Non-ionizing Radiation Protection

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Summary of Research and Policy Options

Edited by

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Foreword

Nonionizing radiation, or NIR for short, is a type of radiation that is defined by what it does not, that is, it does *not* cause ionization of molecules. While this definition conveniently separates NIR from ionizing radiation emitted by radioactive substances, during fission and from certain equipment, it is somewhat unsatisfactory to use a negative definition and it is not even always correct (a certain part of the ultraviolet, UV, spectrum may cause ionization). Furthermore, it is not always *radiation* in a strict sense (e.g., static fields and ultrasound).

Just as we differentiate between different sources and types of ionizing radiation, we may be better off dealing with NIR on the basis of its specific characteristics, which is very different depending on which form of NIR we are considering. For example, radiofrequency radiation, microwaves, laser, and UV have their own very specific characteristics. This leads to different biological actions and responses and ultimately to different types of effects on the health of people and the environment. Understanding the nature of NIR, its biological actions, health effects, and associated risks is vital when deciding on the need for, and nature of, protective measures. Such protective measures also depend on whether the exposure category is the public, workers in their occupational setting, patients undergoing medical examination involving NIR, or the environment.

The real or potential health implications of NIR exposure for both people and environment is a legitimate concern for the community. Exposure to NIR is ubiquitous and exposure to certain forms of NIR has increased with the advent of technologies such as broadcasting and telecommunication. The ability to “opt out” of such exposures is sometimes limited; examples include outdoor work or other outdoor activities leading to UV exposure. The everyday environment in virtually all population centers and workplaces also involves exposure to radiofrequency radiation. At the same time, policymakers and the public in general need to take informed decisions to mitigate risks when they are evident and not invest resources in mitigation of risks that on the basis of current evidence are negligible. Unsubstantiated health concerns could itself cause symptoms of ill health and prevent the beneficial use of technologies involving NIR.

While health effects in both the short and long terms can be clearly attributed to certain forms of NIR exposure in what can be considered "normal" situations (exposure to UV radiation outdoors is one example), there are contrasting views in society as regards the health implications of everyday exposure to, for example, radiofrequency radiation, microwaves, and static fields. Decisions on limitation of exposure and precautionary approaches are often made under uncertainty; one major factor influencing the debate among the public as well as between specialists (whether these are in radiation science, risk communication, or ethics) is how uncertainty, or the "unknown," should frame decisions on exposure limits and justification of technologies leading to exposure to NIR.

This volume explains and explores, based on scientific norms and methodologies, the characteristics of different forms of NIR, analyzes the relationship between exposure and biological effects and the associated dose–response relationships, and explores health effects and inferred and established health risks. It takes a holistic approach to the concept of "health," building on the World Health Organization's definition of "health": which is not only a state of absence of disease but includes also the physical, mental, and social well being of individuals and the population.

It finally addresses awareness, communication, and consultation, all of which are important factors in making it possible for any citizen to form an informed view and for society to take decisions based on the current state of knowledge – including uncertainties. This volume will assist in such judgments. I recommend it to everyone who wants to learn more about the different forms of NIR, the current knowledge on effects of NIR exposure on the health of people and the environment, and the evaluation and mitigation of risks associated with NIR in our everyday environments.

Carl-Magnus Larsson
CEO of ARPANSA

Acknowledgments

We are indebted to the following people who read individual chapters and provided comments: Dr Alireza Lajevardipour and Lydiawati Tjong.

Introduction

This is a book about appropriate ways to protect people (and perhaps the environment) against harmful effects of nonionizing radiation (NIR). NIR includes forms such as ultraviolet, visible light, infrared, microwaves, radio waves, and the electric and magnetic fields associated with electric power lines, magnetic resonance imaging (MRI) machines, and other electromagnetic technologies. There are many books about ionizing radiation (IR) protection because the link between X-rays, subatomic particles, and gamma radiation and serious illness such as cancer or in the case of high dose/high-dose rate death within days has been known about for over a century. NIR has always been viewed as a benign form of radiation, with MRI and ultrasound preferred over X-ray, CT, and PET modalities of imaging. Some radiation protection practitioners have labeled NIR as “not interesting radiation” because it seems that there is nothing very much to talk about in terms of dangers to human health. And yet, in many countries, the radiation source that is responsible for the largest numbers of morbidity and mortality is a NIR source, namely the sun. In other areas, the public outcry over the siting of mobile (cell) phone towers, electric transmission lines, and the roll out of Wi-Fi and smart metering services indicates that in the minds of many, NIR is not benign and is a potent and widespread source of illness, particularly cancer. Many have gone as far as labeling these technologies as the new tobacco smoking or asbestos that are established carcinogens. In addition, a section of the community attribute their being unwell to exposure from NIR sources and some have moved away from urban settings and have sought to shield their homes from man-made NIR fields in an attempt to alleviate symptoms.

The public are in general much more aware of NIR in their environment (since much of modern technology is based on electric power and electronics) than IR, which is perceived to be encountered only in specialist hospital departments (or nuclear power plants). The ubiquity of certain types of NIR coupled with the steady stream of media articles about their possible dangers to health have made sections of the community distrustful of “authority” reassurances and perplexed as to why there seem to be such differing views among scientists.

This has been amplified by a number of legal challenges to planning approvals and personal injury cases on health grounds, which have tended to pit scientific expert witnesses against each other. Rather than trying to explore through public engagement an appropriate way to deal with scientific uncertainty, government agencies have sometimes bowed to community pressure by introducing unrealistically low exposure limits, which are not science based, believing this to be a precautionary approach. The availability of cheap monitoring instruments has also contributed to media coverage, with activists contacting journalists, having made "do-it-yourself" NIR measurements (often incorrectly). The principle of "not in my backyard" (NIBY) has often been a potent factor in these debates, with possible health effects used as a weapon against the true concerns: negative visual impacts and property devaluation.

Allied to this has been the question of who to go to for unbiased information and advice. The industries involved are best placed to devote resources for producing public information material, but face a significant challenge to appear credible. This having been said, there are now a range of national and international brochures and web-based materials to provide information on the nature of particular forms of NIR, the rationale for standards, summaries of relevant scientific investigations, and possibly also ways to reduce personal exposure. These have been produced by government agencies as well as the industry organizations involved. The fact that they tend to give very similar advice indicates, in general, a willingness of industry to "tell it as it is."

