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Assessment of the Health Effects of Radiofrequency Electromagnetic Fields

Québec

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Direction de la santé environnementale et de la toxicologie

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AUTHORS

Mathieu Gauthier, Ph.D.
Denis Gauvin, M.Sc.

Direction de la santé environnementale et de la toxicologie

WITH THE COLLABORATION OF

Daniel Bolduc, M.Sc.
Christiane Thibault, M.Sc.

Direction de la santé environnementale et de la toxicologie

PAGE LAYOUT

Katia Raby

Direction de la santé environnementale et de la toxicologie

TRANSLATION

Anglocom

LINGUISTIC REVISION

Michael Keeling

National Collaborating Centre for Healthy Public Policy

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List of acronyms

AFSSET	Agence française de sécurité sanitaire de l'environnement et du travail, which has merged with Agence française de sécurité sanitaire des aliments (AFSSA) to form Anses
AGNIR	Advisory Group on Non-Ionising Radiation
Anses	Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail
EMF	Electromagnetic field
FCC	Federal Communications Commission
HPA	Health Protection Agency, now Public Health England
HSPA	High Speed Pocket Access
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IEI-EMF	Idiopathic environmental intolerance attributed to electromagnetic fields
INSPQ	Institut national de santé publique du Québec
ITU	International Telecommunication Union
LTE	Long Term Evolution
OR with CI	Odds ratio with confidence interval
PHE	Public Health England, formerly Health Protection Agency
RF	Radiofrequency
RR	Relative risk
RSC	Royal Society of Canada
SAR	Specific absorption rate
SC6	Safety Code 6
UMTS	Universal Mobile Telecommunications System
WHO	World Health Organization
WiMAX	Worldwide Interoperability for Microwave Access

List of units of measure

A/m	Amperes per metre
GHz	Gigahertz
m	Metre
MHz	Megahertz
mW/m^2	Milliwatts per square metre
V/m	Volts per metre
W	Watt
W/kg	Watts per kilogram
W/m^2	Watts per square metre

Highlights

- This report is based on an analysis of scientific articles published in peer-reviewed journals and on expert reports by recognized national and international health organizations.

- Sources of exposure to radiofrequency electromagnetic fields (RF-EMFs) are varied and increasingly prevalent.

- Public exposure to RF-EMFs comes from two types of sources:

  - Local (near-field) sources

    These are sources to which people are exposed at very short distances, namely less than a few centimetres from the body. Cell phones and cordless phones are two examples. Exposure from local sources can be close to the limits established under existing standards.

  - Environmental sources

    These are sources to which the body is exposed at greater distances. They include microwave ovens, wireless Internet routers, smart meters, and radio, TV, and cell phone antennas. Exposure from environmental sources is generally much lower than established exposure limits.

- The effects of RF-EMFs at exposure levels above established limits are well characterized. Exposure limits established by regulatory bodies are determined so as to prevent all established adverse health effects.

- The potential effects of RF-EMFs have been the subject of numerous studies on cells, animals, and humans. Although current research does not allow us to entirely exclude the possibility risks, no short- or long-term adverse effects have been established as a result of exposure to RF-EMFs within the established limits.

- A certain level of scientific uncertainty persists about the potential effects of long-term exposure to cell phones, and a number of epidemiological studies on this topic are underway.

- Some people report symptoms they believe are caused by RF-EMFs. The existence of these reported symptoms is not in doubt. A wide range of symptoms is reported and their severity varies from one person to another. However, the good quality studies conducted on the subject have failed to uncover any links between these symptoms and exposure to RF-EMFs below the established limits.

- It is recommended that monitoring and research be continued, that the public be kept informed of new developments, and that measures be put in place to help people reporting symptoms they attribute to RF-EMF exposure.

Summary

Québec's Ministère de la Santé et des Services sociaux (MSSS) [ministry of health and social services] has tasked the Institut national de santé publique du Québec (INSPQ) [Québec's public health institute] with analyzing the scientific literature on the health effects of radiofrequency electromagnetic fields (RF-EMF). This analysis is based on scientific articles published in peer-reviewed journals and on expert reports by recognized national and international health organizations. Although not a systematic review, this report provides an overview of possible effects of RF-EMFs on health.

Exposure to Radiofrequency Electromagnetic Fields

Sources of exposure to radiofrequency electromagnetic fields (RF-EMF) are varied and increasingly prevalent. Due to the growing number of households using cell phones, cordless phones, and wireless Internet routers, the public is increasingly exposed to RF-EMFs. Exposure from voluntary sources such as cell phones still seems to be the main source of exposure for the public.

In the case of local sources such as cell phones and cordless phones, maximum near-field exposure sometimes approaches recommended maximum exposure levels. The specific absorption rate (SAR)—used to estimate exposure—from a cell phone is generally between 0.5 and 1.5 W/kg. This exposure level is slightly below the basic restriction of Health Canada's Safety Code 6 set at 1.6 W/kg averaged over 1 g of tissue. Cordless phones generate a lower maximum exposure level, the SAR being between 0.008 and 0.06 W/kg.

Sources of environmental exposure, namely those more than a few centimetres from the body (e.g., microwave ovens, wireless Internet, next generation electricity meters, commonly called smart meters, and radio, television, and cell phone antennas), generate lower average exposure levels than local sources. The average electric field to which the public is exposed is generally on the order of 1 V/m (3 mW/m^2). This is below Health Canada's Safety Code 6 reference level of 1.3 and 6.2 W/m^2) for frequencies between 300 and 3000 MHz.

Establishing Exposure Limits for Radiofrequency Electromagnetic Fields

The effects of RF-EMFs at exposure rates above established thresholds have been well characterized. Various effects are observed depending on radiation frequency: stimulation of central and peripheral nervous tissue, electric shocks and burns caused by contact with exposed objects, local tissue heating, and increased body temperature. Exposure limits recommended by recognized health organizations (Health Canada, the International Commission on Non-Ionizing Radiation Protection, and the Institute of Electrical and Electronics Engineers) are designed to prevent adverse health effects of RF-EMFs.

Regarding thermal effects, for example, health organizations have estimated the exposure required to produce significant heating of tissues in humans at 4 W/kg averaged over the entire body. To calculate their exposure limits, or "basic restrictions" these organizations divide this value by 10 for occupational exposure and 50 for the general public. Most sources of environmental exposure for the general public cause exposure levels well below the basic restrictions.

The exposure limits recommended by various recognized organizations are similar. The differences reflect the organizations' assessment methods, but the limits provide equivalent levels of protection.

Potential Health Effects of RF-EMFs

Cell and animal studies

Recent literature reviews on the effects of RF-EMFs on cells and lab animals indicate no adverse effects at exposure levels below those producing adverse thermal effects. Furthermore, health organizations, which have assessed the cell and animal studies, have generally found no convincing evidence of adverse health effects.

Studies in humans

- Studies on cancer risk

Numerous epidemiological studies have been conducted to look for possible links between RF-EMF exposure and brain cancer or other types of head tumours. Cohort and ecological studies have demonstrated no links, but certain case-control studies have produced mixed results. Studies by Hardell et al., for example, showed increased risk in some of the sub-group analyses. However, these results have been contradicted by cohort studies and the INTERPHONE study conducted on cell phone users in 13 countries.

Apart from the working group at the International Agency for Research on Cancer and the expert group at Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail in France [the national agency for food, environmental and workplace hygiene], which consider that there are some "limited" indications that RF-EMFs may be carcinogenic for certain combinations of cancer types and subpopulations, recognized health organizations consider that the evidence on links between RF-EMFs and cancer is negative, insufficient, or far from conclusive.

Epidemiological studies are underway to gather more data, particularly on the potential health risks associated with long-term cell phone use or certain population subgroups (e.g., young people).

- Studies on non-specific symptoms

Some people with health problems, some of which can be debilitating, attribute their symptoms to exposure to various sources of electromagnetic fields, including RF-EMFs. The World Health Organization recommends the term *idiopathic environmental intolerance attributed to electromagnetic fields* (IEI-EMF), to describe this phenomenon. A wide range of non-specific symptoms are attributed to this condition, and these symptoms vary from one individual to another. The prevalence of IEI-EMF also varies considerably from one study to another depending on the severity of the inclusion criteria used, with anywhere from less than 2% to more than 15% of the general population attributing some of the symptoms they feel to an EMF source.

Many good quality studies have been performed to assess the association between exposure to low levels of RF-EMFs and the occurrence of non-specific symptoms. The available scientific evidence suggests that the symptoms people report, which are not in doubt, are not associated with exposure to RF-EMFs.

Conclusion

Although the limitations of current research cannot exclude all possibility of risk, no short- or long-term adverse health effects have been demonstrated for RF-EMF exposure within the established limits. At low levels of exposure, some studies seem to suggest the possibility of biological effects that may be within normal physiological variations.

Some scientific uncertainty remains as to the potential effects of RF-EMFs in relation to long-term exposure from cell phone use. Exposure due to environmental sources, which is generally much lower than that caused by cell phone use, appears unlikely to be associated with adverse health effects.

Proposed measures

In light of these observations, the INSPQ proposes five management measures:

- Continue scientific monitoring of the possible effects of RF-EMFs, particularly with respect to long-term cell phone use.
- Maintain expertise in this field in Québec and help set up a network for sharing information with other experts on the subject.
- Provide the public with tools to help them keep abreast of the latest scientific data on possible links between RF-EMF exposure and health effects.
- Propose measures to help people who report symptoms they attribute to RF-EMFs.
- Take part in research projects that would facilitate the implementation of the other proposed measures.

1 Introduction

Reliance on devices and technologies that use electromagnetic fields (EMF) to transmit information is growing steadily. In addition to radio and television broadcasting, which has been around for several decades, new technologies such as cordless phones, Wi-Fi routers, Bluetooth systems and baby monitors are now available. Cell phone use, in particular, is increasingly widespread. According to the International Telecommunication Union (ITU, 2012), there were already more than 6 billion subscriptions to cellular telephone services worldwide by the end of 2011. Similarly, the Canadian Wireless Telecommunications Association (CWTA, 2012) estimated that 75% of Canadian households had access to a cell phone in 2012, representing over 26 million subscriptions.

The health effects of radiofrequency electromagnetic fields (RF-EMFs) have been studied for several decades. Following the emergence of questions and debates within the population, the potential health effects of RF-EMFs in connection with the development of new wireless technologies are attracting renewed interest. Increasing exposure to radiofrequencies and resulting public concern have led health organizations to undertake major research programs (WHO, 2013). These programs have significantly increased the number of studies on the effects of RF-EMFs.

The Québec health network, especially the Ministère de la Santé et des Services Sociaux (MSSS) and the Institut national de santé publique du Québec (INSPQ), has been interested in the effects of EMFs for a number of years (Levallois, Lajoie and Gauvin, 1991; Levallois, Gauvin, Lajoie and Saint-Laurent, 1996; Levallois et al., 2000; Gauvin, Ngamga Djeutcha and Levallois, 2006; Diallo and Gauvin, 2010). This report analyzes the potential health effects of RF-EMFs at frequencies between 100 kHz and 300 GHz. This part of the electromagnetic radiation spectrum is used for transmitting wireless information.

The report mainly analyzes studies published between 2009 and 2013, but also discusses some important papers published as recently as 2015. It is divided into several chapters, which deal with the main knowledge assessments related to the health effects of RF-EMFs. Chapter 2 presents the possible sources of exposure for the public. Chapter 3 explains the basis for recommendations on RF-EMF exposure limits established by recognized organizations such as Health Canada and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Chapter 4 summarizes the main findings of studies on biological effects in cells and animals. It also provides a synthesis of research findings on a possible link between exposure to RF-EMFs and the incidence of human brain cancers, as well as the association between RF-EMF exposure and the occurrence of nonspecific symptoms reported by people who claim to be hypersensitive to electromagnetic fields. It then presents the conclusions of risk assessments by several national and international health organizations. Finally, Chapter 5 suggests prudent management measures designed to maintain Québec's expertise in this area, assist the public in obtaining the information necessary for informed decision-making and reduce scientific uncertainty.

2 Exposure to radiofrequency electromagnetic fields

2.1 Characteristics of radiofrequency electromagnetic fields

Radiofrequency electromagnetic fields (RF-EMFs) generally refer to electromagnetic frequencies between 3 kHz and 300 GHz, the spectrum used for wireless transmission (Institute of Electrical and Electronics Engineers [IEEE], 2005). This type of radiation, like infrared radiation and visible light, is called non-ionizing, because the photon energy in this frequency range is below the energy level required to ionize atoms and molecules. This characteristic distinguishes this type of radiation from ionizing radiation such as X rays or gamma rays, which are able to cause direct breaks of molecules such as DNA. Table 1 shows this difference and provides some reference energy levels for comparison.

Table 1 Comparison between the energy of RF Photons at a frequency of 1 GHz to the energy of extremely low frequency (ELF) EMF, Visible light, UV Rays, and X Rays

	Frequency	Energy eV
ELF fields	60 Hz	~ 2.5×10^{-13}
RF-EMFs	1 GHz	~ 4×10^{-6}
Visible light	~ 6×10^{5} GHz	~ 2.5
Ionization energy	-	> ~ 12
UV rays	~ 3×10^{6} GHz	~ 12
X rays	> ~ 3×10^{7} GHz	> ~ 120

Note: The ionization energy is given as a reference.

The physical quantities used to characterize RF-EMFs depend on the exposure conditions. In the case of far-field exposure, i.e., at a distance greater than approximately twice the wavelength of the RF-EMF field emitted (Occupational Safety and Health Administration, 1990), RF-EMF exposure can be characterized by the electric field (**E**), the magnetic field (**H**), and the power density (**S**). Equation 1 shows the relation between these three physical quantities (International Commission on Non-Ionizing Radiation Protection [ICNIRP], 1998). The symbols and units of these physical quantities are presented in Table 2. In the far field, power density decreases with the square of the distance from the source.

$$\mathbf{S} = \mathbf{EH} = \mathbf{E}^2/377 = 377\ \mathbf{H}^2 \qquad \textbf{Equation 1}$$

Table 2 Physical quantities used to characterize radiofrequency electromagnetic fields

Physical Quantity	Symbol	Unit
Magnetic field	H	A/m
Electrical field	E	V/m
Power density	S	W/m^2
Specific absorption rate	SAR	W/kg

The near field is located at an approximate distance of less than $\lambda/2\pi$ from the antenna, where λ is the wavelength of the radiofrequencies emitted. In the case of RF-EMFs, the distance is generally a few centimetres (IEEE, 2005). For example, a frequency of 900 MHz corresponds to a near field of about 5 cm. In the near field, exposure is harder to characterize, and both the electric and magnetic fields must be known. Therefore, power density can no longer be used to measure exposure (ICNIRP, 1998) and simple calculations are insufficient for assessing RF-EMF exposure (ICNIRP, 2009a). In this situation, the most appropriate physical quantity for characterizing exposure is the specific absorption rate (SAR).

The specific absorption rate, representing the energy absorbed per unit of mass, is generally used to quantify the energy absorbed by the body (IEEE, 2005). The specific absorption rate can be used to compare exposure to both near-field and far-field sources. The quantity of radiation absorbed depends on the characteristics of the incident field (frequency, intensity, polarization, etc.) and the exposed body (size, exterior geometry and dielectric properties of the tissues), ground effects, and reflection off objects near the body of the person exposed (ICNIRP, 1998). The SAR can be calculated for the entire body, part of the body, a particular organ, or a given volume. A volume corresponding to a 1 g or a 10 g cube of tissue is often used to characterize near-field exposure, and it is calculated from the part of the body that will give the highest exposure value.

