu_0 / \varepsilon_0}} \approx \frac{E^2_{\text{r.m.s.}}}{120\pi} \quad (\text{in W/m}^2)$$

where μ_0 is the magnetic permeability of free space and ε_0 is the permittivity in vacuum. The calculated power densities are shown in table 16.

Note that these values calculated for the electric field strength and power density are valid for continuous exposure of the human body to uniform plane waves and that they pertain only to this specific phantom. It should also be realized that the SAR values and total absorbed power are likely to change considerably when the electromagnetic source is located in the vicinity of the human body, since under such near-field conditions the wavefields cannot be considered uniform plane waves.

Annex **D**

Exposure in specific situations

In this annex, the Committee presents examples of exposure of the general population and of workers in a limited number of specific situations. More information on exposure of workers can be found in (Kle95).

Table 17 Whole body SAR associated with exposure to EM fields in specific situations[a] (All91).

location of exposure	SAR (W/kg)
300 m from the base of a 1000 kW UHF TV transmitter	< 0.001
0.5-1 km from a 100 kW HF transmitter	< 0.001
50 cm from a car-mounted 27 MHz, 4 W antenna	0.05
550 m in the beam of a 1.3 GHz air traffic control radar	0.04
5 m from a 10 GHz 100 mW traffic control radar	< 0.001
30 cm from a microwave oven with maximum allowed leak	0.04
12 m from a 10 GHz, 300 W tracking radar (in the beam)	6.10
100 m from a 10 GHz, 300 W tracking radar	0.04
30 cm from a RF dielectric heating device	0.40

[a] The SAR values in this table are related to measurements made at specific locations. They are not necessarily typical for a source type. The values are calculated for worst-case situations and do not take into account duty factors such as caused by antenna rotation.

Table 18 Exposure of the general population to several specific sources of EM fields (Ber92).

source	frequency	distance (m)	total radiated power (W)	exposure level
microwave oven	2.45 GHz	0.3	-	< 5 W/m^2
		0.5	-	< 2 W/m^2
		1	-	< 1 W/m^2
traffic control radar	9 - 35 GHz	3	0.5 - 100	< 0.25 W/m^2
		10		< 0.01 W/m^2
security systems	0.9 - 10 GHz		-	< 0.002 W/m^2
FM transmitter	87.5 - 108 MHz	1.5×10^3	< 100×10^3	< 0.05 W/m^2
VHF-TV transmitter	47 - 68 MHz 174 - 230 MHz	1.5×10^3	100×10^3 - 300×10^3	< 0.02 W/m^2
UHF-TV transmitter	470 - 890 MHz	1.5×10^3	< 5×10^6	< 0.005 W/m^2
short wave transmitter	3.95 - 26 MHz	220	750×10^3	2 W/m^2
		50		40 W/m^2 [a]
AM transmitter	130 - 285 kHz	300	1.8×10^6	90 V/m[a]
long-wave transmitter	415 - 1606 kHz	50	1.8×10^6	450 V/m[a]
radar stations	1 - 10 GHz	100 - 1000	200 - 20000	0.1-10 W/m^2
		> 1000		< 0.5 W/m^2

[a] exceeds the recommended exposure limit for the general population (see table 9)

Table 19 Exposure of physical therapists to EM fields from heating equipment (Ber92).

source	frequency (MHz)	distance (m)	exposure level (V/m)
short-wave diathermy	27.12	0.2	< 1000[a]
		0.5	< 450[a]
		1	< 140 [a]
microwave treatment	433	0.5	100[a]
		1	60
	2450	0.3 - 3	50 - 200

[a] exceeds the recommended exposure limit for workers (see table 9)

Annex **E**

EM interference of cardiac pacemakers

Since 1992, approximately 1.5 million people world-wide have been implanted with a cardiac pacemaker. Every year this number increases with approximately 100,000. Cardiac pacemakers, especially older models, are susceptible to electromagnetic radiation. Consequently, people with an implanted cardiac pacemaker could experience effects from accidental exposure to EM fields. However, it is extremely difficult to estimate the health risk of electromagnetic interference of cardiac pacemakers and this is beyond the scope of this report.