The source of research funds has also been raised as a possible reason for the disparity of conclusions of scientists, with frequent claims that those who accept research funding from industry are "tainted" and thus unreliable. However, it should be acknowledged that those who believe there to be an unrecognized problem with low-level NIR exposure are also prone to selectivity when quoting earlier scientific studies. The "quality" of individual studies does vary enormously but is very hard to quantify. International agencies have tended to use the "weight of evidence" approach, in which relevant peer-reviewed studies are identified by bibliographic searches and then the outcomes compared for consistency and coherence. Isolated findings that lack replication or confirmation by independent teams of investigators tend not to be given great weight in this approach. However, finding consensus is not always easy and uncertainties remain, particularly where underlying mechanisms have not been identified.

This is not to deny that at sufficiently high intensities of NIR the health effects are immediate and serious: intense beams of ultraviolet and laser light cause tissue burning; radiofrequency (RF) fields at high-power levels can also cause excessive heating and extremely low-frequency (ELF) electric and magnetic fields can induce currents sufficient to cause alteration or cessation of heart or breathing rhythm if high enough. NIR standards are formulated to give a high margin of protection against established effects.

This book attempts to summarize the scientific findings regarding the safety of NIR, the rationale behind prevailing standards, the appropriate instrumentation to monitor this radiation, and the options for handling the associated issues in terms of policy and public information. The first chapter is an overview of the nonionizing portion of the electromagnetic spectrum, to describe the features of the way this energy can be propagated with associated electric and magnetic fields. Some of the NIR spectrum is not strictly *radiated* and this distinction will be made in this chapter. The remainder of the book is divided into nine sections as follows:

Part I deals with generic issues of how to identify hazard, both by studies in the laboratory (short-term and long-term) and by studying relevant human populations, by the methods of epidemiology. It covers the strengths and weaknesses of the experimental method for determining thresholds above which harmful effects are possible in humans. Those who are already familiar with these methods can skip parts of these chapters.

Part II covers aspects of appropriate protection against ultraviolet (UV) light. The most common source of UV exposure to humans is from the sun, which is an unregulated source. The modification of human behavior is the chief way to limit exposure, which may include obligations in the part of employers or business owners to implement these modifications.

Part III considers the visible part of the spectrum and infrared. Again, the sun is a potent source or radiation in this region, but lasers probably represent the greatest potential hazard, because of their high intensity. As well as coherent sources (lasers) a number of incoherent sources such as high-powered light-emitting diodes (LEDs) require consideration for possible eye or skin damage.

Part IV looks at the RF part of the spectrum (which includes microwaves and terahertz (THz) radiation). Although the portions of the spectrum used in telecommunications, broadcasting, and radar represent the most fully studied, lower RFs, used in welding, smelting, and heat-sealing operations, also need consideration.

Part V covers the ELF portion of the spectrum, which includes the electric and magnetic fields associated with the generation, transmission, distribution, and domestic use of electric power at 50 or 60 Hz. Although the most common, ELF fields are also associated with transportation systems, certain forms of welding and smelting are also involved.

Part VI is about static electric and magnetic fields: the former associated with high-voltage direct current (DC) transmission systems and the latter mainly with MRI machines in hospitals. Static electric fields are also encountered in the atmosphere (especially before and during thunderstorms), and the Earth has a familiar magnetic field.

Part VII moves on to community issues: these are of two types, firstly the nature of perceived hypersensitivity to electric technologies and secondly the types of policy options aimed at making proactive changes or limitations ahead of clear scientific conclusion of hazard at commonly encountered levels of exposure, the so-called cautionary approach (or Precautionary Principle). A chapter deals with examples of how to decide on whether or not to spend money on certain mitigation measures, based on cost-benefit analyses.

Part VIII covers the question of how to avoid injury (by occupational training or public awareness programs) and in the event of suspected NIR injury, how a medical assessment could be carried out.

Part IX includes what can be done to involve the public in decision-making in regard to exposure to NIR and what can be done to mitigate or attenuate the exposure at source. A chapter covers some of the public debates that have marked the development of NIR protection strategies in recent decades, with a concluding chapter to set NIR protection into perspective and to predict what may happen in the next decades.

A glance at the list of contributors on the next pages will reveal that all except two are from Australia. This is because the idea for the book arose from collaborations on developing standards and guideline documents for use in Australia. Since these were based, in the main, on international documents and inputs, the collaborators felt well placed to write a book for an international readership. We have sought wherever possible to avoid local references, but in places illustrative examples or practices are local, purely because they are most familiar to the authors.

The editors would like to express their gratitude to Dr Colin Roy, who until his retirement was one of the original editors of this book. We would also like to thank Dr Carl-Magnus Larsson for agreeing to provide a preface.

Many of the chapters have at the end of them a selection of tutorial problems, with answers given at the back of the book.

1

Overview: The Electromagnetic Spectrum and Nonionizing Radiation

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1.1 What Is Nonionizing Radiation (NIR)?

By definition, nonionizing radiation (NIR) does not cause atoms and molecules to be ionized, that is, electrons are not removed from the atom or molecule leaving it with an electrical charge. Before describing the particular features of NIR, it is instructive to consider some of the general properties of electromagnetic radiation, which comprises both NIR and ionizing radiation.

Radiation can be thought of being both wave-like and particulate (this is often referred as the "wave-particle duality"). Ionization occurs when the energy in individual particles (or "quanta") is sufficiently high to remove an electron, by transferring all of the energy of an individual quantum. Because of the "wave-particle duality" just referred to, each quantum can be associated with a particular wavelength. The wavelength of X-rays (a form of ionizing radiation) is approximately a nanometer (or a millionth of a millimeter), and other forms of ionizing radiation have wavelengths even shorter. NIR is regarded primarily as electromagnetic radiation whose wavelength is longer than 100 nm or 0.1 μm (see Figure 1.1). This is in the ultraviolet (or UV) part of the spectrum. To get this into perspective, a biological cell is around 10 μm in diameter and a single molecule of hemoglobin is 6 nm in diameter. Other forms of NIR have longer wavelengths, several thousands of kilometers in the case of waves associated with the domestic electricity supply. The wave itself is made up of two components, an electrical field (*E*-field) and a magnetic field (*H*-field), at right angles to each other and both of these quantities at right angles to the

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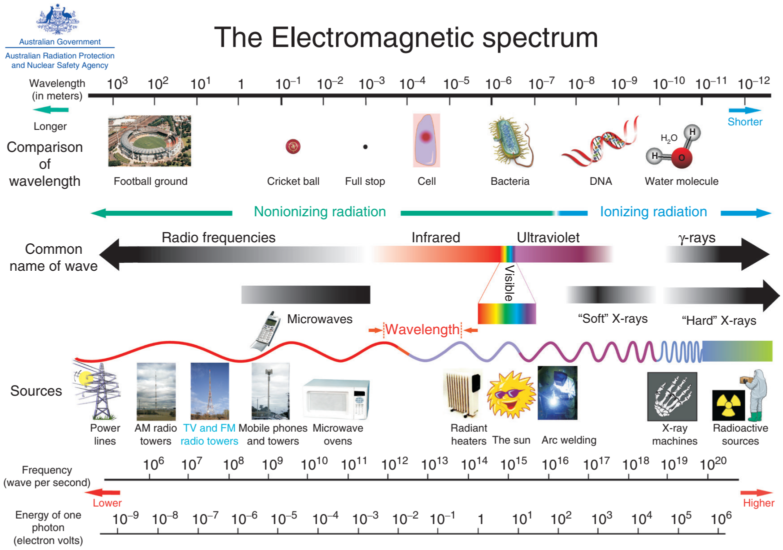

Figure 1.1 The electromagnetic spectrum, from power frequencies through to γ-rays. Top: wavelength in meters; middle: relative sizes of wavelengths, names, and typical sources; bottom: frequency in waves per second or hertz (Hz) and the relative energy of each type. *Source:* K. Karipidis, ARPANSA, Australia.