2.2 Sources of radiofrequency electromagnetic fields and types of exposure

Exposure to RF-EMFs can be attributed to both natural and artificial sources. Natural sources are discussed briefly below for information purposes only.

2.2.1 Natural sources

Any object at a given temperature emits electromagnetic radiation due to thermal radiation. Part of this radiation lies within the radiofrequency spectrum. This is called *black body radiation*. The intensity and characteristics of this type of exposure depend on the temperature and area of the surfaces in the environment. The ground is the main natural source of RF-EMFs and emits a few milliwatts per square metre (mW/m^2) in this frequency range. The human body also emits radiation over a wide range of frequencies. Black body radiation in the radiofrequency range from an individual is generally about 3 mW/m^2 (ICNIRP, 2009a; Advisory Group on Non-Ionising Radiation [AGNIR], 2012). So the general environment, even in the absence of artificial sources, exposes the human body to a small amount of RF-EMFs.

2.2.2 Artificial sources

Human exposure to artificial RF-EMF sources can be divided into two categories (Frei et al., 2009). The first type of exposure is generated by so-called environmental sources such as base stations, radio or television antennas, wireless Internet routers, and so on, which are located at a certain distance from the exposed person. Exposure to RF-EMFs from environmental sources is relatively continuous, but quite low in intensity (ICNIRP, 2009a). A second type of exposure is generated by local sources located close to the user's body, for example cell phones and cordless telephones. RF-EMF exposure from local sources is generally of small duration, but the radiation intensity is greater than that from environmental sources (ICNIRP, 2009a). The characteristics of these two types of sources are summarized in Table 3.

People have been widely exposed to RF-EMFs from a range of environmental sources for several decades. In general, the intensity of the RF-EMFs decreases as the distance between the source and the exposed person increases. However, the level of exposure at a given location depends on several factors, including radiated power, direction of signal transmission, attenuation due to obstructions, and diffusion due to buildings and trees (Neubauer et al., 2007). The combination of these factors means that the intensity of RF-EMFs cannot always be easily calculated using the relative distance of all environmental sources from a given location. For example, measurements taken near a base station in Austria showed that the power density of the signal could vary by up to four orders of magnitude (a factor of 10,000) at equal distances from the transmitter (Neubauer et al., 2007). An analysis of several methods for determining an individual's exposure to RF-EMFs published by Frei et al. (2010) showed that the distance between an individual and environmental sources was not a good indicator of actual exposure over short periods of time.

Exposure from local RF-EMF sources, which are often personal electronic devices, is more difficult to characterize because the exposed person is usually in the emitter's near field (Inyang, Benke, Mckenzie, and Abramson, 2008; ICNIRP, 2009a). Although the intensity of the radiation generally decreases with increasing distance between the source and the person exposed, more complex measurements and digital models are needed to assess actual exposure (Cardis et al., 2011).

An individual's total exposure to RF-EMFs is determined by the intensity of the environmental sources and the length of time personal devices emitting RF-EMFs are used. Until recently, little data have been available on average public exposure to RF-EMFs. In its RF-EMF research guidelines, the World Health Organization (2010a) highlighted the need to quantify individual exposure levels to various sources and to determine the factors that affect public exposure. The following sections present some of the most significant results from studies documenting public exposure levels published in recent years and from reports on health risks associated with RF-EMFs published by national public health organizations. Keyword searches (*electromagnetic fields AND environmental exposure*) in *PubMed* and *Google Scholar,* references cited in these articles, and bibliographies in expert reports by public health bodies were used to identify the studies examined. Consequently, this is not a systematic review of all studies published on the subject.

The following sections describe the methods for measuring RF-EMFs, the level of exposure to RF-EMFs from mobile phones and other sources, and how this exposure has changed over time.

Table 3 Frequency, Power, and Typical Exposure from certain sources of environmental and local exposure

	Frequency MHz	Power[a]	Type of Exposure Measurement	Exposure[a]
Cell phone[b] (OMS, 2014)	824-849 1,710-1,755 1,850-1,915 2,500-2,690	0.1-2 W	Maximum SAR at the ear	0.5–1.5 W/kg
Cordless phone – DECT 6.0 (Repacholi et al., 2012)	1,920-1,930	2-10 x 10^{-3} W	Maximum SAR at the ear	0.008-0.06 W/kg
Microwave ovens (ICNIRP, 2009a)	2,450	500-1 500 W	Maximum	< 50 W/m^2
Wireless Internet routers – Wi-Fi (Joseph et al., 2010)	2,400-2 500; 5,150-5 850	100 mW	Ambient average	18 x 10^{-6} W/m^2
Next generation electricity meters[c] (Hydro-Québec, 2012)	902-928	0.425 W	Average at 1 m	< 50 x 10^{-6} W/m^2
Mobile phone base stations[b] (Rowley and Joyner, 2012)	869-894 2,110-2,155 1,930-1,995 2,500-2 690	< 100 W	Ambient average	730 x 10^{-6} W/m^2
AM radio antennas[d]	0.5-1,7	50 x 10^3 W	-	-
FM radio antennas[d] (Joseph et al., 2010)	88-108	100 x 10^3 W	Ambient average	96 x 10^{-6} W/m^2
Television antennas[d] (Joseph et al., 2010)	54-88 174-216 470-698	2 x 10^6 W	Ambient average	89 x 10^{-6} W/m^2

[a] The power and exposure figures are provided as examples; they vary depending on the sources' individual characteristics, the measurement protocols and instruments used, and many other factors.

[b] The 698-764 and 776-794 MHz frequency bands are also to be auctioned for cellular telephone service. Part of the 2,500-to 2,690 MHz band is still available.

[c] The power data do not take into account the duty cycle.

[d] The power data refer to effective radiated power (ERP).

2.3 Methods of measuring exposure to radiofrequency electromagnetic fields

The technique used to determine exposure to RF-EMFs depends on the type of exposure to be measured. Exposure to RF-EMFs from environmental sources can be measured with various instruments that quantify the level of exposure at a given location, for a given individual, or population. Assessing exposure from local sources can be done using a combination of point measurements, numerical simulations and estimates of exposure times.

Three types of device are generally used to measure far-field exposure: broadband instruments, narrowband instruments and personal exposure monitors. In near-field situations, digital simulations or laboratory measurements on physical models are usually used to calculate the SAR of a particular exposure source.

Broadband instruments are able to simultaneously capture RF-EMFs from different sources, even if they are of different wavelengths. They can measure the total intensity of the magnetic fields at one location but generally cannot determine the individual contributions of the various sources within its sensitivity range.

Narrowband instruments are able to discriminate between different RF-EMF sources at the same location and are generally more sensitive than broadband devices (Rowley and Joyner, 2012). They can be used to determine the relative contribution of each source to the total EMF by taking multiple measurements in a frequency range.

Personal exposure monitors are easily portable and can be either broadband or narrowband. They can be used to determine the average EMF to which a person is exposed by taking measurements at regular intervals over the period of time the exposure monitor is worn. Although they can provide estimates of personal exposure, disturbance of the incident fields by the body of the person wearing the exposure monitor can result in considerable uncertainty regarding the accuracy of the measurement (ICNIRP, 2009a). Furthermore, personal exposure monitors cannot be used to assess near-field exposure.

Near-field exposure can be characterized using the SAR, based on digital models of the human body. These digital models can be simple (models based on spheres, for example) or complex (high resolution anatomical models from medical images). The SAR can also be used to determine near-field exposure in the laboratory using physical models called "phantoms" that simulate the dielectric properties of the human body (ICNIRP, 2009a). This type of measurement is regulated, and test parameters are adjusted to give a maximum reading in order to ensure compliance with the exposure limits of all users (Agence française de sécurité sanitaire de l'environnement et du travail [AFSSET], 2009; Beard et al., 2006).

2.4 Exposure to radiofrequency electromagnetic fields from mobile telephones

Exposure of the population to RF-EMFs from mobile phones is the result of individuals' own cell phone use, the use of cell phones by others, and RF-EMFs from base stations. Cell phones emit RF-EMFs within a frequency range of 450 to 2,700 MHz, with a maximum power of 0.1 to 2 W (OMS, 2014). The power and frequency depend on the technology used and the service provider. For example, fourth generation phones (Long-Term Evolution – LTE) have a maximum average power of 200 mW (Ahlbom, Feychting, Hamnerius, and Hillert, 2012).

Since the distance between a cell phone antenna and the user is only a few centimetres, the user is within the emitter's near field. As mentioned above, the most appropriate physical quantity for characterizing exposure in this case is the SAR. The maximum SAR of cell phones averaged over 1 g or 10 g of tissue is generally 0.5 to 1.5 W/kg (AGNIR, 2012; International Agency for Research on Cancer [IARC], 2013). When the phone is held at the ear, 97% to 99% of the energy absorbed by the brain is absorbed by the brain hemisphere located next to the phone (Ahlbom et al., 2009). The user's size also affects the amount of energy the body absorbs. Since the skull and tissues around the brain are thinner in children, exposure characterized by the SAR should be higher for a given source (AGNIR, 2012; ICNIRP, 2009a).

In practice, individual exposure to RF-EMFs emitted by cell phones varies depending on a number of factors, including the user's location (distance from sources, presence of obstacles, etc.), the phone's position in relation to the head, and the size of the head. An individual's total exposure also depends on how long and how frequently the phone is used (AGNIR, 2012). Adaptive power control systems in modern cell phones adjust the signal emitted to the minimum power necessary for good radio communication and enable the phones to reduce the power emitted by a factor of up to a thousand (ICNIRP, 2009a). Studies have shown that under varied conditions of use, this technology has helped reduce the average radiated power by 50% (Vrijheid et al*.*, 2009). Mobile phones using more recent technology should perform even better in this regard (AGNIR, 2012). Generally speaking, hands-free devices (wired or wireless[1]) reduce the head's exposure to RF-EMFs by about 10 to 100 times (Kühn, Cabot, Christ, Capstick, and Kuster, 2009; IARC, 2013). When cell phones are not transmitting information during a call, i.e., when they are in standby mode, their emissions are negligible (Mild, Andersen, and Pedersen, 2012).

As for exposure to RF-EMFs from base stations, Rowley and Joyner (2012) recently published an analysis of a database of 170,000 EMF measurements from 21 countries, including Canada. Based on this analysis, the average power density from base stations is 7.3×10^{-4} W/m^2. This power density corresponds to an electric field of about 0.5 V/m. The authors noted that it is difficult to directly compare measurements generated by a range of different research protocols. Indeed, factors that are hard to quantify or compare influenced the measurements, two major factors being the use of instruments with different characteristics and sensitivities and the absence of a standard way of selecting where the measurements were to be taken (Rowley and Joyner, 2012).

To compare exposure from base stations to exposure from cell phones, the SAR generated by the base stations first has to be calculated. These calculations can be complex because as indicated above, RF-EMF absorption depends on environmental conditions. A number of studies have been carried out comparing near-field to far-field exposure. In the case of adults, exposure to a far-field plane wave of 1 W/m^2 corresponds to a SAR averaged over the entire body of less than 0.008 W/kg at 2000 MHz (ICNIRP, 2009a). In children, the same exposure produces a SAR averaged over the entire body that is nearly 40% higher (ICNIRP, 2009a). Lauer et al*.* (2013) compared near-field and far-field exposure levels and found that near-field sources such as Global System for Mobile Communications (GSM) cell phones and digital enhanced cordless phones (DECT) are responsible for 73% to 80% of exposure to the body and head. Only phones using more recent Universal Mobile Telecommunications System (UMTS) technology generate exposure levels lower than environmental sources – representing 44% of the exposure (Lauer et al*.*, 2013).

2.5 Other sources of radiofrequency electromagnetic fields

Although cellular telephony is an increasingly prevalent source of RF-EMF exposure, there are a number of other sources that emit this type of radiation, and the public has been exposed to some of these sources for many years. Microwave ovens, wireless Internet routers (Wi-Fi), cordless phones, smart meters, and AM radio, FM radio, and television antennas are all common sources of public RF-EMF exposure. A number of other electronic devices such as baby monitors and remote control toys

[1] In most cases, wireless devices using Bluetooth technology have a maximum radiated power of a few mW (Foster, 2013).

also emit RF-EMFs at various power levels and frequencies. The following subsections briefly describe these sources.

2.5.1 Microwave ovens

Microwave ovens generally emit radiation at a wavelength of 2,450 MHz and radiated power levels of 500 to 1000 W. Consequently, microwave ovens can potentially cause serious injuries if incorrectly used. However, the ovens are designed in compliance with established standards that prevent them from emitting RF-EMFs when the oven door is open. Furthermore, exposure to leakages at 5 cm from the oven while it is in operation are well below the regulatory exposure limit of 50 W/m^2 (ICNIRP, 2009a). On this subject, Health Canada has specified that “Some microwave energy may leak from your oven while you are using it, but this would pose no known health risks, as long as the oven is properly maintained” (Health Canada, 2003).

2.5.2 Wireless Internet routers (Wi-Fi)

Routers used for wireless networks have an effective radiated power[2] (ERP) of up to 4 W, but their maximum radiated power is generally below 100 mW (Foster, 2013). In practice, the radiated power level is even lower because it varies based on a number of factors, including the type of router and level of network use (AFSSET, 2009).

2.5.3 Smart meters

Next generation electricity meters, or smart meters, use radiofrequencies to transmit data on electricity consumption. According to Hydro-Québec data, the smart meters used in the province emit in the 902–928 MHz frequency band. RF-EMFs are emitted for about 50 milliseconds, 1,500 to 2,000 times a day. The maximum radiated power during data transmission is 0.425 W. Based on Hydro-Québec’s analysis and measurements conducted over 6-minute periods, the duration specified by Health Canada’s Safety Code 6 (SC6), the average power density at 1 m from the smart meter is less than 5.0 x 10^{-5} W/m^2.

Public exposure to RF-EMFs emitted by this type of device is relatively low compared to the ambient radiation already present in the environment. For example, average exposure to RF-EMFs generated by smart meters—5.0 x 10^{-5} W/m^2—at 1 m is almost 15 times lower that the average exposure to RF-EMFs produced by base stations—7.3 x 10^{-4} W/m^2 (Rowley and Joyner, 2012), and direct exposure at 3 m would represent 3% to 7% of the exposure due to environmental sources[3].

A theoretical analysis in the grey literature (Sage Associates, 2011) postulates that under normal circumstances, RF-EMFs from smart meters could exceed the U.S. standard. Unfortunately, no experimental measurements are presented to support this hypothesis. Furthermore, the analysis is based on hypothetical exposure levels that do not seem to be based on the calculation methods specified by the U.S. standard, it does not take into account the variation in EMFs at short distances from smart meters, it puts forward a hypothesis about EMF reflections that is not supported by scientific evidence and it refers to outdated recommendations on exposure limits. These criticisms

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2 Effective radiated power, which takes the antenna’s gain factor into account, must be used because radiation from the antenna is sometimes emitted in specific directions rather than being omnidirectional.

3 According to Lauer et al., (2013), the SAR averaged over the entire body over a period of 24 hours is between 34.2 and 73.5 mJ/kg. An exposure of 5.6×10^{-6} W/m^2 (at 3 m from a NGM) corresponds to $4.5 \times 10^{-3} \times 24 \times 3\,600 \times 5.6 \times 10^{-6} = 2.2 \times 10^{-3}$ J/kg over a 24 h (See equation 1 and Figure 2).

are detailed in another grey literature document produced by the Electric Power Research Institute (EPRI, 2011).