Electromagnetic interference of cardiac pacemakers

In normal circumstances, the heartbeat is regulated by its natural pacemaker, the sinoatrial node located inside the upper-right chamber of the heart. If for some reason this natural system does not function properly, a cardiac pacemaker, an artificial device designed to support the natural regulatory system, might be implanted. The pulses generated by cardiac pacemakers are very similar to the natural pulses. A distinction can be made between devices generating pulses at a fixed rate (non-synchroneously or non-demand pacemakers) and those that support the natural system in case this is unable to generate a next heartbeat. The latter pacemakers are known as sensing, non-comparative or demand cardiac pacemakers. It is well known that this type considerably enhances the comfort of the patient. Another advantage is its low power consumption, which necessitates less frequent changing of the batteries. The majority of the cardiac pacemakers used are of the latter kind.

The regulatory action of a pacemaker depends on detection of the electrical signals produced by the heart. These sensing circuits of the pacemaker may be influenced by other externally generated electrical signals. The effect of this influence increases as the signals are alike the signals produced by the natural pacemaker of the heart. EM fields can interfere with cardiac pacemakers in two ways:

- direct influence on the circuits of the pacemaker
- indirect influence by induction of currents in the catheter wire.

Measurements show that indirect influence dominates for frequencies below 200 MHz. The catheter wire acts as an antenna and generates currents into the pacemaker that may cause interference with its functionality. Negative effects of indirect coupling can be reduced by using appropriate filters. Direct influence is generally caused by microwave sources which can be circumvented by using effective shielding of the pacemaker's enclosure. In general, most electromagnetic interference of cardiac pacemakers is caused by indirect influences.

In vitro measurements (Del89) carried out on a number of cardiac pacemakers implanted around 1989 showed interference with exposure to electric fields between 0.23 and 10 V/m. The effective field strength depends strongly on the type of pacemaker.

In vivo measurements (Tof88) showed that a number of cardiac pacemakers of the same types used as in the *in vitro* measurements showed no interference at all. This might be caused by the lower antenna efficiency of the catheters used in the *in vivo* measurements in comparison with that of the simulated antennas used in the *in vitro* measurements. Although cardiac pacemakers are susceptible to EM fields, the effects found might overestimate the real risk for people carrying these devices.

In a comprehensive report, Wireless Technology Research (WTR) evaluated the available data on interference of pacemaker function by EM fields from hand-held wireless telephones (Car96). The conclusion is that interference is possible, but that it depends strongly on the type of pacemaker. Several, but not all, modern types that have adequate electronic filtering of external signals are not interfered. With a relatively weak source such as a hand-held telephone, the distance from the pacemaker to the telephone is also very important. Interference was only detected when the telephone was very close to the pacemaker. WTR therefore recommends to keep the telephone at all times at a minimum distance of approximately 15 cm from the pacemaker.

In the German prestandard DIN VDE 0848 (DIN91) exposure limits pertaining to people with cardiac pacemakers are formulated, using the measured disrupting voltages present at the input connectors of the pacemaker. Exposure has been carried out with amplitude-modulated fields and in the far field. The exposure limits are presented in table 20.

Table 20 Exposure limits for patients wearing cardiac pacemakers.

frequency (MHz)	exposure limit (V/m)	
	prestandard DIN VDE 0848, part 2	European standard EN 50061/A1
0.5	26.4	587
1	19.7	587
2	14.3	587
10	8.8	470
20	5.0	235
30	1.2	156

These exposure limits generally apply to cardiac pacemakers manufactured before 1990. As of January 15, 1996, the European standard EN 50061/A1 'Safety of implanted cardiac pacemakers' is in effect and all pacemakers implanted since then have to comply with this standard (CEN95c). Exposure limits have been calculated, using the same procedure as followed in the DIN standard, for compliance with this European standard. These limits are also shown in table 20.

The field strengths presented in the table do not occur under normal circumstances. Only in close proximity (several meters) of radiating antennas could electric field strengths of this order exist. Exposure limits for the general public, that are based on thermal effects, are approximately 87 V/m at 0.5 MHz and 28 V/m at 30 MHz (see section 4.4.1).

Conclusion

Cardiac pacemakers can be susceptible to electric fields strengths lower than the exposure limits based on thermal effects. This necessitates special precautions to be taken. The Committee recommends to maintain a minimum distance of 15 cm between an operational hand-held telephone and a pacemaker. Although modern cardiac pacemakers have to comply with EN 50061/A1 (CEN95c), it has to be stressed that the lifetime of pacemakers is approximately 5 to 8 years. Hence, the exposure limits formulated in the table are realistic until approximately the year 2004.