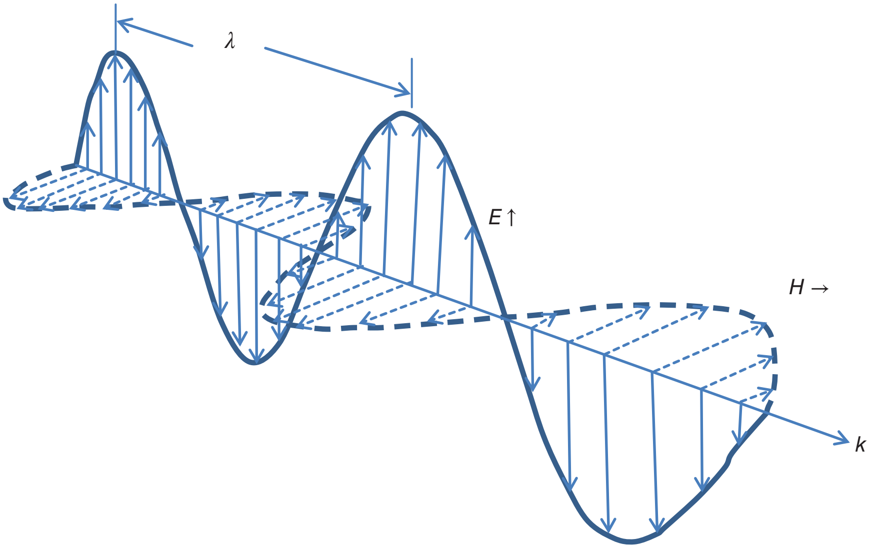

Figure 1.2 A propagating electromagnetic wave, showing electric (*E*) and magnetic (*H*) vectors (arrows), the direction of propagation (*k*), and the wavelength (*λ*). Note that the *E* and *H* vectors are at right angles to each other and also to the direction of propagation. See diagram as supplied for location of all of these symbols (*λ, E, k*).

direction of propagation (see Figure 1.2). The wavelength is the physical distance between one peak and the next for either the *E* or the *H* field. The speed of propagation in vacuum is the same for all forms of electromagnetic radiation, whether ionizing or NIR, and is 300,000 km/second (or 3×10^8 m/second). It should perhaps be remembered that in media (such as human tissue), the speed will be somewhat less than this value and will contribute to the phenomenon of refraction or deviation in the direction of propagation when going from one medium to another (e.g., air to tissue). This phenomenon is most familiar in the case of visible light (optical radiation), but applies to NIR generally. In a vacuum, the ratio of the magnitude of the *E*-field to that of the *H*-field has a fixed value for positions more than a few wavelengths from the generator. The fields are said to be *coupled*. When the wavelengths are of the order of kilometers, most positions of interest are much closer than one wavelength, and the fields are then said to be *uncoupled*.

The fundamental unit of measurement of *E*-field is the *volt per meter* (or V/m) and of *H*-field is *amperes per meter* (A/m). The ratio *E*/*H* has units of resistance (ohms) and for a vacuum has the value 377 Ω, which is related to fundamental electrical constants. In a medium such as body tissue, the value reflects more complex interactions and is referred to as impedance. In fact, 377 Ω is usually referred to as the impedance of free space.

The *E*/*H* ratio is analogous to Ohms law (i.e., that electrical resistance is the ratio of voltage to current), so in the same way that the power dissipated by a

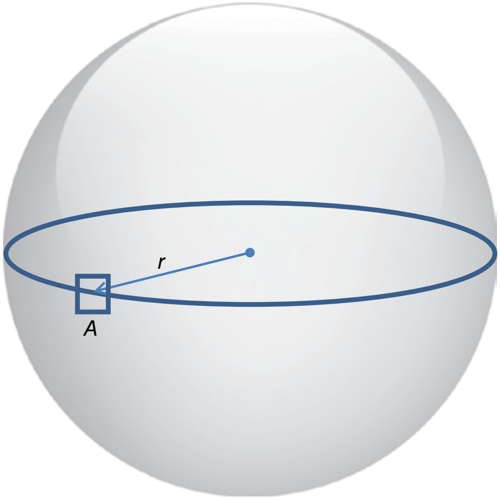

Figure 1.3 The relationship between power density and power. The sphere represents an expanding wavefront from the origin. Alternatively, it can represent an imaginary spherical surface across which the radiated power is flowing. Power density is expressed as power per unit area, so if the area considered is A in the diagram, proportion of the total power P crossing A will be $P{\cdot}A/(4\pi r^2)$ watts, since $4\pi r^2$ is the surface area of the entire sphere. Dividing by A gives the power density in $\mathrm{W/m^2}$.

resistor is the product of the voltage and the current (in W), the product of $E \times H$ is a measure of *power density* of the fields in watts per meter squared ($\mathrm{W/m^2}$, see Figure 1.3). These measures have relevance throughout the spectrum of NIR, but at the longest wavelengths, the individual E and H field values are more important than power density and at the shortest wavelengths the opposite applies.

In general, the quantal nature of electromagnetic radiation is less important for NIR, but for the very shortest wavelengths of the NIR spectrum (UV and visible light), more quantal energy-specific modes of interaction (*photoreactions*) become very important. Unlike the ionizing radiation case, where an electron can leave a molecule, specific wavelengths of NIR can induce electron transitions to produce excited molecular states. Thus, as well as power density, the precise wavelengths of the radiation are very important in determining the precise biological effects which could follow exposure. At longer wavelengths (radiofrequencies or RF), the applied E and H fields cause ions and charged molecules to try to align with them. In the resulting motion, the friction between charged particles and surrounding molecules gives rise to an increase in temperature, the so-called thermal effect of RF. At longer wavelengths (longer than a few tens of meters), mobile charge carriers in living tissue, such as ions, contribute to *induced currents*, which may have direct influences on cellular function.