2.5.4 CORDLESS PHONES

Historically, a number of technologies have been used in cordless phones. Most cordless phones today are DECT phones (ConsumerReports, 2013). The average transmitting power of this type of device is about 10 mW (European Telecommunications Standards Institute [ETSI], 2015). The low power levels of the handsets lead to a local SAR of 0.008 to 0.06 W/kg, which is significantly lower than that of a cell phone, i.e., 0.5 to 1.5 W/kg (Repacholi et al., 2012). Unlike handsets, which only emit when in use, cordless phone base stations emit continuously (AFSSET, 2009).

2.5.5 AM RADIO, FM RADIO, AND TELEVISION ANTENNAS

Radio and television antennas are RF-EMF sources that have been around for many years. The effective radiated power (ERP) of these antennas, which depends in part on the type of license granted, can reach very high levels. AM radio, FM radio, and television antennas can have a maximum ERP of 50 kW, 100 kW, and 1 MW, respectively (Industry Canada, 2009, 2011, 2010). These high levels of radiated power can cause higher exposure levels near the antennas, even though most of the power is directed toward the horizon rather than toward the ground (Office of Engineering and Technology [OET], 2012).

2.6 Comparison with exposure from environmental sources

A number of studies have attempted to characterize far-field RF-EMF exposure from all sources in the environment. This type of study does not allow for assessment of local exposure to a cell phone user's head, which requires complex calculations similar to those performed by Lauer et al. (2013), but it does provide an overview of exposure sources in a given population's environment (Frei et al., 2011a).

In 2005 and 2006, Viel, Cardis, Moissonnier, de Sèze, and Hours (2009) used personal exposure monitors to measure the environmental RF-EMF exposure of 377 individuals in two French cities over periods of 24 hours. The instrument they used had a detection threshold of 0.05 V/m (6.6×10^{-6} W/m^2) and was configured to take readings in 12 frequency ranges every 13 seconds (Viel, Cardis, Moissonnier, de Sèze, and Hours, 2009). The total electric field exceeded the instrument's detection threshold in 46.6% of the readings taken. The individual radiation sources that exceeded the detection threshold in more than 10% of the readings were cordless phones (17.2%), Wi-Fi and microwave ovens[4] (14.1%), and FM radios (11.0%) (Viel, Cardis, Moissonnier, de Sèze, and Hours, 2009). The authors also determined which exposure sources produced the highest intensity electric fields based on the proportion of measurements above 1 V/m. The only exposure sources producing such levels of intensity were the research subjects' cell phones (0.1 to 0.3%), cordless phones (0.2%), and microwave ovens (0.1%) (Viel, Cardis, Moissonnier, de Sèze, and Hours, 2009). For all the RF-EMF sources, total average electric field strength was 0.2 V/m (1.06×10^{-4} W/m^2). The average exposure to individual sources was higher for FM radios (0.044 V/m), Wi-Fi and microwave ovens (0.038) V/m, cordless phones (0.037) V/m, and cell phones and base stations (0.012 to 0.037) V/m (Viel, Cardis, Moissonnier, de Sèze, and Hours, 2009).

[4] Since the frequency range of microwave ovens and Wi-Fi routers is quite similar, it is not possible to distinguish between these two exposure sources. Activity logs can be kept by individuals wearing the personal exposure monitors to identify when the microwave ovens were used, but even this method still leaves room for uncertainty.

A study by Joseph et al. (2010) compared exposure levels in Belgium, Switzerland, Slovenia, Hungary, and the Netherlands, where exposure studies using personal exposure monitors had been conducted from 2007 to 2009. The authors observed that in all the microenvironments studied, exposure to RF-EMFs from cell phones and relay antennas was substantial. In most cases, these sources were the dominant exposure sources (Joseph et al., 2010). The exposure levels in the different countries were of the same order of magnitude and the average power density from all power sources in most of the microenvironments studied was between 10^{-4} and 10^{-3} W/m^2 (0.2 to 0.6 V/m) (Joseph et al., 2010). Although exposure levels in houses were generally similar in all the countries, individual exposure source contributions to total RF-EMFs differed from one country to another (Joseph et al., 2010).

In 2009, Bolte and Eikelboom (2012) recruited volunteers in the Netherlands in an attempt to characterize exposure to RF-EMFs using personal exposure monitors worn for 24 hours. Total average exposure, apart from personal cell phone use, was 1.8 x 10^{-4} W/m^2 (0.26 V/m). The authors found that apart from cell phone use by the research subjects, the main environmental sources of RF-EMF exposure were cell phone use by people other than the research subjects (37.5%), cordless phones and their base stations (31.7%), and cell phone base stations (12.7%). The authors concluded that total average exposure depends mainly on phone use patterns, given the high short-term exposure involved with this type of exposure, which makes it difficult to categorize and predict average RF-EMF exposure based on a person's activities.

Lauer et al. (2013) compared exposure levels to near-field and far-field sources. In the exposure scenario based on environmental exposure data collected from the research volunteers, the combined use of GSM cell phones and DECT cordless phones was responsible for 73% to 80% of whole body exposure. The authors noted that the use of UMTS cell phones, which are more recent than GSM cell phones and have a smaller average power output, reduced exposure. For the same exposure scenario, the use of UMTS phones represented only 1% of whole body exposure, while the use of DECT cordless phones accounted for 43% of total exposure.

2.7 Changes in exposure levels over time and the introduction of new technologies

A study by Rowley and Joyner (2012)[5] sought to compare RF-EMF exposure levels from base stations over time. To do so, the authors used exposure measurements for the period 2001 to 2009 from a number of national RF-EMF exposure databases. The study compared narrowband measurements from the United Kingdom, Spain, Greece, and Ireland, as well as broadband measurements from the United States. Over the course of the study period, the number of mobile phone subscribers increased by 81% in the United Kingdom and 456% in the United States, and third generation technologies were deployed. However, the average RF-EMF exposure levels recorded in the databases Rowley and Joyner consulted did not change. The authors concluded that it would be reasonable to expect RF-EMF radiation from base stations to become increasingly prevalent during the period studied, given the increase in cell phone coverage. They note, however, that exposure remained relatively stable, despite the increase in the number of emitters. Rowley and Joyner explain this phenomenon by noting that signal strength at a given location is generally no greater than necessary to provide quality phone service. They concluded that the data gathered to date suggest no significant rise in public exposure to RF-EMFs emitted by base stations following the

[5] One of the authors of this study is a member of the GSM Association, a group of mobile phone service providers, which represents a possible conflict of interest.

introduction and deployment of GSM technology. They consider that the deployment of new mobile telephone technologies is not likely to affect average exposure.

In 2006 and 2009, Tomitsch and Dechant (2012) measured RF-EMFs from all environmental sources in Austrian bedrooms. During this period, the median total power density increased by 44%. From 2006 to 2009, median exposure to 900 MHz GSM signals rose in a statistically significant manner (54.6 %), whereas median exposure to 1800 MHz GSM and DECT cordless phone signals declined (22% and 22.4%, respectively) in a non-statistically significant manner. Median exposure to UMTS signals, deployment of which continued from 2006 to 2009, increased, as did exposure to RF-EMFs from Wi-Fi networks in 55 additional homes. However, major variations in exposure levels were observed at the different measurement sites.

Based on measurements made in 2009 and 2010, Joseph, Verloock, Goeminne, Vermeeren, and Martens (2012a) analyzed the effect of new technology on RF-EMF exposure levels in Belgium, the Netherlands, and Sweden. Point measurements of electric fields were made using narrowband instruments. The study by Joseph et al. (2012a) indicated that the maximum electric field varied from 0.023 to 3.9 V/m, with an average of 0.7 V/m for all the microenvironments studied, the main source of exposure being the 900 MHz and 1800 MHz GSM base stations. GSM antennas accounted for an average of 60% of the total electric field, while LTE and WiMAX (Worldwide Interoperability for Microwave Access) antennas accounted for less than 1% of the signal. The authors of the study explained that their results were probably due to the fact that GSM had been the most prevalent technology when they made their measurements, that more recent technologies generally emitted at a lower power, and that these new technologies had not yet been fully deployed.

In 2011, Joseph, Verloock, Goeminne, Vermeeren, and Martens (2012b) measured RF-EMFs from environmental sources in order to determine the impact of a new trial LTE network on exposure levels. The total electric field from all the base stations varied from 0.06 to 4.2 V/m. On average, LTE signals accounted for 0.4% of total exposure, compared to 56.3% for FM radio signals, 17.4% for 1800 MHz GSM signals, 11.9% for 900 MHz GSM signals, and 6.8% for UMTS-HSPA (Universal Mobile Telecommunications System – High Speed Pocket Access) signals. As these measurements were made on a phone network without active users, the authors also extrapolated the data to the same type of network under conditions of maximum use. The maximum expected electric field was estimated at 1.9 V/m.

2.8 Summary of current knowledge of exposure levels

Sources of RF-EMF exposure are varied and increasingly prevalent. As Rowley and Joyner (2012) noted, it is reasonable to expect that the deployment of telecommunications networks has probably helped reduce the number of places where environmental exposure to radiation from base stations is low. Similarly, the rise in the number of households equipped with wireless Internet routers, cell phones, cordless phones, and other wireless devices has undoubtedly resulted in increased public exposure to RF-EMFs. However the available data suggest that exposure levels due to these relatively new sources seem to be comparable with those already produced by radio and television communications towers.

Despite the substantial contribution of environmental sources to RF-EMF exposure, sources of voluntary exposure such as phones and wireless devices remain the predominant source, especially for exposure to the head. The total average electric field to which the public is exposed is generally less than 1 V/m (3 mW/m^2). The introduction of new wireless devices may slightly increase exposure levels. However, in the case of sources such as smart meters, exposure is very low, due in part to the their short duty cycle and the distance between these devices and the individuals exposed, which is much greater than the distance between a cell or cordless phone and the user. Exposure from this new source is therefore very low compared to historic levels of exposure attributable to cell phones and other environmental sources that have existed since the introduction of radio and television broadcasting systems.

Recent data on public exposure to RF-EMFs generally show that it has not increased significantly since the assessment by the World Health Organization (WHO) in its Backgrounder No. 304 published in 2006, in which it concluded that "[…] RF exposures from base stations range from 0.002% to 2% of the levels of international exposure guidelines, depending on a variety of factors such as the proximity to the antenna and the surrounding environment. This is lower or comparable to RF exposures from radio or television broadcast transmitters" (WHO, 2006a).

3 Recommendations on exposure limits

3.1 Approach used by organizations having assessed the health risks of radiofrequency electromagnetic fields

All the recommendations on RF-EMF exposure limits issued by recognized organizations such as Health Canada, ICNIRP, and the Institute of Electrical and Electronics Engineers (IEEE) are based on reviews of the published scientific literature on the subject. These organizations have identified all possible impacts of RF-EMF exposure and have drawn up recommendations. The main objective of these recommendations is to prevent adverse health effects due to overexposure to RF-EMFs (ICNIRP, 1998; IEEE, 2005; Health Canada, 2009a, 2015).

To determine RF-EMF exposure limits, these bodies review the scientific literature to identify the mechanisms of action governing the interaction between exposure and the physical, chemical, and biological processes in living tissues. They also look at the biological effects on isolated tissues (*in vitro*) and organisms other than humans (*in vivo*), as well as the biological and health effects in humans. The organizations use a weight of evidence approach in evaluating the scientific literature on each of these topics and in summarizing the data (Health Canada, 2009a, 2015; ICNIRP, 2002; IEEE, 2005). This approach considers the quality of the studies and the reliability and reproducibility of the results. For example, the quantity and quality of the data are sometimes insufficient to determine the energy levels that would produce clear and reproducible effects since subsequent replication studies are either lacking or have failed to produce the same results (IEEE, 2005). Such studies are given less weight in evaluations of the scientific literature.

It is not necessary to identify the mechanisms of action of RF-EMFs on living tissue to determine a human health risk. Convincing evidence from biological experiments or direct observation of adverse health effects in humans may be sufficient to demonstrate risk. However, identifying mechanisms of action makes it easier to establish causal relationships between the exposure and the observed effects as well as the exposure threshold below which the observed adverse health effects would be prevented.

Similarly, it is not necessary to determine the biological or health effects at the cellular or animal level to demonstrate a health risk for humans. However, identifying such effects can help establish causal relationships between exposure to a specific agent and observed health effects in humans. For example, all agents known to cause cancer in humans and that have undergone carcinogenicity studies in animal models gave positive results (IARC, 2006).

However, it is important to note that demonstrating a biological effect does not necessarily mean there is an adverse health effect. For example, a cellular response observed in the wake of a slight rise in body temperature caused by an increase in ambient temperature is normal and is not known to cause any adverse health effects. Such a response—by means of heat shock proteins for example—is to be expected and is one of the complex and often still unknown ways in which cells react to disturbances in the environment to which they are so well adapted (AGNIR, 2012). If the potential impact of the observed biological changes is unknown, it is necessary to refer to the data on animals and humans to establish whether these biological effects have a perceptible impact on health, or whether they are considered as part of the human body's normal responses to external stimuli. This is how health organizations separate biological effects that have been observed in the lab but that have no demonstrated health impacts from adverse health effects that are both predictable and measurable.

Determining direct effects on human health is generally a very important part of the risk assessment process regarding exposure to a specific agent. It can be done through laboratory studies and epidemiological studies, or by extrapolating animal data if there is reason to believe that human and animal responses would be similar. Establishing human health effects is sometimes difficult because of the potential presence of confounding factors, cost considerations (large-scale studies are required to detect small effects), and ethical issues (if safety guarantees are lacking, it may be unethical to voluntarily expose vulnerable individuals).

Health Canada, ICNIRP, and the IEEE have analyzed hundreds of articles in order to conduct a thorough scientific assessment. For example, in its assessment published in 2005, IEEE indicated that it had examined over 1,300 articles published in peer reviewed journals over a period of 50 years (IEEE, 2005).

3.1.1 UPDATES TO EXPOSURE LIMIT RECOMMENDATIONS

Certain advocacy groups consider that the exposure limits recommended by ICNIRP, the IEEE and the Federal Communications Commission (FCC) are obsolete because they were last updated in 1998, 2005, and 1997, respectively (AFSSET, 2009). Health Canada was also criticized for not updating its recommendations between 1999 and 2009.

In reality, all these organizations continuously monitor the scientific literature on RF-EMFs (Health Canada, 2009a, 2015; ICNIRP, 2002; IEEE, 2005). However, they take different approaches to updating their recommendations. Health Canada, for example, updates its recommendations periodically based on scientific advances and changes its exposure limits when there is reason to do so (Health Canada, 2009a, 2015). ICNIRP releases new recommendations only when new scientific data justify changing its standards (ICNIRP, 2002). In fact, it has not released new recommendations on RF-EMFs since 1998 because it considers that the data published in recent years has brought no evidence of adverse health effects at exposure levels within the established limits (ICNIRP, 2009b). Health Canada, ICNIRP, and the IEEE are all in the process of reviewing their recommendations (Industry Canada, 2013; ICNIRP, 2013; International Committee on Electromagnetic Safety [ICES], 2012). Health Canada has asked the Royal Society of Canada (RSC) to provide an independent opinion on the most recent update of its Safety Code 6 (SC6). The Royal Society published its report in 2014 (Royal Society of Canada Expert Panel, 2014), suggesting some minor adjustments to the exposure limits in SC6. It also stressed the importance of continued monitoring of the scientific literature on the health effects of RF-EMFs, especially with respect to cancer and idiopathic environmental intolerance attributed to electromagnetic fields.

3.2 Mechanisms of action

As shown in Table 2, the quantity of energy in each RF photon is very low, on the order of ~ 4 x 10^{-6} eV at 1 GHz. Therefore electromagnetic radiation in this frequency range is considered to be nonionizing, i.e., an RF photon does not have the ability to ionize matter directly in the way that X rays and gamma rays do. Although ionization by the simultaneous absorption of hundreds of thousands of low-energy RF photons is theoretically possible, the probability of this happening is low. RF photons do not have enough energy to directly ionize atoms or damage biological molecules such as DNA, which has a well-known repair mechanism (ICNIRP, 2009a).