There are two types of NIR that do not strictly belong to the spectrum: static fields, because they are in no way radiated, and ultrasound, which is not an electromagnetic wave (it is a mechanical wave). Health effects evaluation for static fields are similar to that for fields in the extremely low-frequency (ELF) range, so this is included in this book. On the other hand, since ultrasound is, in some ways, a specialist area (and since outside of medical uses and vehicle parking technologies, ultrasonic beams are not commonly encountered), this area will not be covered.

1.2 Types of NIR

Table 1.1 summarizes the main features of the types of NIR dealt with in this book.

Table 1.1 Types of nonionizing radiation.

Type	Chapters	Subtypes	Sources of concern	
			Natural	**Artificial**
Ultraviolet	4–7	UV A 400–315 nm; UV B 315–280 nm; UV C 280–100 nm	Solar UV: typical 1 k W/m^2 for summer day noon	Sun lamps, sterilizing lights, and lasers
Visible light	8–11	400–700 nm, traditionally divided into spectral colors	Solar blue light hazard	Lasers and high-intensity LEDs (above around 1 W/m^2)
Infrared	9	IR A 760–1400 nm; IR B 1.4–3 μm; IR C 3–1000 μm (1 mm)	None of concern	Furnaces and welding equipment flames (above 100 W/m^2)
Radiofrequency	12–16	Extremely high frequency 1–10 mm; super high frequency 10–100 mm; ultrahigh frequency 0.1–1 m; very high frequency 1–10 m; high frequency 10–100 m; medium frequency 100–1000 m; low frequency 1–10 km	None of concern	Proximity to antennae of high powered transmitters; induction heaters and welders (above around 50 W/m^2)

(*Continued*)

Table 1.1 (Continued)

Type	Chapters	Subtypes	Sources of concern	
			Natural	**Artificial**
Extremely low frequency (ELF)	17–21	Very low frequency 10–100 km, as well as extremely low frequency proper, 100–1000 km or more		Electrical switchyards, certain welding equipment, and sewing machine operators
Static fields	22–23	Static electric Static magnetic		Magnetic resonance imaging devices and direct current powerlines
Ultrasound	–	Air-borne Liquid-borne		Descalers and cleansers

Note: 1 mm = 1000 and 1 μm = 1000 nm.

1.3 How Dangerous is NIR?

Since the nature of NIR is *not* to cause ionization, the damage to biomolecules such as strand breaks in DNA, normally associated with ionizing radiation, is not expected. There is a perception among the scientific community that most health issues from NIR are media generated, concerned as they are with sources that are part of the normal home or work environment. This contrasts with ionizing sources, which are limited to specialist environments such as hospital diagnostic and therapy units and uranium mining. Relatively few people are exposed on a regular basis to these sources (ignoring, for the moment, the background natural ionizing radiation which we are all exposed to continuously). The notion of the electromagnetic environment of home appliances, mobile phones, and electrical power lines being possibly harmful to health is something that patently affects everybody and makes for commanding headlines in the media. It should be said that, except for consequences of UV and laser exposure, scientific evidence for harm at levels of other forms of NIR commonly encountered is considered by most of the scientific community to be inconclusive and inconsistent. Moreover, there is the suspicion that scarce research funds are being diverted from more pressing health needs because of public misconceptions. Community campaigns against particular siting of powerlines and mobile phone base stations tend to marshal multiple arguments, including adverse visual impacts, property values, and loss of amenity, as well as possible health effects. Unfortunately, in this process, the language of ionizing radiation hazard (being made to "glow in the dark" near to powerlines and "nuking" food in a microwave oven) is borrowed to enhance the dread factor of certain types of NIR. There is also a tendency to lump different forms of NIR together, for example, by using research pertaining to powerline safety to mobile phone base station safety and vice versa, despite the widely different interaction mechanisms with tissue and the billion-fold difference in frequency.

This being said, the health detriment due to overexposure to a natural and ubiquitous form or NIR, namely, the sun, is underrated by the public and represents an area in which more effective control and public awareness could lead to significant improvement in health outcome, in certain areas of the world at least. Again, drawing a comparison with ionizing radiation, which is usually controlled via strict licensing and registration provisions at state legislature level, the question of whether or not to regulate NIR exposures is an interesting one to answer. This will be covered in Chapter 33. Penalties for infringing radiation legislation are fairly severe in the case of ionizing radiation. While it is advisable to encourage responsible behavior, including the avoidance of NIR overexposure, solar UV, for example, is uncontrollable at source, so legislation, if there is to be any, has be directed, in this and other cases, toward exposure limitation rather than source control.

Public perceptions of the seriousness of certain types of NIR exposure cannot be ignored. Apart from the community actions on siting of infrastructure just mentioned, there are many in the community who sincerely believe themselves to be adversely affected by such NIR sources. In surveys investigating the risk perception of NIR sources, the majority of participants did not rate, for example, mobile phone handsets or base stations as being a major health concern; however, over half were at least "a little bit" concerned (Schreier, Huss, and Roosli, 2006; Siegrist et al., 2005). Similar perceptions were reported for fields from powerlines and electrical devices (Schreier, Huss, and Roosli, 2006). An early study from Carnegie Mellon University (Morgan et al., 1985) showed that university students were more concerned about powerline than electric blanket exposure, even though in terms of actual exposure the latter is higher than the former. This also showed that supplying detailed information actually increased the concern over the risk, which has been born out in more recent studies on risk perceptions of mobile phones (Wiedemann et al., 2006).

Part VII will explore the notion of risk having two components, the probabilistic assessment of hazard by risk professionals and the "outrage factor", which is a measure of how upset people feel (Sandman 1987). This impinges on how the "Health" of an individual is defined. According to the World Health Organization (WHO), "Health is a state of complete physical, mental, and social well being and not merely the absence of disease or infirmity." On this definition, health is about *not* being upset or outraged over NIR exposure. Note that how upset people feel is related more to feelings of the exposure being involuntary and mysterious than the strength or even the existence of *any* credible scientific evidence of harm. A successful strategy for managing NIR exposures must pay particular attention to public perception. It could be argued that this is true for most environmental agents for which there is concern, but certainly in the case of ELF and RF, the absence of a generally accepted mechanism of interaction at low levels of exposure has been a reason for sections of the scientific and regulative community dismissing such concerns as groundless. While most of those expressing a belief that phones and electrical appliances do not find this affects their quality of life, a significant number declare themselves to be "electrically sensitive". Chapter 24 will discuss the characteristics of this syndrome and will suggest effective strategies for its management.