As for the acute effects of exposure to high intensity RF-EMFs, the mechanisms of action on physiological systems in the human body are well known (Health Canada, 2009a, 2015; ICNIRP, 1998; IEEE, 2005). Between 3 kHz and 10 MHz, RF-EMFs are capable of stimulating central and peripheral nervous tissue. Between 100 kHz and 110 MHz, RF-EMFs are capable of producing electric shocks and burns through the effect of surface charges in contact with objects in an RF field or that go to ground (ICNIRP, 1998). Between 100 kHz and 10 GHz, heat absorption can lead to localized heating of tissues or an increase in body temperature. Finally, between 10 and 300 GHz, the heating of tissues is still the predominant effect, but it occurs close to the surface of the body. These effects and their associated dosimetric quantities are summarized in Table 4.

Table 4 Health effects of radiofrequency electromagnetic fields at different frequencies

Frequency	Anticipated Effect	Unit of Measure
3 kHz to 10 MHz	Stimulation of nervous tissue due to an electrical current	Induced electric field [V m^{-1}] or current density [A m^{-2}]
100 kHz to 10 GHz	Increase in average body temperature and localized heating	Specific absorption rate – SAR [W kg^{-1}]
10 GHz to 300 GHz	Heating of tissues near body surface	Power density [W m^{-2}]

Sources: ICNIRP, 1998; IEEE, 2005; and ICNIRP, 2010.

Due to potential biological effects at low exposure levels observed by certain laboratories, researchers have tried to determine the mechanisms of action that could explain such effects by RF-EMFs.

Sheppard, Swicord, and Balzano (2008) analyzed all the proposed mechanisms and concluded that the only mechanisms that had been established with respect to biological environments were tissue heating through dielectric and resistive loss. They added that of all the other proposed mechanisms, only spin-coupled radical pairs deserved more experimental and theoretical attention. In its latest assessment of the scientific literature, ICNIRP (2009a) noted that although it is impossible in principle to prove the absence of nonthermal effects, the various methods suggested to date to explain potential biological effects at low exposure levels are not very plausible. The IEEE (2005) concluded that the only recognized mechanisms of interaction between RF-EMFs and biological systems are those that cause tissue heating.

Other recognized health organizations have evaluated mechanisms of action and have come to similar conclusions. AFSSET (2009) considered that "[…] none of the biological mechanisms analyzed are indicative […]" [free translation] of health effects due to long-term exposure to low levels of RF-EMFs. Committees in Norway (Norwegian Institute of Public Health [NIPH], 2012), Sweden (Ahlbom, Feychting, Hamnerius, and Hillert, 2012), and England (AGNIR, 2012) came to the same conclusion. Health Canada, in its 2009 update of Safety Code 6, noted that thousands of studies published in recent years had done nothing more than confirm the previously identified tissue heating and stimulation mechanisms (Health Canada, 2009a, 2015). It also considered that "At present, there is no scientific basis for the occurrence of acute, chronic, and/or cumulative adverse health risks from RF field exposure at levels below the limits outlined in Safety Code 6" (Health Canada, 2009a).

3.2.1 Signal modulation

Amplitude-modulated RF signals, i.e., those whose intensity varies over time, can cause different effects than continuous signals. Generally speaking, modulated signals of the same power are more capable of producing a biological response than continuous signals, especially if an intensity threshold has been reached (ICNIRP, 1998). For example, the phenomenon of microwave hearing caused by thermoplastic expansion of tissues, which stimulates the auditory system, has been known for more than 50 years (ICNIRP, 1998).

Juutilainen, Höytö, Kumlin, and Naarala (2011) reviewed the scientific literature on the effects of RF modulation. The authors analyzed articles published since 1998 that compared the effects of exposure to modulated and unmodulated RFs. The authors reported possibly real effects on the human central nervous system. Six of the 18 studies published on the subject had positive results, with modulated signals that produced SARs of around 0.3 to 1 W/kg. The authors noted that the observed effects were minor and that no conclusions could be drawn about their potential health impacts. No reproducible effects of modulation are reported for the other endpoints analyzed, including *in vitro* and *in vivo* experiments on genotoxicity and carcinogenicity. The authors noted that although the research methods used in certain studies allow for a comparison, none of the studies producing positive results were followed by direct replication experiments. More studies will be needed before concluding that effects do in fact exist. However, no plausible mechanism of action can explain possible effects of modulating of low intensity signals, and demodulation of RFs in biological tissues is not possible (Juutilainen, Höytö, Kumlin, and Naarala, 2011; Kowalczuk et al*.,* 2010). Generally speaking, health organizations have concluded that despite the introduction of different signal modulation techniques, it is extremely unlikely that demodulation[6] of the carrier frequency could cause an independent biological response (AGNIR, 2012).

3.3 Recommendations on exposure limits

All the scientific literature reviews conducted by recognized organizations conclude that exposure to RF-EMFs of 100 kHz to 10 GHz can increase body temperature in lab animals (Health Canada, 2009a, 2015; ICNIRP, 1998; IEEE, 2005; Ahlbom, Feychting, Hamnerius, and Hillert, 2012). These organizations also concluded that an increase in body temperature of approximately 1°C caused by such RF-EMF exposure leads to significant but reversible changes in animal behavior. When the animal data is extrapolated to humans, the exposure required to produce a similar rise in temperature corresponds to a SAR averaged over the entire body of about 4 W/kg. In humans, however, a comparable rise in body temperature for an equivalent RF-EMF exposure is hard to produce, given the greater effectiveness of the human thermoregulatory system (IEEE, 2005).

The scientific community has reached a consensus on these thermal effects, which are the basis of the recommendations of all recognized health organizations. To determine the occupational exposure limit, a safety factor of 10 is applied to the SAR capable of producing significant tissue heating (4 W/kg). For the general public, an additional safety factor of 5 is applied to take into account a potentially longer exposure time and the possible presence of vulnerable individuals in the population (e.g., people with health problems affecting thermoregulation, children, etc.). This gives the basic restriction of 0.08 W/kg (Table 5).

The limits that organizations set for local exposure, such as to the head, arms, and legs, as well as the appropriate volumes over which the SAR should be averaged in these situations, are comparable. The small differences in these values reflect discrepancies among the organizations' assessment methods, but all the standard exposure limits provide equivalent protection. Reference levels, expressed in terms of power density, electric field (EF), or magnetic field (MF), are calculated from the basic restrictions using various models in order to facilitate compliance with the recommendations (Table 6). Because these calculations are based on cautious assumptions, compliance with the reference levels ensures compliance with the basic restrictions. For exposures at a distance of a few

[6] If demodulation of a modulated digital signal were possible, it would generate a low frequency EMF, which could have a direct effect on tissues (AGNIR, 2012).

dozen centimetres from RF-EMF sources, it is generally not necessary to calculate SARs to compare the exposure to the basic restriction. It is better to characterize exposure in terms of power density, EF, or MF in order to compare it to the reference values. For example, SC6 stipulates that the SAR must be calculated only for situations where individuals are exposed to devices at a distance of less than 20 cm (Health Canada, 2009a).

Table 5 Recognized organizations' SAR Limits in an uncontrolled environments for frequencies between 100 kHz and 6 GHz

SAR	Unit	SC6[c]	FCC	IEEE[d]	ICNIRP[c]
Whole body	W/kg	0.08	0.08	0.08	0.08
Head, neck, and trunk	W/kg	1.6[a]	1.6[a]	2[b]	2[b]
Arms and legs	W/kg	4[b]	4[b]	4[b]	4[b]

[a] SAR averaged over a volume of 1 g of tissue, which maximizes the value obtained.

[b] SAR averaged over a volume of 10 g of tissue, which maximizes the value obtained.

[c] SAR averaged over a period of 6 minutes.

[d] SAR averaged over a period of 30 minutes between 100 kHz and 5 GHz, but over a shorter period above this frequency.

Table 6 Recognized organizations' reference values in an uncontrolled environments for frequencies between 100 MHz and 6 GHz

Frequencies	Unit	CS6[a]	FCC[b]	Frequency	IEEE[b]	ICNIRP[a]
100 to 300 MHz	W/m^2	1.291	2	100 to 400 MHz	2	2
	V/m	22.06	27.5		27.5	28
	A/m	0.05852	0.073		0.0729	0.073
300 to 1500 MHz[c]	W/m^2	0.02619 $f^{0.6834}$	f/150	400 to 2000 MHz	f/200	f/200
	V/m	3.142 $f^{0.3417}$	-		-	1.375$f^{1/2}$
	A/m	0.008335 $f^{0.3417}$	-		-	0.0037$f^{1/2}$
1500 to 6000 MHz	W/m^2	10	10	2000 to 6000 MHz	10[d]	10
	V/m	61.4	-		-	61
	A/m	0.163	-		-	0.16

[a] Temporal average of 6 minutes.

[b] Temporal average of 30 minutes up to 5 GHz. The duration of the temporal average varies according to the frequency between 5 and 6 GHz.

[c] Frequency, f, is expressed in MHz.

[d] For frequencies above 5000 MHz, the duration of the temporal average goes from 30 min to 150/f min, where the frequency, f, is expressed in GHz.

As the WHO has indicated (2006b), the approach generally adopted by health organizations, i.e., determining adverse health effects associated with RF-EMF exposure and selecting an appropriate exposure level that protects the public against these effects, differs from that taken by certain countries and stakeholders. Eastern European countries prefer to base their recommendations concerning exposure limits on protection against *potential biological effects* rather than health effects. The WHO notes that this approach generates much stricter exposure limits, but does not necessarily protect the public's health any more effectively because the observed biological effects have not undergone a rigorous risk analysis. This method is based on the potential existence of uncertainties and an incomplete understanding of the phenomena in question, and therefore assumes that all biological effects represent a health risk, despite the lack of a formal risk assessment. According to the WHO (2006b), it is hard to justify such an approach given the risks and benefits associated with it.

3.3.1 COMPARISON BETWEEN ACTUAL EXPOSURE AND RECOMMENDED LIMITS

Typical public exposure to RF-EMFs can be compared to the exposure limits recommended by ICNIRP, the IEEE and Health Canada.

In the case of cell phones, maximum near-field exposure is close to the recommended limits: the SAR averaged over 1 or 10 grams of tissue is generally between 0.5 and 1.5 W/kg (AGNIR, 2012; IARC, 2013). In practice, the use of hands-free kits and power modulation systems in modern phones can considerably reduce exposure (ICNIRP, 2009a). Maximum exposure with cordless phones is much lower, with a SAR averaged over 1 or 10 grams of tissue of between 0.008 and 0.06 W/kg (Repacholi et al., 2012). Therefore, maximum exposure from cordless phones is 25 to 200 times lower than the recommended limit, whereas exposure from cell phones is only one to two times lower.

Average exposure to environmental sources is much lower. For example, when Joseph, Verloock, Goeminne, Vermeeren, and Martens (2012b) made their series of measurements in England in 2011, they observed an average power density of 5.0×10^{-3} W/m^2 from all sources of between 80 and 3000 MHz. This power density is about 400 times lower than the reference level recommended by Health Canada at the most restrictive frequency (1.291 W/m^2 at 100 MHz). Even for the most exposed locations, the power density was around 5.3×10^{-2} W/m^2, which is about 24 times lower than Health Canada's reference level. Similarly, the Rowley and Joyner study (2012) using a database of over 170,000 EMF measurements, indicates an average power density from base stations of 7.3×10^{-4} W/m^2. This is at least 3,000 times lower than the recommended exposure limit for the general public in SC6.[7]

Electricity meters emitting RF-EMFs, another environmental source, generate a low level of exposure. The average power density from smart meters at one metre is less than 5.0×10^{-5} W/m^2, which is about 55,000 times lower than the reference level recommended by Health Canada. If a smart meter continuously emitted at peak power, for example because of a breakdown, the average power density at 1 m would be about 5.0×10^{-2} W/m^2. This power density, which corresponds to the peak power density during the emission, would still be less than 2% of the reference level in SC6.

3.4 Other exposure limits

Certain municipalities, regions, and countries have adopted or recommended RF-EMF exposure limits that differ from those recommended by recognized health organizations (Stam, 2011; British Columbia Centre for Disease Control and National Collaborating Centre for Environmental Health, 2013). Even though most countries in the Western world have adopted, formally or otherwise, the recommendations issued by ICNIRP or the IEEE, other countries have set lower RF-EMF exposure limits. The following subsections briefly discuss the recommendations in Russia and Italy to illustrate the main reasons for the differences between the limits in these countries and those recommended by ICNIRP.

3.4.1 RUSSIA

Russia's public health approach to setting exposure limits is based on the principle that people should not have to compensate for a biological effect of RF-EMF exposure, even if the effect does not cause adverse health impacts (Repacholi, Grigoriev, Buschmann, and Pioli, 2012). This approach, which is unique to Russia, contrasts with that adopted by ICNIRP and the IEEE. It involves determining the lowest exposure level causing adverse health effects and dividing it by a safety factor

[7] 2.52 W/m^2 at 800 MHz, the frequency at which the exposure limit is the most restrictive in this analysis.

of 50 to calculate the exposure limit. Russia also differs in the way it interprets the proposed exposure limits. The Soviet and Russian committees that set the exposure standards did not take into account the difference between absorption of RF-EMFs by lab rats and mice and absorption by humans. Therefore, Russia imposes exposure limits that are lower than those set in Canada and a number of other countries.

The Russian exposure limits are based on its results in several areas of research, but principally on immune system studies (Repacholi, Grigoriev, Buschmann, and Pioli, 2012). According to experts who analyzed the scientific underpinnings of the Russian standards, these studies were conducted 20 to 40 years ago, when many aspects of the immune system's functioning were poorly known. They also predate the development of modern lab techniques and the establishment of quality standards for experimental research (Repacholi, Grigoriev, Buschmann, and Pioli, 2012). The authors of this analysis concluded that studies of such poor quality could not be used for setting current exposure standards.

Following a recommendation by the WHO, researchers attempted to replicate the results of the main Russian immunological studies (Repacholi, Grigoriev, Buschmann, and Pioli, 2012). After analyzing the raw data from the new studies, the committee supervising these experiments concluded that the previous results could not be confirmed in a convincing manner (Repacholi, Grigoriev, Buschmann, and Pioli, 2012).

3.4.2 ITALY

Italian standards define three RF-EMF exposure levels. The first level consists of *exposure limits*, which should never be exceeded and are based on ICNIRP reference levels (AFSSET, 2009). The second level involves *attention levels* (6 V/m or 0.1 W/m^2), which are precautionary values that should not be exceeded in residential areas. They are not designed to protect the public from specific health effects, but to prevent potential long-term health effects that, in the Italian government's view, could have been underestimated in the recommendations issued by ICNIRP (AFSSET, 2009). The third level involves *quality goals*, precautionary values whose exposure levels are the same as those of the attention levels. The attention levels and quality goals are not aimed at protecting the population against known risks, but rather against as yet unknown health effects by lowering the exposure limits by an arbitrary factor (Vecchia and Foster, 2003).

AFSSET (2009) notes in its updated literature review that no grounds are given for these attention levels in Italian law and that they have no scientific basis. AFSSET also mentions that attention levels do not take into account the frequency of the RF-EMFs. It concluded that the Italian approach was based on "[…] criteria that are not scientifically founded […]" [free translation] and therefore is hard to reconcile with the international scientific trend.

Moreover, the adoption of these arbitrary exposure limits appears to have exacerbated public anxiety as well as the controversies around the possible health effects of RF-EMFs. The public seems to have interpreted these new exposure limits as proof that long-term adverse health effects exist, and that exposure over the precautionary limit of 6 V/m involves an unacceptable level of risk (Vecchia and Foster, 2003). These observations echo the warnings issued by the WHO (2008), which cautioned public health authorities against adopting arbitrary RF-EMF exposure limits that could undermine public confidence in scientifically-established standards.

3.5 Management measures not based on exposure limits

Certain health organizations have adopted recommendations aimed at reducing public exposure to RF-EMFs without recourse to a legislative approach. For example in its most recently updated literature review, the committee of scientific experts at France's Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (Anses, 2013), recommended: "[…] that users should be provided with information on maximum exposure levels (e.g., SARs) generated by personal devices that use RF-EMFs (DECT phones, touchscreen tablets, baby monitors, etc.) on the basis of the regulatory model and obligations in force for mobile phones […]" [free translation] and "[…] that measures should be proposed to enable users to reduce their exposure if they wish […]" [free translation]. Anses itself has gone even farther, recommending "[…] that children's exposure should be reduced by encouraging moderate use of mobile phones and the use of hands-free devices and mobile phones with the lowest SARs […]" [free translation]. It also recommended that "[…] adults who intensively use mobile phones in conversation mode should use hands-free devices and mobile phones with the lowest SARs […]" [free translation].

Similarly, Health Canada (2011a) has issued recommendations on reducing RF-EMF exposure. It "[…] reminds cell phone users that they can take practical measures to reduce their RF exposure by limiting the length of cell phone calls, using 'hands-free devices', and replacing cell phone calls with text messages." It also encourages "[…] parents to take these measures to reduce their children's RF exposure from cell phones since children are typically more sensitive to a variety of environmental agents." In the same notice, Health Canada also indicates that "precautions to limit exposure to RF energy from cell phone towers [base stations] are unnecessary because exposure levels are typically well below those specified in health-based exposure standards."

3.6 Québec's position on managing risks related to radiofrequency electromagnetic fields

In recent years, Québec public health authorities have been asked to take a position on the risks related to exposure to electromagnetic fields (Levallois, Lajoie and Gauvin, 1991; Levallois, Gauvin, Lajoie, and Saint-Laurent, 1996; Levallois et al*.,* 2000; Gauvin, Ngamga Djeutcha, and Levallois, 2006; Diallo and Gauvin, 2010; Beausoleil and Brodeur, 2010; Beausoleil, 2011). In their report on the state of knowledge on exposure to RF-EMFs from cell phone base stations, Diallo and Gauvin (2010) conclude that "although the biological effects of RF-EMF exposure are still poorly understood, most experts believe that exposure levels below the recommended limits are unlikely to cause adverse health effects" [free translation]. The authors also provide recommendations on communicating with the public and scientific monitoring.

More recently, the Ministère de la Santé et des Services sociaux issued a public health notice in cooperation with the public health directors at the province's health and social service agencies in response to the project to introduce smart meters (Beausoleil, 2012). The notice concluded that "in light of current scientific knowledge on the health effects of RF-EMFs and considering the extremely low levels of RF-EMF exposure from Hydro-Québec's smart meters, these devices do not pose a health risk […]" [free translation]. This assessment was backed up by the position adopted by Québec's public health directors on RF-EMFs emitted by smart meters (Massé, 2013).

3.7 Summary on exposure limits

The recommendations on exposure limits issued by two of the leading scientific organizations specializing in the health effects of RF-EMFs, namely ICNIRP and the IEEE, are based on the need to prevent adverse human health effects that have been established and recognized by the scientific community. To date, these organizations consider that for the most commonly used frequencies in telecommunications applications, only tissue heating due to short-term exposure should be taken into account and that the mechanisms of action that have been identified do not suggest any other health effects.

Although the exposure limit recommendations issued by ICNIRP and the IEEE differ slightly in some respects, on the whole they are very similar. This is to be expected, given that both organizations base their recommendations on the scientific consensus derived from all articles published in this field.

Exposure of the general public to RF-EMFs is well below the recommended exposure limits, which themselves include a safety factor of 50 relative to the exposure level causing adverse health effects. Although some countries have adopted more stringent exposure limits, it is not clear that those lower limits make the public safer.

4 Health risks

Health risk assessments must take into account cell, animal, and human studies published in peer-reviewed journals. Other studies on the biological and physical plausibility of the effects in question, discussed briefly in Section 3.2, are also an important part of health risk the assessments.

4.1 Cell and animal studies

The scientific literature on the effects of RF-EMFs on cells and animals is very vast, and new studies are published every year. For example, the section of the IEEE International Committee on Electromagnetic Safety (ICES) database that deals with RF-EMF effects contains more than 500 cell studies and over 1,000 animal studies (Institute of Electrical and Electronics Engineers, 2015).

Recent literature reviews on genotoxicity, carcinogenicity, reproduction, development, and the nervous system will be examined in the following subsections. A number of other potential effects have been studied and will be covered briefly.

4.1.1 Genotoxicity, carcinogenicity, and gene expression

Considerable research has been done on the potential genotoxicity[8] and carcinogenicity[9] of RF-EMFs. This work is summarized in the review articles by Verschaeve et al*.* (2010) and Juutilainen et al*.* (2011), which provide an overview of the cell and animals studies on these topics. Most of the authors of these articles also belong to ICNIRP, and the articles are based in part on the reviews updating the organization's knowledge on the subject (ICNIRP, 2009a).

Verschaeve et al*.* (2010) examined all cell, animal, and human studies on genotoxicity published since the WHO assessment in 1993. The authors concluded that most of the studies provided no evidence of RF-EMFs being genotoxic, but that some studies did yield a few positive results. They noted, however, that a number of these positive results were due to high exposure levels and that the effects could be the result of temperature increases. Verschaeve et al*.* (2010) reported some controversy regarding the genotoxicity of RF-EMFs, as some studies on low exposure levels also found positive results. Nevertheless, the authors suggested a number of hypotheses to explain these results and concluded that, in general, the evidence of any genotoxic effects from exposure to RF-EMFs is very weak.

Juutilainen et al*.* (2011) looked at all the animal studies on the potential carcinogenicity of RF-EMFs. The studies examined the potential for direct carcinogenicity, the ability of RF-EMFs to increase the carcinogenicity of known cancer agents (co-carcinogenicity), and their capacity to promote the growth of existing tumours. Overall, the authors found no evidence as to the presence of carcinogenetic effects of RF-EMFs. They cite a major study published by Repacholi et al*.* (1997, cited in Juutilainen et al*.*, 2011) that produced positive results, but note that two subsequent studies were not able to replicate them. The same authors also mention that many studies, especially older ones, show various methodological weaknesses and fail to describe their methods in sufficient detail. Juutilainen et al*.* (2011) note that a number of recent studies have been of good quality and have followed state-of-the-art laboratory practices. These studies unanimously report an absence of carcinogenetic effects of RF-EMFs in various animal models. The authors concluded that the results

8 Genotoxicity refers to the capacity of an agent to damage a cell's genetic material (Larousse, n.d.-a).

9 Carcinogenicity is the capacity of an agent to cause the development of a cancer, regardless of the mechanism (Larousse, n.d.-b).

of the studies on the carcinogenicity of RF-EMFs show no effects at exposure levels up to 4 W/kg, which is higher than the level generated by cell phones or the exposure limits established by ICNIRP, the IEEE, and Health Canada.

4.1.2 REPRODUCTION AND DEVELOPMENT

The Advisory Group on Non-Ionising Radiation (AGNIR), an expert group at the Health Protection Agency (HPA), or Public Health England (PHE) as it is now known, reported that prenatal exposure studies indicate an absence of teratogenic effects as long as the exposure level does not cause tissue heating (AGNIR, 2012). AGNIR (2012) considers that the few effects observed were not consistent with other parameters measured within each study, or with results concerning the same parameters in other studies. As for AFSSET (2009), it considered that the few studies available showed no effects on development. It also noted that recent studies, including one on four generations of mice, were unable to establish adverse effects either on development or reproduction (AFSSET, 2009). Moreover, according to the group of independent experts at AGNIR (2012), it is impossible to interpret the results of the studies showing significant effects on rat testicles. They note that these studies contain certain shortcomings, particularly regarding the characterization of exposure, and argue that they should not be used for assessing risk (AGNIR, 2012).

4.1.3 NERVOUS SYSTEM

A number of studies have analyzed the potential effects of RF-EMFs on animal brains and nervous systems in the lab (AGNIR, 2012). AGNIR considers that they provide evidence that measurable biological effects may exist. However, the organization believes that the possibility that the observed effects may be due to tissue heating cannot be excluded (AGNIR, 2012). AGNIR and AFSSET found no effects on the brain's electrical activity or the blood-brain barrier (AGNIR, 2012; AFSSET, 2009).

4.1.4 CONCLUSIONS BY HEALTH ORGANIZATIONS ON THE STUDY OF RF-EMF EFFECTS IN CELLS AND ANIMALS

Cell and animal studies have been conducted on other potential effects of RF-EMFs, including impacts on the nervous, endocrine, auditory, cardiovascular, and ocular systems, the blood-brain barrier, as well as immunological and hematological effects. Generally speaking, the health organizations that have assessed studies on these potential effects and on those mentioned in Sections 4.1.1 to 4.1.3, found no convincing evidence of adverse health effects.

The International Agency for Research on Cancer (IARC, 2013) has also evaluated the carcinogenetic potential of RF-EMFs and concluded that there is "limited" evidence of carcinogenicity in animals. The IARC uses this classification when the evidence comes from a small number of studies or when the validity of the experiments has not been fully established (IARC, 2013). Despite the effects reported in certain studies, the European Health Risk Assessment Network on Electromagnetic Fields Exposure (EFHRAN, 2010) concluded that no effect can be associated with exposure to RF-EMFs, which have been shown to be below the levels that produce tissue heating. AGNIR (2012) concluded that although some studies have shown subtle biological responses, most studies on isolated cells or animals provide no solid proof of the existence of adverse health effects at low levels of exposure. AFSSET, in its 2009 literature review, evaluated 182 *in vitro* and *in vivo* studies, and in only 78 studies was the dosimetry validated and good methodology used for the biological aspects. Of the 182 studies, 69 reported no effect (AFSSET, 2009). The agency noted that "in light of the working group's detailed analysis and critique of the studies, and given the state of knowledge at the time, there was no convincing evidence of a specific biological effect due to RF-EMFs at nonthermal exposure levels, under the experimental conditions used" [free translation]. The Norwegian Institute of Public Health (NIPH, 2012) also concluded that many of the publications on potential effects of RF-EMFs at exposure levels below the established limits provide no evidence of adverse health effects.

The International Commission on Non-Ionising Radiation Protection (ICNIRP) considers that recent cell and animal studies have shown that genotoxic and carcinogenetic effects at exposure levels below the recommended limits are unlikely, and that the mechanisms proposed to explain them are not very plausible (ICNIRP, 2009a). Although the commission does note that some studies on other topics have produced more equivocal results, it indicates that these were weak and with limited functional impacts (ICNIRP, 2009a).

4.2 Studies in humans

As with cell and animal studies, research on potential effects in humans has looked at a broad range of subjects and criteria. In its latest report, Anses analyzed studies on carcinogenetic effects (brain and salivary gland tumours, leukemia, and melanoma, as well as cancer incidence and mortality rates for all cancers combined) as well as numerous other effects, including cognitive functions, sleep, circadian rhythms, auditory functions, neurological disease, reproduction and development, the immune and cardiovascular systems, wellbeing and self-reported health status, and overall health (mortality from all causes). Of all the potential effects studied, those most often mentioned in discussions on risks associated with RF-EMFs are cancer and the appearance of nonspecific symptoms, often called electrosensitivity (Ahlbom, Feychting, Hamnerius, and Hillert, 2012).

4.2.1 Cancer studies

There is still some debate as to the possible links between RF-EMF exposure and cancer in humans by both the public and the scientific community. Many types of cancer have been studied, including non-Hodgkin's lymphoma, leukemia in adults and children, and testicular cancer (AGNIR, 2012). However, most of the research has focused on head cancers, more specifically glioma, meningioma, acoustic neuroma, and cancer of the salivary gland (Ahlbom et al., 2009). The reason for this is the fact that during cell phone use, certain parts of the head are much more exposed than the other parts of the body. Two major systematic literature reviews looked at studies on links between cancer and cell phone use. Together they surveyed articles published up to November 13, 2010 (Ahlbom et al., 2009; Repacholi et al., 2012).

The most recently published systematic review (Repacholi et al., 2012) looked at the possible link between RF-EMF exposure from cell phones and the risk of brain cancer and other types of head tumours. All articles published up to November 13, 2010, were considered, and the authors of the study used a strict, well-defined assessment protocol in evaluating the quality of the studies. Overall, there appeared to be no statistically significant increase in the risk of developing glioma (odds ratio [OR] 1.07; 95% confidence interval [CI] 0.89–1.29); meningioma (OR 0.93; CI 0.77–1.12); acoustic neuroma (OR 1.05; CI 0.77–1.42); or cancer of the parotid gland (OR 0.87; CI 0.73–1.04). The authors, who also analyzed *in vitro* cancer studies, concluded that none of Hill's criteria for causality (Hill, 1965) support a causal relationship between cell phone use and brain cancer or other types of cancers of the head, the part of the body that absorbs the most RF-EMFs emitted by cell phones.

At least 20 additional studies have been published since November 13, 2010, including the results of the INTERPHONE case-control study on acoustic neuroma and ecological studies on cancer incidence rates in various countries. Some studies also focused on the association between cancer and exposure of certain groups of people working near RF-EMF sources such as base stations. Moreover, a systematic literature review on the association between various health effects, including cancer, and the proximity of base stations was recently published (Röösli, Frei, Mohler, and Hug, 2010). All the cancer studies, including those on industrial exposure, were analyzed in the IARC monograph published in April 2013 (IARC, 2013).

The following subsections discuss the main case-control and cohort studies on possible links between cancer and cell phone use, as well as the data from new ecological studies on the incidence rate of brain cancer[10]. The conclusions of the literature review on cancer risk related to base stations will then be briefly presented.

4.2.1.1 Case-control studies on cell phone and cordless phone use

This section presents the studies on which IARC's assessment are based, namely the INTERPHONE and Swedish case-control studies. The results of the other case-control studies, which were also examined for this report, are not presented here, but are analyzed and discussed in the literature reviews by Ahlbom et al*.* (2009) and Repacholi et al*.* (2012) and the IARC monograph (IARC, 2013).

To date, the biggest study on the link between cell phone use and cancer is the INTERPHONE case-control study conducted from 2000 to 2004. This collaborative study was carried out by 16 research centres in 13 countries and involved 13,953 participants age 30 to 59. The main results, which concerned glioma and meningioma, were published in 2010, while the results on acoustic neuroma were published in 2011 (INTERPHONE Study Group, 2010, 2011).

Exposure to RF-EMFs was determined in the INTERPHONE study through a detailed questionnaire on past cell phone use. The questions were posed in person during interviews with participants or their proxies. When a person died or was too sick to answer, a family member or friend filled out the questionnaire. Four different exposure measurements were analyzed: regular cell phone use, the number of years since initial phone cell use, the total duration of cell phone use and the total number of calls made with a cell phone. To calculate the odds ratio (OR), the exposed participants were compared to a control group made up of people who had never used a cell phone or had never been a regular user. Regular users were defined as people who averaged more than one call a week for six months. A total of 2,409 people with meningioma, 2,708 people with glioma, and 1,105 people with acoustic neuroma participated in the study, and the participation rates of these groups were 78%, 64%, and 82%, respectively. The participation rate of the controls was 53% (for a total of 7,658 controls matched with the cases).