1.4 Overview Summary of NIR Health Effects Evaluation: Status

The following represents a brief overview of the status of NIR health issues at the time of writing.

UV: The immediate effects on skin are well established – delayed effects (skin cancer and cataract) are also well researched and accepted. Safety limits are based on the notion of preventing sunburn. The assumption is made that if the skin is not allowed to burn, the risks of malignant and nonmalignant melanoma are not elevated.

Lasers: The thermal and photochemical effects on the retina, eye lens, and skin are well established. The "blink" and other aversion reflexes, which normally prevent overexposure of the retina are well understood. The frequency range of lasers and intense light emitting diode sources is constantly extending further into the invisible part of both UV and IR regions, where more hazard evaluation may need to be done.

RF: The thermal effects stemming from temperature rise within certain sensitive organs is well understood – the evidence for the so-called nonthermal effects is currently not compelling; however, research in this area is continuing. Some epidemiological studies have reported an association between heavy mobile and cordless phone use and brain cancer; however, other research has not confirmed these results.

ELF: Protection levels for ELF exposure are based on the prevention of activation of nervous tissue in the most sensitive areas of the body. Epidemiological research has left open the possibility of a raised risk of childhood leukemia in homes where average magnetic fields are within the top few percent of the total range; however, these results have not been shown to be causal.

Static fields: The mechanisms by which static fields affect the human body are well understood. Exposures within guideline limits will protect against established effects. Specific procedures will minimize transient effects experienced in certain situations, for example, moving within a strong magnetic field such as when undergoing a magnetic resonance imaging examination.

Tutorial Problems

1 The wavelengths given in Table 1.1 relate to the frequencies of the radiated waves via the relationship f (frequency in Hz) = c (velocity of propagation in m/second)/λ (wavelength in m). What frequency corresponds to the following: 1 m waves; 1 mm waves; 1 km waves. What regions of the NIR spectrum do these correspond to?

2 At a point 100 m from a radiofrequency transmitter at 1 GHz frequency, a survey meter measures a steady power density of 1 mW/m^2. What is the value of the electric field (E-field) vector at this point (in V/m). What is the magnetic field vector (in A/m)? (Assume in air).

3 Estimate the power of the source in question 2 (in watts).

4 What interaction mechanism with the human body is the chief concern for the following types of NIR: UV, microwaves, and power frequency magnetic fields?

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Part I

Hazard Identification and Assessment: What are the Dangers and How are the Sources Dangerous?

2

Hazard Identification: Laboratory Investigation

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2.1 Introduction

As a preliminary to discussing investigations into possible health effects from various specific forms of nonionizing radiation (NIR), this chapter and Chapter 3 will deal with more general aspects of identifying the conditions under which an agent could be considered hazardous. This chapter considers investigations carried out in a laboratory, whereas Chapter 3 deals with studies of groups of the human population going about their normal duties at home or at work. This general introduction will set bioeffects research into a proper perspective regarding limitations on setting safe levels with any degree of certainty. What will become apparent in later chapters is a lack of consistency in experimental evidence of harm from environmental NIR, particularly those forms with a frequency less than 300 GHz. In this chapter, some discussion of the strengths and weaknesses of various forms of laboratory studies in this hazard identification process is thus in order, starting with human volunteer experiments down through various levels of biological complexity to studies of individual molecular components and mathematical modeling of interaction mechanisms. Those with some familiarity with the so-called scientific method could skim over the following few sections.

2.2 The Scientific Method

Ideally, this is a method for distinguishing truth from falsehood. It applies to the physical world, since it involves making observations or making measurements on processes amenable to measurement. It also involves hypothesis

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making, in order to characterize these measurements or observations. These hypotheses, once formulated, will suggest further sets of observations that should be done to give further support to the hypothesis. If these observations do not do this, then the hypothesis is further modified to take account of this divergence. As the hypothesis is refined, the subsequent observations will be more and more consistent with it. Moreover, if independent scientists were to repeat these measurements under similar conditions, they too should find behavior consistent with the hypothesis. Indeed, sufficient details should be reported to allow such replication to take place. Logically, it is a process of induction, rather than deduction, since it is arguing that specific observed behavior can be generalized.

To take an example, if we observe people sunbathing on the beach, we will notice that at the end of a period of 2 hours, some will be sunburnt, others not. We can then hypothesize that, for example, the lighter the hair color, the more extensive the sunburn. We may then construct a meter to measure (i) reflectivity of hair and (ii) severity of sunburn. We may want to modify the hypothesis in the light of further measurements to allow for similar reflectivities of hair but different color (i.e., ginger vs blonde). We may wish to analyze skin and hair for specific compounds such as melanin, to see if they are correlated. We may wish to measure the differential expression of genes in those who sunburn versus those who do not, further modifying the hypothesis.

An essential feature of a scientific hypothesis is "falsifiability", that is, it must be capable of being shown to be false by experimentation. An individual may have a strong conviction that, for example, wearing a copper wristband will alleviate pain. This is falsifiable by substituting a look-alike plastic band for a copper one and asking the individual to rate the severity of pain. However, if there turns out to be a *placebo* effect, where the plastic band is more effective than no band and may be of similar effectiveness as a copper band, it becomes unclear what the hypothesis actually is.

2.3 Human Volunteer Experiments

This type of experiment consists of recruiting groups of volunteers, representative of the general community or sections of the community (such as "electrical utility workers" or "regular mobile phone users"), to determine what immediate effects result from short-term exposure to forms of agent; in this case, types of NIR. Sometimes, these are termed "provocation" studies because responses are deliberately evoked, in contrast to "survey" experiments, in which responses to everyday exposures are studied. In a provocation experiment, once a level has been established for the occurrence of a certain bioeffect and this bioeffect becomes the basis for safety standards, subsequent experimentation will concentrate on identifying any previously undetected effects at lower levels, since it would be unethical to continue to expose volunteers to

Table 2.1 Human (provocation) studies.

Extremely low-frequency (ELF) electric and magnetic fields	Perception, pain, phosphenes, heart rate, blood pressure, cognitive function, sleep quality, and hormone levels. Muscle responses. Physiological responses in those who perceive themselves to be electrosensitive
Radiofrequency (RF) radiation	Thermal responses (sweating rate, skin and core temperatures, perception, cognitive function, sleep quality, hormone levels, and effects on sensation) Physiological responses in those who perceive themselves to be electrosensitive
Infrared (IR) radiation	Thermal responses, perception, and eye responses
Visible radiation (including laser and LED radiation)	"Blink" responses
Ultraviolet (UV) radiation	Skin tanning and burning

levels deemed unsafe. Some of the endpoints investigated to establish safety limits and at lower levels are summarized in Table 2.1.