Generally speaking, cell phone use in the INTERPHONE study was not associated with an increased risk of developing meningioma, glioma, or acoustic neuroma. For these three types of cancers, the ORs and 95% CIs for regular cell phone users compared to those who had never been regular users were 0.79 (0.68–0.91), 0.81 (0.70 – 0.94), and 0.85 (0.69–1.04), respectively. The authors observed no increase in risk for participants based on the number of years since initial cell phone use. The ORs and CIs for 10 years of use were 0.83 (0.61–1.14), 0.98 (0.76– 1.26), and 0.76 (0.52–1.11) for meningioma, glioma, and acoustic neuroma, respectively. The ORs and CIs for the decile of users having made the most calls (more than 27,000 calls) are similar: 0.80 (0.55–1.17), 0.96 (0.71–1.31), and 0.93 (0.61–1.41) for meningioma, glioma, and acoustic neuroma, respectively. However, the results for the decile of users having accumulated the most hours of use (more than 1,640 hours) showed a slightly increased risk (1.15 [0.81–1.62], 1.40 [1.03–1.89], and 2.33 [1.23–4.40]) for meningioma, glioma, and acoustic neuroma, respectively.

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[10] As a reminder, cohort studies are generally considered to be more reliable than case-control studies, which in turn are considered more reliable than ecological studies.

In their analysis, the authors of the INTERPHONE study concluded that cell phone use is not associated with a higher risk of developing meningioma. As for glioma, the authors explain that the results for the heaviest users based on the cumulative calling duration (OR 1.40; CI 1.03 – 1.89) were not conclusive and could be attributed to the presence of one or more biases, which are briefly discussed below. The authors reported that among the heaviest users, 38 cases and 22 controls mentioned using their cell phones more than five hours a day, and 10 cases said they used their cell phones more than 12 hours a day, whereas no controls reported this level of use. The authors doubted the credibility of these unreasonably high figures and indicate that a validation study seemed to indicate that cancer patients tended to overestimate their cell phone use compared to controls. Furthermore, they noted that the increased risk of glioma is only observed for the cumulative calling duration, and not for the total number of calls made, whereas the validation studies showed that the participants in this type of research remembered the number of calls they made more accurately than their duration. The authors also looked at the ratio of ORs for tumours on the side of the head where the cell phone was held compared to the ORs for tumours on the other side of the head. The highest ratio was obtained for cases who used their cell phones less than 5 hours, which indicated that these cases perhaps tended to mention that they used their cell phones more on the side of the head where the tumour was located. Ultimately, the authors concluded that their study indicated no increased risk of developing either glioma or meningioma due to cell phone use. They added that the possible biases and errors in their study prevented a causal interpretation of the risks observed in certain subgroup analyses.

With regard to acoustic neuroma, the authors of the INTERPHONE study reported no increased risk of developing this type of tumour due to regular cell phone use. They also noted that their data indicated no dose-response relationship with regard to use and that the lowest OR was in the ninth decile in terms of cell phone use. They added that the increased risk to which the heaviest users seemed to be exposed (10th decile, more than 1,640 hours) could be attributed to either chance, biased information in the collected data, or a causal relationship. Lastly, the authors point out that acoustic neuromas are slow-growing tumours and that the period of time between exposure and development of the illness evaluated in the study is too short to observe an effect.

Hardell's research group, based in Sweden, also published a number of case-control studies on the association between RF-EMFs emitted by cell phones and cordless phones on the one hand and brain cancer and other head cancers, on the other. The group conducted four studies and published the data in five articles (Hardell, Näsman, Påhlson, Hallquistm, and Mild, 1999; Hardell et al,. 2002; Hardell, Carlberg, and Mild, 2005, 2006, 2010). It also published numerous reanalyses of the data collected during the studies, including a pooled analysis of data collected on diagnosed cases from 1997 to 2003, published in 2011 (Hardell, Carlberg, and Mild, 2011).

The first study by Hardell, Näsman, Påhlson, Hallquist, and Mild (1999) involved 209 cases aged 20 to 80 who developed cancer between 1994 and 1996 (all head cancers and acoustic neuroma, combined) and 425 controls. The participation rate was not calculated in the conventional manner, but once deceased patients, patients whose doctors refused to have them included in the study, and patients who had refused for health reasons are included in the denominator, the rate appears to have been on the order of 25% to 36% (AGNIR, 2003). The reference group to which the cell phone users were compared was made up of people whose cumulative cell phone use was less than 8 hours. The authors observed no association between cell phone use and cancer. The overall OR and 95% CI for cell phone users versus nonusers were 0.98 (0.69–1.41). The authors also observed a nonstatistically significant increase in the risk of developing a tumour on the side of the head on which the phone was mainly held (OR 2.45; CI 0.78–7.76 for the right side and OR 2.40; CI 0.52– 10.9 for the left side). However, since there was no overall increase in cancer risk in the cell phone users who participated in the study, this data would suggest that cell phone use could be associated with a reduced risk of cancer on the side opposite where the phone is generally used (AGNIR, 2003). Given this improbable result, it is more likely that information or selection bias could explain this finding.

In a second study by Hardell et al*.* (2002), similar in design to the first, brain cancer patients and controls aged 20 to 80 were recruited from 1997 to 2000. In all, 1,429 cases (i.e., about 56% of the eligible patients) and 1,470 controls (participation rate of 91%) answered the questionnaire. Unlike in the first study (Hardell, Näsman, Påhlson, Hallquist, and Mild, 1999), the reference group to which the cell phone users were compared was made up of people who had never used a cell phone or cordless phone. This very strict nonexposure criterion is different than that used in the first study, and the possibility that it could have led to a confounding bias should have been examined. For a latency period[11] of one year or more, the odds ratio for cell phone users versus nonusers indicated no increase in risk (OR 1.0; CI 0.8–1.2). The results for cordless phones are identical (OR 1.0; CI 0.8–1.2). Use of analog cell phones showed a slight increase in risk (OR 1.3; CI 1.02–1.6), but the increase was not associated with duration of use, the ORs being similar regardless of duration: OR 1.3; CI 0.99–1.8 for less than 85 hours and OR 1.2; CI 0.9–1.6 for more than 85 hours. A number of other association measurements were also calculated; in all, more than 200 measurements for different subgroups are presented in the article by Hardell et al. (2002, cited in Boice and McLaughlin*,* 2002). Among other things, the authors reported, for a latency period of more than 5 years, an almost identical increase in the risk of tumour development in the temporal lobe for analog cell phones (OR 1.9; CI1.1–3.3) and cordless phones, (OR 1.9; CI 1.1–3.5). According to Boice and McLaughlin (2002), this association is not very plausible, because analog cell phones in Sweden emitted 25 to 100 times less RF-EMFs than cordless phones. As in the previous study (Hardell, Näsman, Påhlson, Hallquist, and Mild, 1999), analysis of the location of the tumours showed a slight increase in risk on the side of the head where the phone was most often held and a reduced risk on the opposite side.

A third study was conducted on patients with malignant brain tumours or benign tumours (mainly meningioma and acoustic neuroma) from 2000 to 2003 (Hardell, Carlberg, and Mild*,* 2005, 2006). The cases and controls were between 20 and 80 years old. In all, 317 people with malignant tumours and 413 people with benign tumours participated, with 692 controls (participation rate of 84%). The reference group to which the cell phone users were compared was of the same composition as in the previous study. The data presented in the two resulting articles (Hardell, Carlberg, and Mild*,* 2005, 2006) do not make it possible to calculate the participation rate for each type of tumour separately in a conventional way. The overall participation rate for the tumour cases, when calculated regardless of the type of tumour, is about 67%. The study design is different than that of earlier studies, and the association measurements do not always allow a direct comparison with previous results. For example, unlike in the first two studies by Hardell's group (Hardell, Näsman, Påhlson, Hallquist, and Mild,1999; Hardell et al*.,* 2002), the analyses did not necessarily combine all types of head cancers. For a latency period of one year or more, use of a digital cell phone (OR 1.5; CI 1.1–2.1), cordless phone (OR 1.5; CI 1.1–2.0), or analog cell phone (OR 2.4; CI 1.5–3.9), was associated with an increased risk of developing a benign tumour. There was a similar increase in risk in the case of malignant tumours, with ORs and CIs of 1.9 (1.3–2.7), 2.1 (1.4–3.0) and 2.6 (1.5–4.3), for digital cell phones, cordless phones, and analog phones, respectively. These risks are higher than those observed in the previous study, despite similar median durations of use.

Finally, a fourth study analyzed the association between RF-EMFs emitted by cell phones and cordless phones and brain and other head cancers in cancer patients who were deceased, and who had thus been excluded from the studies conducted from 1997 to 2003 (Hardell, Carlberg, and Mild*,*

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[11] In these studies, the latency period seems to be the period between the time the exposure started and the time the illness was diagnosed. Exposure in the year preceding the diagnosis was not considered.

2010). A total of 346 of the 464 deceased cancer patients for whom a proxy had been identified were included in the study (87%). The participation rate of proxies of the control group, which was made up of a group of deceased persons with cancers other than brain or other head cancers and a group of deceased persons with chronic illnesses, was 67%. From November 2006 to August 2008, the proxies for the cases and the controls were asked to evaluate the deceased persons' use of cell phones and cordless phones. Analog cell phone use was associated with a statistically significant increase in brain cancer risk (OR 1.7; CI 1.1–2.7), while digital cell phone use was associated with a nonstatistically significant increase in brain cancer risk (OR1.4; CI 0.97–2.1). In contrast, there was no association between combined use of analog and digital cell phones, the use of a cordless phone, or the combined use of cell phones and cordless phones and an increased risk of brain cancer (OR 1.3; CI 0.9–1.9, OR 1.1; CI 0.7–1.5, OR 1.1; CI 0.8–1.5). However, the results of this study are hard to interpret. It is difficult to assess the validity of the information supplied by the proxies, who were asked about their loved ones' phone use dating back 10 to 20 years. The comparison of the median use durations in this study revealed that the proxies tended to greatly overestimate their loved ones' phone use compared to the self-evaluations by cases reported in the two previous studies covering the same period (Hardell et al., 2002; Hardell, Carlberg, and Mild, 2006; AGNIR, 2012). Despite efforts in this study to limit recall bias due to differences between phone use estimates by case and control proxies, it seems unlikely that in a brain cancer study, a respondent answering for a person who died of lung cancer or cardiovascular disease would be subject to the same bias as the proxy of someone who died of brain or other form of head cancer. No validation studies have been conducted to check the potential influence of such a bias.

4.2.1.2 Cohort studies on cell phone use

Two cohort studies on cell phone use have been carried out, one in the U.S., which unfortunately was very short[12], and a Danish study, most recently updated in 2011 (Ahlbom et al., 2009; Frei et al., 2011a). Another cohort study, called COSMOS (*Cohort Study of Mobile Phone Use and Health*), was also launched recently (http://www.ukcosmos.org/index.html).

The Danish study involved a cohort of people aged 30 and over, born in Denmark after 1925. They were separated into two groups, exposed and unexposed, depending on whether they had a subscription to a cell phone service in their name before 1995. This method of evaluating exposure has the advantage of being based on objective data provided by cell phone network operators. The down side, however, is that it can lead to errors in exposure classification for some people because all subscribers are not necessarily cell phone users, and vice versa. Furthermore, subscriptions that were not in the name of an actual person had to be excluded from the analysis, and the users of these phones, if they didn't own a personal cell phone, were considered as unexposed. This group represented about 28% of the subscriptions identified, but less than 5% of the Danish population in the reference group (unexposed).

In the latest update of the cohort, the data were combined with those of another cohort in order to adjust them based on socioeconomic factors. This reduced the number of participants in the cohort. The incidence of central nervous system cancer was evaluated for the period between 1990 and 2007. The authors found no association between cell phone subscriptions and cancer. ORs and CIs for central nervous cancer in subscribers and nonsubscribers were 1.02 (0.94 – 1.18) for men and 1.02 (0.86 – 1.22) for women. The study showed no increase in risk based on subscription duration. The authors concluded that their study provided no evidence for an association between central nervous system cancer and cell phone use (Frei et al., 2011b).

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[12] Legal proceedings interrupted the study after one year. See IARC (2013).

4.2.1.3 Ecological studies

Ecological studies on cancer incidence in the population give a general overview of medium- and long-term trends. Because of the problems encountered in case-control studies, especially in determining exposure, and the high cost of cohort studies, a number of ecological studies on cancer incidence trends in a range of countries and regions have been published in recent years. In particular, the authors of two of these studies also performed numerical simulations of expected cancer incidence rates based on the hypothesis of a causal relationship between exposure to RF-EMFs and brain cancer. They evaluated the plausibility of the relative risks (RR) determined in case-control studies by calculating the expected effect that an increase in the risk of brain cancer due to RF-EMF exposure would have on the incidence rate, assuming the other risk factors remain constant.

The first study, published by Deltour et al*.* (2012), analyzed the glioma incidence rate in Nordic countries (Denmark, Finland, Norway, and Sweden). The authors performed numerical simulations of expected incidence rates, assuming cell phone use led to a relative risk (RR) between 0.8 and 2.0, with a latency period of 1 to 15 years, as reported in certain epidemiological studies published to date. The authors concluded that the absence of a clear trend in brain cancer incidence in Nordic countries seemed to be inconsistent with the results of a number of case-control studies. For example, the authors calculated that if the actual RR associated with cell phone use was 1.5, this risk should have been detected if the induction period was less than 10 years (100% probability of detection) and would probably have been detected in the case of a 15-year induction period (84%). Furthermore, with a latency period of one year, even assuming an RR of 1.5 which would only be associated with the heaviest cell phone use (assumptions similar to the results of the INTERPHONE study), there is a 98% probability that an increase in the incidence rate would have been detected. According to the authors, the absence of a temporal trend in the incidence rate suggests that the latency period could be longer than the periods studied up until now, that the risk related to cell phone use could be lower than indicated in the case-control studies, or that there is no association between cell phone use and cancer (Deltour et al*.*, 2012).

Another ecological study, published by Little et al*.* (2012), looked at the glioma incidence in part of the U.S. population. Using simulations, the authors calculated the expected variation in the glioma incidence rate using the RRs from the Hardell and INTERPHONE studies. Latency periods of 1 to 10 years were considered, namely the latency periods used in the above studies. The authors concluded that the RRs published in the pooled analysis study by Hardell, Carlberg, and Mild (2011) are not consistent with the brain cancer incidence rate observed in the U.S. population. They note, however, that the observed trend does not exclude the possibility of a slightly increased risk limited to heavy cell phone users, as reported in the INTERPHONE study (Little et al*.*, 2012).

Generally speaking, despite some variation in incident rates, the causes of which are not necessarily clear, the other studies published since the article by Repacholi et al*.* (2012) show no trend in the incidence rates of brain, head, or neck cancers that can be attributed to cell phone use (Shu, Ahlbom, and Feychting, 2012; Aydin, Feychting, Schüz, Röösli, and CEFALO Study Team, 2012; Ding and Wang, 2011; Vocht, Burstyn, and Cherrie, 2011; Vocht, 2011; Duan, Zhang, and Bu, 2011).

However, incidence rate trends cannot be used to detect the impact of a possible carcinogen in all situations. For example, a slight increase in risk that applies to only a small part of the population would be hard to detect. It is also possible for a variation in the incidence rate to be amplified or masked by other factors that are hard to control. Nevertheless, if cell phone use caused brain cancer, the rapid increase in use from 0% to almost 100% in 20 years should have changed the incidence rate of this type of cancer (Deltour et al*.*, 2012). The absence of such a trend to date is reassuring.

4.2.1.4 Studies on the proximity of base stations

In their literature review on the health effects of cell phone base stations, Röösli, Frei, Mohler, and Hug (2010) found only one article evaluating the association between base stations and cancer incidence that met their inclusion criteria. The article showed no association between cancer incidence and residency in a municipality classified as more exposed, based notably on the proportion of residents living less than 400 m from a base station.

Among the studies published since the review by Röösli, Frei, Mohler, and Hug (2010), one study in the United Kingdom reported no association between estimated exposure of mothers to RF-EMFs from base stations during pregnancy and the risk of cancer in young children (Elliott et al., 2010). In contrast, the authors of a study in Taiwan observed a slight, statistically significant increase in cancer risk in children living in an area where the estimated exposure was higher than the median (Li, Liu, Chang, Chou, and Ko, 2012). However, the increase was not statistically significant for brain cancer or leukemia. The authors concluded that it would be hard to interpret their results without additional studies and that the slight increase in risk could be attributed to the numerous shortcomings in their methodology. Lastly, a third study reported an association between the increase in certain types of cancers and the proximity of base stations. However, the methodological weaknesses in this study limit the conclusions that can be drawn (Dode et al., 2011; Foster, and Trottier, 2013).

4.2.1.5 Cancer risk assessment by health organizations

A number of health organizations have made in-depth assessments of possible links between cancer and exposure to RF-EMFs. Generally speaking, except for the IARC, expert groups consider that the evidence available to date is insufficient and does not support the notion of a causal relationship.

In 2011, the IARC working group on RF-EMFs concluded that there were “limited” indications of an association between RF-EMF exposure in humans and carcinogenicity, specifically glioma and acoustic neuroma, as well as “limited” indications of carcinogenicity in animals (Baan et al., 2011). Although some members of the IARC working group issued a minority opinion to the effect that they considered the evidence in humans “insufficient,”[13] a large majority of the members of the working group classified this type of radiation in the agent group “possibly carcinogenic” to humans (Group 2B). This category is used when a cause and effect relationship is considered credible, but the possibility that chance, bias, or confounding factors could explain the association cannot be eliminated with reasonable certainty (IARC, 2006).

Although the IARC working group based its assessment mainly on the results of the INTERPHONE and Hardell studies on cell phone use, it applied them to all RF-EMFs between 30 kHz and 300 GHz. However, this assessment does not quantify risk based on the source of the radiation. For the general public for example, almost all other sources of RF-EMFs generate a lower level of exposure to the head than cell phones. Thus, Robert A. Baan, responsible officer for Monograph 102 on RF-EMFs at the IARC, considers that even if the cause and effect relationship were real, the risk of developing one of the cancers identified by the IARC due to exposure to radiation from a low-intensity environmental source would be considerably lower than the risk due to exposure to a local source such as a cell phone (PRIARTEM, 2012).

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[13] The minority members’ opinion was based on the contradictions between the results of the main case-control studies, the absence of a dose-response relationship in the INTERPHONE study, the lack of a rise in glioma and acoustic neuroma incident rates in the Danish user cohort, and the absence of temporal trends in glioma incidence rates, which would reflect cell phone use rates in the population.

In June 2011, the WHO published a fact sheet called *Electromagnetic fields and public health: mobile phones*. The fact sheet comments both on the results of the INTERPHONE study and on the IARC's classification of RF-EMFs. The WHO specified that "To date, no adverse health effects have been established as being caused by mobile phone use" (WHO, 2014). The WHO noted, however, that "there are some indications of an increased risk of glioma for those who reported the highest 10% of cumulative hours of cell phone use […]," but reported the conclusions of the INTERPHONE study, namely "[…] that biases and errors limit the strength of these conclusions and prevent a causal interpretation."

In 2011, ICNIRP, which monitors the scientific literature on nonionising radiation, issued an opinion following the publications of the INTERPHONE results. ICNIRP concluded that these results, combined with those of other epidemiological, biological, and animal studies, suggest that an increased risk of brain cancer in adults within 10 to 15 years of the start of cell phone use is unlikely (Swerdlow et al., 2011). ICNIRP added that although it is impossible to be certain, the current trend in results does not support the hypothesis that cell phone use may cause brain cancer.

In the literature review the IEEE conducted in 2005 as part its update of the C95.1 standard, it noted that the epidemiological studies so far had provided no clear and convincing evidence of a causal relationship between exposure to RF-EMFs and cancer or other illnesses in humans (IEEE, 2005). The IEEE added that although results at the time did not support a strong association, they did not exclude the possibility of a risk. According to the IEEE, however, the results showed that for the exposure levels generally measured, any adverse health effects, if they existed, would be weak.

In 2009, AFSSET updated its expert report on RF-EMFs. The agency concluded that "[…] to date there was no evidence of an increased risk of developing an intracranial tumour due to regular use of mobile phones" [free translation] (AFSSET, 2009). It noted, however, that there were not enough data to draw a conclusion about other types of cancer. In its updated literature review, Anses (2013) considered that the evidence for an association between cell phone use and glioma in the general public was insufficient, but that there was limited evidence for "intensive" users. Anses also believes that the evidence for an association between cell phone use and neuroma involving the vestibuloacoustic nerve is limited.

In its 2012 report on health effects associated with RF-EMF exposure, AGNIR reported that despite the methodological weaknesses in the studies published so far, the assessment of the scientific evidence had not demonstrated an increased risk of brain cancer or acoustic neuroma for the first 15 years of cell phone use (AGNIR, 2012). However, the group notes that the data based on longer latency periods or longer usage durations were still limited, especially for mobile phone use by children and teens. Lastly, AGNIR concluded that the studies carried out to date gave no indication that salivary gland cancers, pituitary gland tumours, leukemia, non-Hodgkins lymphoma, testicular cancer, and melanoma of the uvea can be linked to cell phone use.

In 2012, the Norwegian Institute of Public Health, following its review of the scientific literature, noted that generally speaking, the available data did not show an association between RF-EMF exposure from cell phones and quickly-growing tumours such as glioma with short induction periods (NIPH, 2012). As for slow-growing tumours, including meningioma and acoustic neuroma, this institute considered that the available data gave no indication of increased risk. The data on other types of cancer (leukemia, lymphoma, salivary gland tumours, etc.) were considered to be insufficient, but did not suggest an increased risk.

In 2012, the Swedish Council for Working Life and Social Research (SCWLSR) published an assessment of the research on RF-EMF exposure over the ten preceding years (Ahlbom, Feychting, Hamnerius, and Hillert, 2012). The council concluded that most of the epidemiological studies provided no evidence that cell phone use was associated with an increased risk of developing glioma, meningioma, acoustic neuroma, or other tumours. Furthermore, it attributed the increased risks observed in some studies to biases and noted that the increased levels of risk observed in these studies, if real, should have led to a measurable rise in brain cancer incidence rates.

In 2011, Health Canada updated the *It's Your Health* fact sheet entitled *Safety of Cell Phones and Cell Phone Towers* (Health Canada, 2011b). Health Canada summarizes the scientific controversy on the association between cell phone use and the development of certain forms of cancer as follows: "There are a small number of epidemiology studies that have shown brain cancer rates may be elevated in long-term/heavy cell phone users. Other epidemiology studies on cell phone users, laboratory studies and animal cancer studies have not supported this association" (Health Canada, 2011b). Health Canada noted that the evidence for an association was far from conclusive and that further studies would be necessary to clarify whether there is a causal relationship.

4.2.1.6 Conclusions on epidemiological studies on cancer

Interpreting epidemiological studies is often complex because their results can be influenced by variations due to chance, biases, and confounding factors (AGNIR, 2012).

Therefore, to interpret the result of these studies properly, it is important to try to detect any biases and determine their direction[14] and magnitude. So far, the INTERPHONE study has carried out the most thorough evaluation of biases that could influence its results (Repacholi et al., 2012). The research group that conducted the study performed validation studies to evaluate aspects such as the magnitude of the selection and recall biases as well as the influence of the participation rate and the time elapsed between case interviews and control interviews (INTERPHONE, 2010). These validation studies showed, for example, that for at least some of the participants, the most exposed cases overestimated their exposure more than the controls and that the participation rate of the controls who did not use cell phones was lower (Repacholi et al., 2012). However, some research groups, such as Hardell's team, published no validation studies, which makes it very difficult to assess the magnitude and direction of any biases that could have interfered with their results (Repacholi et al., 2012).

Generally speaking, apart from the IARC working group and the expert group at Anses, which both consider that there are "limited" indications that RF-EMFs are carcinogenetic for certain combinations of cancer types and subpopulations, health organizations consider that evidence of a relationship between cancer and RF-EMFs is negative, insufficient, or far from conclusive. A number of recognized health organizations believe that research on the link between cancer and cell phone use should be continued, particularly where the data are still too limited, for example on use durations exceeding 15 years and on young users (WHO, 2010).

4.2.2 STUDIES ON NONSPECIFIC SYMPTOMS

Certain individuals with sometimes debilitating health problems attribute their symptoms to exposure to various sources of electromagnetic fields. According to the WHO, the preferred term to describe this phenomenon is *idiopathic environmental intolerance attributed to electromagnetic fields* (IEI-EMF). A number of other terms are still used in the literature to describe this condition, including

[14] Increase or decrease the size of the effect measured.

electromagnetic hypersensitivity, electrosensitivity, electrohypersensitivity, and so on (Baliatsas, van Kamp, Lebret, and Rubin, 2012). A broad range of symptoms are attributed to this condition, and they vary from one individual to another. There are no clinical criteria for identifying people who report having IEI-EMF. The WHO, in its 2005 fact sheet, noted that IEI-EMF was not a medical diagnosis and that it was not clear that it represented a single medical problem (WHO, 2005).

In their systematic literature review, Baliatsas, van Kamp, Lebret, and Rubin (2012) examined 63 original studies published before June 2011 that sought to characterize people who report having IEI-EMF. The authors noted that in observational and experimental studies, cases were identified based primarily on participants' self-diagnosis or the attribution of their symptoms to an EMF source (Baliatsas, van Kamp, Lebret, and Rubin, 2012). The prevalence of this condition varies considerably from one study to another, depending on the strictness of the inclusion criteria, with less than 2% to more than 15% of the population attributing some symptoms to an EMF source (Baliatsas, van Kamp, Lebret, and Rubin, 2012).

A number of types of studies have been conducted on people reporting IEI-EMF symptoms. The research has looked at these individuals' capacity to detect EMFs compared to the general public, the association between reported symptoms and exposure to different EMF sources in the laboratory, and the association between reported symptoms and exposure to environmental sources.

Two systematic literature reviews, the first published in 2005 and an update published in 2010, examined articles on the association between EMF exposure in the lab and the appearance of subjective symptoms in people who report having IEI-EMF (Rubin, Das Munshi, and Wessely, 2005; Rubin, Nieto-Hernandez, and Wessely, 2010). The objective of these literature reviews was to compile a list of studies that examined whether people with IEI-EMF are able to detect RF-EMFs and whether they experience more symptoms during controlled exposure in the lab. They looked at a total of 46 double-blind and single-blind studies on a total of 1,175 participants who report having IEI-EMF. The authors of the reviews concluded that there was no evidence demonstrating the existence of a biophysical hypersensitivity to EMFs. The studies' results did not support the hypothesis that there is a connection between RF-EMF exposure and the reported symptoms, but the authors found additional evidence that psychological factors may play an important role in triggering, maintaining, or exacerbating the symptoms. They pointed out that since sham exposure in the lab seemed sufficient to trigger symptoms in participants who report having IEI-EMF, it seemed likely that many of the symptoms people experienced in daily life could be caused by similar nocebo effects. Rubin, Das Munshi, and Wessely (2005) noted that although most people who report having IEI-EMF say that their symptoms occur within a few minutes or hours following exposure, a minority say that they feel the effects over the longer term, a phenomenon that has been less well studied. The authors list only three studies that evaluated long-term effects (three days to three months) and noted that none of these studies had produced convincing results showing an improvement once the participants' RF-EMF exposure had been reduced (Rubin, Nieto-Hernandez, and Wessely, 2010). The authors concluded that the most convincing evidence to date indicates that IEI-EMF should not be considered as a bioelectromagnetic phenomenon (Rubin, Nieto-Hernandez, and Wessely, 2010).

Another literature review also analyzed articles on the association between exposure to an EMF source in the lab and the appearance of objective symptoms in people who report having IEI-EMF (Rubin, Hillert, Nieto-Hernandez., van Rongen, and Oftedal, 2011). The authors looked at a total of 29 studies published before May 2010 that measured a variety of parameters on the autonomic nervous system, blood biochemistry variables, cognitive and sensory functions, the immune system, sleep, and so on. A minority of studies (5 out of 29) showed effects in people who report having IEI-EMF. The authors note, however, that the effects measured in these studies were often never reproduced and were sometimes contradictory. Therefore, they were unable to identify a pattern of objective, measurable changes that could be used to characterize or diagnose IEI-EMF.

Numerous studies have analyzed the association between symptoms and RF-EMF exposure at levels present in the environment. A systematic literature review on this topic was conducted by Röösli (2008) and was then expanded to include articles published up to November 2010 (Röösli and Hug, 2011). The articles focused particularly on people's ability to detect RF-EMFs in the environment and the capacity of RF-EMF exposure to cause symptoms. The publications also sought to determine whether people who report having IEI-EMF are more likely to have symptoms after being exposed to RF-EMFs than members of the general population. Röösli (2008) concluded that the studies published to date generally show that a large majority of people who report having IEI-EMF and who say that they can detect RF-EMFs are not able to do so under controlled conditions (Röösli, 2008). Furthermore, they noted that there is no evidence that exposure to RF-EMFs leads to nonspecific symptoms in individuals, whether they report having IEI-EMF or not. In their updated literature review, Röösli and Hug (2011) concluded that the most recent articles confirm the preceding conclusions to the effect that it is unlikely that short-term exposure to RF-EMFs affects health. Baliatsas et al*.* (2012) also analyzed articles on the association between nonspecific symptoms and RF-EMFs. They performed a meta-analysis of 22 studies meeting their inclusion criteria. The authors concluded that the associations observed between RF-EMF exposure and symptoms in the general population in the various studies were contradictory. Baliatsas et al. found that the studies often showed no association or, when a statistically significant association was present in some studies (e.g., acute headaches, trouble concentrating, sleep disorders), they did not occur in other comparable studies. They also noticed that studies with more rigorous designs were less likely to observe statistically significant associations (Baliatsas et al*.*, 2012). The same authors observed that even though there does not appear to be any association between RF-EMF exposure and the reported symptoms, there does seem to be an association between these symptoms and the subjective impression of being exposed. The authors noted, however, that the evidence to this effect was not sufficient to draw a definitive conclusion on the nature of the IEI-EMF phenomenon (Baliatsas et al., 2012).

Röösli, Frei, Mohler, and Hug (2010) conducted a literature review on all health effects associated with cell phone base stations. Most of the articles they found (14 of 17) concerned the association between RF-EMF exposure and nonspecific symptoms reported by individuals. Although the designs of some of the studies only allowed for cross-sectional measurements, a number of them included randomized trials with controlled exposures. A broad range of symptoms were analyzed, including headaches, concentration problems, sleep disorders, dizziness, and more. Overall, the authors indicated that no symptom or group of symptoms could be consistently associated with RF-EMF exposure. They noted that studies using low-quality dosimetry found effects associated with exposure, whereas studies that characterized exposure more rigorously rarely detected associations. The authors concluded that the evidence for a lack of association between symptoms and RF-EMF exposure from base stations was strong because it was based on controlled trials on humans. The authors noted, however, that the data they analyzed are insufficient to draw any conclusions regarding long-term exposure at levels experienced by the population.