Human volunteer studies have certain strengths: if effects can be clearly demonstrated, they can be directly assessed in terms of general human performance, without the need for extrapolation from animals, in vitro studies or from simulations. Secondly, the exposure conditions can be accurately controlled and varied by the experimenters. In fact, the laboratory environment can be accurately monitored and standardized to eliminate many confounding variables encountered in survey studies outside the laboratory. Thirdly, volunteers can be categorized into subgroups according to age, gender, education, and so on, to account for covariation. On the other hand, there are clear limitations on this type of study, the main one being that only immediate or short-term effects can be identified, the effective upper limit on exposure duration being the time constraints on volunteers. It is rare for participants to be able to devote more than a 24-hour period to be in a laboratory. Even if a participant makes several return visits to the laboratory over a longer period, it is hard, if not impossible to control incidental exposures when away from the laboratory. Another limitation concerns volunteer compliance: under most ethics provisions, participants can withdraw at any time, even after several segments of a repeated-measures trial. Usually, as part of initial experimental design, numbers in subgroups (such as age ranges) are carefully planned to provide adequate statistical power. Volunteers who fail to keep appointments or who withdraw sometimes cause the group sizes becoming less than optimal. *Post hoc* analysis and multiple comparisons both weaken statistical design, and unfortunately, these are often a feature of human volunteer studies.

Double-blind experiments are those in which neither the volunteer participants nor the experimenters attending the participants are aware of whether the exposure is real or sham. This is done each time the test is conducted, for example, maybe with the exposure coded "A" or "B". This way of conducting trials is considered to be "best practice" because subjective responses and biases are removed. In these experiments, a second experimenter maintains a "key" or list of the actual real/sham exposure status on each occasion. At the conclusion of the experiment, the key to the codes is revealed, preferably after the group analyses have been carried out.

2.4 Whole Organism Experiments

This type of experiment is fundamental to bioeffects research and for establishing the nature of adverse health effects. A "traditional" health effects assessment will involve exposing populations of typically laboratory-bred rodents to various levels of agent and comparing health-related outcomes in these groups with those in a separate group of animals maintained in exactly the same conditions, except that the agent is not given (sham exposure). With respect to NIR, the sham exposure usually consists of the generator of NIR (of whatever type) being placed in the same position as for the other parts of the experiments, but with the power supply turned off. For nonvisible forms of NIR, the experimenter is often made unaware of the level of exposure given to avoid bias in the interpretation of results. The size of groups of animal is determined by the magnitude of the effects expected: for small effects, the groups have to be large – see Section A.6. The duration of these experiments is typically over the lifetime of the animal, which for rodents is around 2 years. Exposure systems have to be such that they are representative of human exposures and ethical considerations preclude experimenting in ways which would cause pain or distress. However, ethical standards have become more stringent in recent years and data from early work, which cannot now be repeated, provide a backdrop that can be correlated with or predictive of effects of accidental overexposure in humans. The issue of coexposure (e.g., the question of whether UV exposure preconditions an animal to subsequent ionizing radiation effects or vice versa) is one that has been widely investigated using animal models. In most cases, the disease type of major concern is cancer (i.e., the carcinogenic or mutagenic potential of the agent) but possible effects on birth outcomes (teratogenicity) have also been extensively studied. In shorter term experiments, effects of NIR agents on physiological and behavioral responses can be studied (as shown in Table 2.2)

The main disadvantage in this type of research is extrapolation, that is, of projecting to the animal model what an appropriate level of exposure should be, to be equivalent to human exposure, and the extrapolation of outcomes of animal models of disease to the human. For example, a human will absorb RF

Table 2.2 Experiments carried out on experimental animals to determine existence of health effects and level of exposure these occur (if they do occur).

NIR type	Endpoints	Coexposures
ELF	Specific tumor incidence Mortality Birth defects Behavioral effects Hormone levels Electrophysiological effects	Chemical carcinogens Ionizing radiation
RF	As above Thermal effects	As above
Visible/laser	Eye damage	
UV	Skin cancer Cataract	

energy strongly at 80 MHz (where there is a resonant condition for the whole body), whereas the equivalent resonant condition for a mouse is several hundred megahertz. A four times stronger electric field applied to a human compared to that of a pig will induce the same amount of current in the legs of the respective organisms. As an example of the second, the Eμ Pim-1 strain of mouse, which has an abnormally high lymphoma rate, cannot easily be compared to human susceptibility to lymphoma because the Pim-1 oncogene (gene whose inappropriate activation leads to cancer formation) appears to be associated with different cancer types in the human. The other disadvantages of this type of experiment are the relatively large cost and the length of time required to plan and execute the experiment and analyze the results. The standard duration of a rodent experimental phase is 2 years, which corresponds to the life expectancy of the animals. It is customary to use several levels of exposure of the agent in order to establish a dose–response relationship, if one exists. For each level, a cohort of 100 animals or more is required, bringing the total number of animals per health effects assessment to around 1000 or more. One way around this problem of cost and time is to use whole organisms that are more primitive and whose lives are shorter. Because of recent advances in genomics, organisms such as the nematode worm (*Caenorhabiditis elegans*) with a 3-week lifespan have recently become popular. It consists of roughly 1000 cells, has a nervous system and "brain", and exhibits behavioral characteristics akin to learning. The genome, that is the molecular sequence of the 20,000 genes, is now known. Other simple organisms, which are often used as a standard biological preparation, are the fruit fly (*Drosophila melanogaster*) and the Zebra fish. These are perhaps not the best models for human cancer unless, for example, human oncogenes are inserted into the host genome.

2.5 Studies on Isolated Cells, Organs, or Subcellular Organelles

The development of reliable and replicable tissue and organ culture techniques has made it possible to carry out tests for toxicity on colonies of living cells maintained in special flasks. Since the labware was originally glass, the name *in vitro* (in glass) is applied to this experimentation. It is now possible to maintain slices of brain taken from a freshly killed rodent in an artificial biological fluid (media) for several weeks with some degree of functionality (e.g., electrical activity) persisting over this period. It is also possible to grow colonies of individual nerve cells in such a way that they form spontaneous connections and show rudiments of memory formation. Other cells types will continue to secrete hormones and neurotransmitters in response to stimuli over several cell generations, more or less indefinitely. These so-called immortalized cell lines continue to divide for many decades. An example is the HeLa cell line, which was established from a human cervical tumor in 1951 and is still used around the world, despite the fact that the donor has long since died. HeLa cells continue to possess similar characteristics to the original colony, so provide a stable in vitro model, which can be compared between laboratories and between countries. Colonies of these cells (which are derived from cancers and are referred to as transformed cells) and hybrid cells (which have the nucleus of one cell transplanted into another) can be obtained from recognized suppliers, such as the American Type Culture Collection or ATTC (http://www.atcc.org/). Other commonly used single-cellular organisms include bacteria (*Escherichia coli* or *E. coli*), yeasts, and amphibian eggs (oocytes). The advantages of exposing single-cell organisms to physical agents are that it is relatively easy to perform a large number of replicated trials, the basic materials are cheap, interlaboratory comparisons are easy to specify, and many ambient conditions are readily controllable. In studying basic cellular processes, such as membrane channels and pumps, the regulation of enzymic or cell signaling pathways, or the development of chromosomal abnormalities, these single-cell preparations are ideal. For example, various types of white blood cells (T or B lymphocytes) are widely used to investigate possible alterations in immune system responses.

There are two main drawbacks in the use of this type of data in human risk assessment are (i) the design of an exposure system that will produce a measured dose relevant to human exposure and (ii) the interpretation of any changes in biological function at the cellular level in terms of implications for human health. Since some of the cell lines used are transformed (i.e., already showing characteristics of cancer cells), extrapolation of findings to considerations of carcinogenicity is not easy. The mere fact that these cellular systems are isolated from their usual environment (which would control for temperature, pH, and nutrient supply) implies that the processes studied may not be the same as those *in vivo*.

At the lowest level of complexity, various components can be isolated from individual cells, such as enzymes (ornithine decarboxylase and ATP-ase), proteins (hemoglobin, myosin, and heat-shock protein), and nuclear material (DNA and RNA), to discover whether there are any modes of interaction at the level of single molecules, as there is, for example, in UV-induced dimerization of DNA components.

The determination of an "equivalent dose" (i.e., equivalent to human exposure) is not straightforward. For example, the rate of absorption of radiofrequency (RF) energy in a test tube or culture flask varies from position to position, making it hard to design an *in vitro* exposure system in which nonuniform heating effects can be eliminated. Questions of dosimetry have been reviewed in a supplement to Bioelectromagnetics (Guy, Chou, and McDougall, 1999) and more recently (Paffi et al., 2015).

2.6 Sources of Artifact and Importance of Independent Replication and Quality Control

An artifact is an effect that does not occur in the undisturbed organism but is the result of the way in which the experiment was conducted or in the preparation of the organism for investigation. An experiment that appeared to show reduced drinking behavior in animals (exposed in a laboratory) to high electric fields, but in which it was later revealed that the animals were suffering microshocks from the metallic feeding troughs is an example of an effect being an artifact. However, in this case, it was the specific aspect of the exposure leading to a bioeffect that needed proper identification – it was not electric fields per se, but their interaction with the experimental setup that caused the observed bioeffect. Other examples are unintentional statistical bias (caused by skew-symmetric data, inappropriate choice of reference or control observations, omission of outlying data, inconsistent inclusion criteria, etc.); systematic error (due to drift in measuring apparatus, electromagnetic interference, as examples); observer bias (if the experimenter is not "blind" to the exposure status); and, in the case of human experimentation, subject bias. Biological experiments are inherently variable, due to the stochastic nature of many biological processes: to a certain extent, this is reflected in the standard deviation in repeated measurements, but an outcome may still achieve statistical significance via an inexplicable anomaly.

The concept of statistical significance needs further clarification: an appendix to this chapter gives the rudiments of statistical testing and power calculations, but it needs to be kept in mind that the accepted criterion for a change to be significance is that the odds for the "effect" being due to chance variation is 1 in 20 or 5%. Many would argue that this is not conservative enough and that odds of only 1% or even 0.1% for the observed change being due to chance alone represent a better basis for identifying "effects". This emphasizes the

Table 2.3 Check list for inclusion of research report in overall risk assessment process.

Check list	Yes/No?
Peer reviewed	
Replicated	
Effect robust	
Consistent with other findings	
Mechanistically plausible	
Clear health implication	

need for corroboration or replication of experiments reporting bioeffects, particularly if the levels of exposure chosen are so low as to appear out of step with everyday experience. Replication should be carried out ideally by independent groups following similar if not identical procedures and outcomes should be consistent across several levels of investigation (e.g., if an agent causes an increased release of hormone in a cell culture, the same agent should produce similar rises in hormone levels in blood of human subjects). It is not unusual for a scientific paper to contain flaws. In an Editorial (2003), the prestigious scientific journal Nature noted that "it is regrettable but inevitable that the scientific record contains errors". Several of its issues contain retractions of papers in which flaws were discovered subsequent to publication. With this in mind, the above would represent a reasonable check list, before an "effect" can be considered as a reliable piece of information in an overall risk assessment process (Table 2.3).

The last two considerations will be explored further in the following two sections. "Peer reviewed" refers to the method used by most reputable scientific journals of only accepting articles after extensive review and approval by two or more independent experts in the field. Although this method of review does not guarantee that the methodology has been appropriate and the conclusions drawn from the results valid, it is a method that reduces the risk of this.

2.7 Difference Between "Effects" and "Harmful Effects": Extrapolation to Human Health Outcomes

Many effects of physical agents (such as raised skin temperature in response to RF or UV exposure), although statistically significant, represent a change that is within the normal range of changes produced by everyday experiences. The unclothed human body can cope comfortably with environmental temperatures ranging between around 15 and 35 °C. Shivering and sweating are normal physiological adjustments designed to maintain core temperature at 37 °C. While prolonged exposure to excessive heat or cold can be fatal, there are various degrees of discomfort that can lead to impaired physical or mental performance. The point at which a "biological effect" becomes a "health effect" may be somewhat difficult to pinpoint, but taking the World Health Organization definition of "health" referred to in Chapter 1, it would be wise to err on the side of conservatism. The identification of "discomfort" is relatively easy in the case of human volunteer experiments, in the short term at least. Extrapolation from other types of experiment to health implications for humans requires considerable scientific judgment based on careful quantitative argument. It is regrettable that many scientific papers engage in vague speculation on possible health outcomes without due regard to the plausibility or consistency of the assertions made.

2.8 Role of Mathematical Modeling and Mechanism Studies

One way to place laboratory findings in a clearer context of health effects research is to be able to model the interaction of a physical agent at a molecular or tissue level and then to integrate this model to assess effects in the complete human body. We will see this as being particularly relevant in the case of regional or whole body exposure to RF fields, in which the rate of energy absorption can be represented point by point, with the effects of different tissue and blood flow properties being taken fully into account. Some of these models of the human body are extremely sophisticated, involving resolution down to a few millimeters. Another area where modeling is crucial is in the evaluation of putative forms of interaction of agents with biological system beyond those currently accepted. Even where an interaction mechanism has been accepted, there are often considerable areas of uncertainty, and it is in these areas that elucidation can be provided using this approach. An example is the area of extremely low-frequency (ELF) fields, where understanding of the relationship of induced electrical current to cell stimulation is still incomplete. A number of interactions of ELF fields with tissue (not involving induced current) have been proposed. This is in order to account for incomplete experimental evidence that low-level fields give rise to effects that cannot be explained by accepted mechanisms. By modeling these proposed mechanisms, their plausibility can be gauged and further experimental tests can be formulated.