The possible association between nonspecific symptoms reported by a sample population and the distance between participants' homes and the nearest base station was also examined by Baliatsas et al*.* (2011). In this study, 3,611 people answered a questionnaire. The authors observed no association between participants' symptoms and how far their homes were from base stations, but concluded that various psychological and sociodemographic factors could have affected the reported symptoms (Baliatsas et al*.*, 2011). They observed that the symptoms the participants described were more closely associated with their perception of the distance between the base stations and their homes than the actual distance.

4.2.2.1 Treatment

Treatments for IEI-EMF symptoms have been examined in a limited number of studies. Rubin, Munshi, and Wessely (2006) reviewed the literature on the efficacy of treatments for IEI-EMF published before January 2004. They selected nine clinical studies on a range of treatments. The authors concluded that cognitive behavioral therapy seemed to be effective in treating IEI-EMF (Rubin, Munshi, and Wessely, 2006). However, the authors noted that since the evidence on the efficacy of this treatment is still limited, additional studies would be required before definitive recommendations could be made.

The WHO gives a number of recommendations for treating IEI-EMF in its Fact Sheet No. 296 (WHO, 2005). In particular, it recommends that physicians establish an effective physician-patient relationship in order to properly treat patients' symptoms. Patient care should include a physical and psychological examination to identify pathologies that may explain the observed symptoms, as well as an assessment of environmental factors that may be contributing to the condition (air pollution, noise, inappropriate lighting, stress, and so on).

4.2.2.2 Assessment of nonspecific symptoms by health organizations

The health organizations that have analyzed the literature on the association between RF-EMF exposure and nonspecific symptoms have come to similar conclusions. Health Canada considers that "[…] there is no scientific evidence that the symptoms attributed to [electromagnetic hypersensitivity] are actually caused by exposure to EMFs" (Health Canada, 2009b). In its Fact Sheet No. 296, *Electromagnetic Fields and Public Health: Electromagnetic Hypersensitivity,* the WHO indicates that the symptoms experienced by people with IEI-EMF "[…] are certainly real and can vary widely in their severity." The WHO notes, however, that there is "[…] no scientific basis to link [electromagnetic hypersensitivity] symptoms to EMF exposure," and that "[…] [electromagnetic hypersensitivity] is not a medical diagnosis" (OMS, 2005). AGNIR considers that the studies conducted to date constitute a solid body of evidence that suggests that short-term exposure to RF-EMFs at levels below the exposure limits do not cause symptoms either in the general public or in those who report having IEI-EMF (AGNIR, 2012). The Swedish Council for Working Life and Social Research notes that despite considerable effort, no association has been established between RF-EMF exposure and IEI-EMF symptoms (Ahlbom, Feychting, Hamnerius and Hillert, 2012). The organization considers that the lack of such a relationship, combined with the fact that the reported symptoms are associated with people's belief that they are exposed even in the absence of RF-EMFs, suggests that some of the symptoms could be attributed to a nocebo effect (Ahlbom, Feychting, Hamnerius, and Hillert, 2012). The Norwegian Institute of Public Health (NIPH, 2012) considers that many of the scientific studies provide evidence that the symptoms of IEI-EMF are not caused by RF-EMFs. It believes that social factors and" a variety of psychological factors could explain why these people think that RF-EMFs cause their symptoms (NIPH, 2012). In its literature review, AFSSET (2009) concluded that no author "[…] has provided evidence of a causal relationship between exposure and electromagnetic hypersensitivity" [free translation] and that "[…] a consistent body of evidence has been gathered strongly suggesting that individual neuro-psychic factors are responsible, at least in part, for electromagnetic hypersensitivity" [free translation]. Lastly, the literature review by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2015), an expert group mandated by the European Commission, also concluded that there was no causal relationship between the reported symptoms and exposure to RF-EMFs.

4.2.2.3 Conclusion on nonspecific symptoms

Numerous good-quality studies have been conducted to evaluate whether there is an association between exposure to low levels of RF-EMFs and nonspecific symptoms. The scientific evidence, which is increasingly strong, indicates that there is no association between IEI-EMF and exposure to EMFs. However, it is important to note that the symptoms described by people with IEI-EMF are in fact real. Some studies indicated that some of these symptoms may be explained by psychological or social factors, but that more research is required before a definitive conclusion can be drawn. A number of other physical or psychological causes could also explain the reported symptoms, and according to the WHO's recommendations, those experiencing IEI-EMF symptoms should receive medical help and personalized care.

4.3 Conclusions regarding health risks

Numerous scientific articles have been, and continue to be, published on the potential health effects of RF-EMFs. For example, while this report was being written, Anses published an update of its expert report on RF-EMFs (Anses, 2013), in which it listed 308 documents published between April 2009 and December 2012. In 2009, while updating its previous expert report, AFSSET compiled 226 documents published from the beginning of 2005 to April 1, 2009 (AFSSET, 2009). These documents, as well as articles published before 2005 and those on related subjects, represent a vast and important pool of data.

Based on this literature, numerous health organizations have assessed the potential health risks of RF-EMF exposure. Health Canada considers that RF-EMF exposure from cell phones "[…] poses no confirmed health risks […]" and that when emissions from cell phone base stations comply with established limits, "[…] there is no scientific reason to consider cell phone towers dangerous to the public" (Health Canada, 2011b). Health Canada (2011a) also affirms that "[…] current scientific evidence supports the assertion that RF energy emissions from Wi-Fi devices are not harmful*."*

In its May 2006 backgrounder, the WHO considers that wireless networks, including base stations, produce very low exposure levels and that to date, "[…] there is no convincing scientific evidence that the weak RF signals from base stations and wireless networks cause adverse health effects" (WHO, 2006a).

AFSSET, in its updated expert report released in 2009, asserted that the available experimental data "n'indiquent pas d'effets sanitaires à court terme ni à long terme de l'exposition aux radiofréquences" [indicate no short-term or long-term health effects of RF-EMF exposure] (AFSSET, 2009). As for human epidemiological data, AFSSET considers that they "[…] indicate no short-term effects of RF-EMF exposure either" [free translation] (AFSSET, 2009). The agency also mentions that although questions remain concerning potential long-term effects, "[…] none of the biological mechanisms studied currently support this hypothesis" [free translation] (AFSSET, 2009). Anses, in its updated expert report published in 2013, expresses similar conclusions (Anses, 2013). It says that the biological effects found in some studies must be validated and that they "[…] seem to be transitory or represent a simple biological variation" [free translation] (Anses, 2013). It argues that for the moment, it is "[…] impossible to conclude that the observed biological effects cause health impacts" [free translation] (Anses, 2013).

In its 2012 report, AGNIR noted that none of the hundreds of laboratory studies on cells published to date have provided solid evidence of an observable effect (AGNIR, 2012). The agency considers that, in general, the reported effects were weak and the attempts to replicate the results were unsuccessful (AGNIR, 2012). AGNIR also notes that among the laboratory studies conducted on animals, those showing a rise in body temperature are the most robust and there is no clear evidence of effects at lower exposure levels (AGNIR, 2012). In the human studies it looked at, AGNIR found no convincing evidence of an effect, carcinogenic or not (AGNIR, 2012).

The Norwegian Institute of Public Health mentioned the large quantity of published studies on potential effects of RF-EMFs (NIPH, 2012). It concludes that although certain biological and physiological effects cannot be excluded, these studies do not provide evidence that RF-EMF exposure causes adverse health effects (NIPH, 2012).

The Swedish Council for Working Life and Social Research (SCWLSR) mentions that two topics have received particular attention in connection with the potential effects of RF-EMFs, namely IEI-EMF (electrosensitivity) and brain cancers (Ahlbom, Feychting, Hamnerius, and Hillert, 2012). It considers that in both cases, concerns are based on a general fear that some aspects of this rapidly developing technology may have been overlooked rather than on any specific hypothesis or initial study. It believes that the evidence gathered to date does not suggest an increased risk and that it seems increasingly unlikely that there is any link between either of these endpoints and exposure to RF-EMFs. The SCWLSR also believes that except for certain observations that need further study, in particular potential effects on electroencephalograms, the many other potential effects that could be studied are based on no credible hypotheses requiring testing. The council concluded that the studies conducted to date provide no evidence indicating that exposure limits based on tissue heating are insufficient to protect the public’s health.

In short, although some scientific uncertainty about RF-EMFs remains, notably with respect to exposure to local sources and long-term exposure, no adverse health effects have been demonstrated so far. As for exposure to environmental sources, which is generally much lower, it seems unlikely that it could cause adverse health effects.

5 Conclusion

RF-EMF exposure can be attributed to multiple sources. It is influenced by personal choices regarding the use of devices that emit RF-EMFs on the one hand, and by a number of environmental sources and factors on the other. Data from the scientific literature show that current levels of public exposure are well below the exposure limits recommended by health organizations (ICNIRP, IEEE, and Health Canada). Although exposure levels vary in complex ways as technology evolves, it is reasonable to believe that average public exposure will increase in the coming years. Nevertheless, it should remain well below the exposure limits.

The potential health risks associated with RF-EMF exposure have been examined in hundreds of studies on isolated cells, lab animals, and humans. Exposure to high levels of RF-EMFs causes well-documented thermal effects (tissue heating), which are the basis of the exposure limit recommendations issued by most health organizations. Specific approaches to managing human health protection seem to explain the differences in exposure limits adopted throughout the world. In certain countries such as Russia, recommendations are aimed at preventing all biological effects, even when no evidence indicates that these biological effects lead to adverse health effects. Other countries, such as Italy, have adopted arbitrarily low exposure limits without any scientific basis. These approaches contrast with those used in most Western countries, which consider that biological effects that are within the range of normal physiological variation do not necessarily lead to adverse health effects. Recommendations in these countries are designed to prevent established adverse health effects, namely thermal effects.

Some studies seem to show the possibility of biological effects within the range of normal physiological variation at low exposure levels. Although current research limitations do not enable us to exclude all possibility of risk, no short- or long-term adverse health risks have been established.

Along with this scientific consensus, there exists a substantial discrepancy between the risk perceived by part of the population and the risk assessed by recognized health organizations. Few studies are available to help interpret this perception gap, but it may be due in part to the results of certain studies whose validity has not been proven. Historically, much of the scientific literature on the effects of RF-EMF exposure has been of low quality (AFSSET, 2009). These quality issues were often caused by difficulties in using appropriate methodology, both for the physical aspects of the experiments (control and characterization of the exposure) and the biological aspects (choice of appropriate endpoints, replication, interpretation, etc.). However, good methodology is essential to ensure the validity and scope of the results. Although the scientific literature published to date also contains many good-quality studies, it is still possible to find isolated or contradictory studies to support a predetermined position. Because of this variability in the quality of the research, it is very important to examine all available data in order to produce a comprehensive evidence-based assessment.

Precautionary measures

Some stakeholders involved in the debate on RF-EMF exposure recommend a precautionary approach. According to the INSPQ’s reference framework for managing health risk in Québec’s health network (*Cadre de référence en gestion des risques pour la santé dans le réseau québécois de la santé publique)*, precaution “[…] aims to prevent **potential risks**, namely risks that are poorly known, unclear, and associated with a hypothetical but plausible risk” [free translation] (INSPQ 2003). In light of the research and analyses presented here, however, it is clear that the plausibility criterion has not been established for most of the risks that have been studied.

Some uncertainty remains about the possibility of an increased risk of developing certain types of brain cancer (glioma). Given certain "limited" evidence of increased risk for the heaviest cell phone users in the INTERPHONE study, the possibility of an increased risk of developing a glioma cannot be excluded, even though it is not very plausible and is not supported by studies on isolated cells and animals. Furthermore, the evidence presented to date seems to indicate that if this risk were real, it would be low (increase in risk of less than 20%), limited to only part of the population (e.g., heaviest cell phone users), and associated with certain types of glioma and long-term induction periods, i.e., more than 15 years (Anses, 2013). However some organizations, even though they recognize the limits of current evidence, consider that new evidence tends increasingly to demonstrate that no such effect exists (AGNIR, 2012; Ahlbom, Feychting, Hamnerius, and Hillert, 2012).

Given this uncertainty, some health organizations have concluded that a recommendation encouraging reduced cell phone use by children would be justified (Health Canada, 2011b; Anses, 2013). With regard to the adult population, Health Canada (2011a) considers that it is enough to provide adults with information on how to reduce their exposure to RF-EMFs, without actually issuing a recommendation that they do so. Furthermore, Health Canada believes that measures to limit RF-EMF exposure from base stations would not be useful (Health Canada, 2011b). According to a number of organizations, the available data do not support the need for precautionary measures regarding cell phone use or exposure to other sources (Ahlbom, Feychting, Hamnerius, and Hillert, 2012; NIPH, 2012).

5.1 Risk management

Management of potential risks related to RF-EMF exposure must be based on available evidence and related uncertainty. For high exposure levels, Health Canada's SC6 limits are designed to prevent increases in body temperature and the adverse health effects they may cause. In the case of low levels of exposure, the lack of evidence indicating adverse health effects, despite considerable research on the subject, is reassuring. Nevertheless, current research does not allow us to entirely exclude the possibility of risk, even though no short- or long-term adverse health risks have been demonstrated. However, as INSPQ's reference framework on risk management mentions, "[…] absence of risk is often hard to prove definitively" [free translation] (Ricard, 2003).

Management measures, therefore, must be reasonable. The measures suggested in this report are based on what is known as a prudent management approach, which applies in situations where the existence of an actual risk is considered unlikely. The main purpose of these measures is to maintain and acquire knowledge in this field, reduce scientific uncertainty, and provide decision makers and the population with the information they need to make informed decisions.

Based on our analysis of the scientific literature on potential health risks associated with RF-EMFs, we suggest the following risk management measures:

Monitoring of the scientific literature

- Measure 1: Continue monitoring the scientific literature on possible effects of RF-EMFs.

Particular attention should be paid to studies on variations in incidence rates of brain cancer in humans, studies on children, and the results of expert assessments produced by recognized national and international health organizations.

- Measure 2: Help maintain expertise in this field in Québec and set up a network for sharing information with other experts on the subject.

A number of expert committees (e.g., Anses) monitor the scientific literature on RF-EMF exposure. Interaction with such expert committees could help maintain and update Québec's expertise in this area.

Communication of scientific knowledge

- Measure 3: Provide the public with information tools to help them keep abreast of the latest scientific data on possible links between RF-EMF exposure and effects on the public's health.

These tools (electronic documents, publications, etc.) should help reduce the discrepancy between the public perception of risk and the scientific consensus on the state of knowledge in this field, thereby helping risk managers and the public make more informed decisions.

- Measure 4: Propose measures to help people who report symptoms they attribute to RF-EMFs.

Although no link has been established between RF-EMF exposure and the symptoms experienced by people who report having IEI-EMF, the fact that they experience these symptoms is not in doubt. The symptoms these people report may be caused by underlying pathologies that could have serious consequences if not treated appropriately. Communication tools could be developed to inform them about the state of knowledge on IEI-EMF. In keeping with the WHO's recommendations, people reporting symptoms of IEI-EMF should also be directed to the appropriate resources to ensure they receive the care they need to improve their health.

Research

- Measure 5: Participate in research projects on the potential health effects of exposure to RF-EMFs.

The work should be based on the research recommendations issued by the WHO (van Deventer, van Rongen, and Saunders, 2011). Some social science research, especially on evaluating public perception of risk and developing and assessing communication tools, could help implement management measures aimed at communicating the state of scientific knowledge on RF-EMFs (measures 3 and 4).

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