Appendix: Statistical Concepts

A.1 Averaging

If we need to get a reliable estimate of, say, resting blood sugar concentration or blood pressure, a single measurement is inadequate. This is because there is variation throughout the day, even for someone sitting in a relaxed state, due to food intake, diurnal variations, and so on. The measuring instrument is also subject to variation in terms of the care the measurer takes in making the measurement, the calibration of the instrument, random variations due to natural electronic or chemical reaction "noise", "drift" in instrument response, and so on. For this reason, several measurements are taken and then an average or mean determined. A large "spread" of the measurements would suggest than a large number of separate determinations should be made. The amount of spread is estimated by subtracting each determination from the average, squaring this difference, and then finding the average squared difference (root mean square). Actually, for reasons we do not need to go into here, rather than dividing the sum of the square differences by the *number of observations* (before taking the square root), the number of observations is *reduced by 1.* This is called the "Standard Deviation" or "SD", and the formula for calculating it can be written as

$$\mathrm{SD} = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \tag{A.2.1}$$

where $\bar{x}$ is the mean value and x_i is the particular value, with n observations.

A.2 Standard Error of the Mean

A way of estimating how confident we are that the estimated average or mean value is close to the actual mean value (which is what we would get if we took an infinitely large set of measurements) is to compute the standard error of the mean (or SEM). Effectively, this is the SD divided by the square root of the number of observations ($\sqrt{n}$).

A.3 When Is a Difference Significant?

Often, we want to know if a certain treatment (exposure to NIR for instance) produces a difference that is "statistically significant". Given the spread of measured values, what we want to know is if the change is within normal variation or not. There are ways of estimating what the chances are of a difference of 10%, for example, being due to normal variation. The variation could be quite low (0.1% of the mean, perhaps), in which case we would regard this 10% change as being significant. A useful test for significance is the "Student t-test" (if we are sure the observations fit within what is known as a "normal" distribution). The way of estimating the value of "t" varies according to the type of experiment done, but in an example where each person involved in a trial can be compared before and after exposure (paired t-test), the t value is given by the difference in means (before and after) divided by the standard error (SE) of the difference in the means. If all the changes have about the same magnitude, the SE will be small so the t value will be large. Finally, the number of paired observations *minus 1* is then used in a standard table of values of t to determine whether a particular value is greater than a *critical value* for the difference to be significant at the 5% or 1% level. It is usual for anything below 5% to be taken as being sufficient to declare a change is being "significant". This is equivalent to saying that the odds of the change being due to natural fluctuation are less than 5%.

A.4 Correlations

Instinctively, one would expect that the weight of humans is correlated with their height. However, since people of the same height can be fat or thin, the correlation is expected to be moderate rather than good. The coefficient of correlation (or "r") is a measure of how good this correlation is, ranging between 0 (no correlation at all) to ±1, being a perfect correlation (the minus sign indicating that as the first variable increases, the second decreases, "negative correlation"). The formula for finding r is given in standard books on statistics, but in order to determine whether the correlation is significant or not, a t value can be calculated using the following formula:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{A.2.2}$$

where n is the number of pairs of observations. The t value is then compared in the table as before to determine whether the critical value has been exceeded for the correlation to be considered significant (usually at the 5% or 0.05 level). Of course, correlation does not indicate *causation* since both factors may be dependent on a third factor, which contributes to variation in both of them. In our example of height and weight, the weight is related to volume (weight divided by density) and the height is a major contributor to volume; thus, a correlation is not unexpected.

A.5 Analysis of Variance

As we saw above, the reason for variability in measured values can be due to a number of sources, the exposure/nonexposure being one of them. Analysis of variance (variance is defined as the square of the SD) looks at the way various factors contribute to the overall variance, including *within*-experiment and *between*-experiment variances (if, e.g., testing is spread over several groups of participants).

A.6 Statistical Power

Just as it is possible to jump to false conclusions if the reported change due to the exposure is in reality just due to chance (false positive), it is also possible to wrongly conclude that the exposure is causing no effect if insufficient observations were made to reveal the change among the naturally occurring variation (false negative). There are ways of estimating how many observations are required in order to correctly identify a change (due to the agent, in this case NIR) of a predetermined amount, given a knowledge of the underlying variation in the unexposed observations. For example, if we want a good chance of correctly identifying let us say a 10% change in the measure of interest (due to NIR exposure) and the underlying SD is, say, also 10% of the mean value, then a table will reveal that 21 separate "before and after" observations are required. Of course, the level at which we consider the change to be significant (usually 5%) and the level of chance of correctly identifying the change (say 90%) also has to be specified. This latter figure is known at the *statistical power* of the study and in the planning stage these calculations are used to determine the number of volunteers to recruit, the number of animals to use or the number of test tubes to employ in order to have some guarantee of a unequivocal outcome. Unfortunately, many studies in peer-reviewed literature neglect to indicate how the numbers of observations were chosen and in some cases clearly show inadequate statistical power.

A.7 Multiple Comparisons

Sometimes, if the mechanism of interaction of an agent is unknown or unclear, numerous endpoints are tested to see if any of them show a significant change (a study on volunteers could include measures of blood pressure, plasma glucose, melatonin, cortisol, and other hormones in essentially a surveillance-type experiment). If any one of these shows changes significant at the 5%, this cannot be taken as truly significant, since the inclusion of at least five comparisons increases the chances of this change being due to natural fluctuations. One way of dealing with this is to use the so-called Bonferroni correction, where the *critical* level for statistical significance is divided by the number of endpoints. So, if there were five different comparisons, the critical significance level is 5% divided by 5 or 1%. (In other words, the criterion for deeming a change "statistically significant" becomes stricter.)

Tutorial Problems

1 How would you go about designing a double-blind experiment to detect whether emissions from a mobile- (cell-)phone handset caused changes in human heart rate?

2 The level of a certain hormone is determined from blood samples of 10 people, who varied in age from 23 to 79. There were two males and eight females in the group. It is intended to compare these values with values obtained the next day after exposing each participant to a low-frequency magnetic field for 60 minutes prior to sampling. What are the weaknesses of this approach? What would be the best (least poor) way to identify whether the magnetic field was having any effect?

3 A cell monolayer colony is grown on each of 10 Petri dishes and then the activity of a certain enzyme is measured, using a standard kit, in each of them. The activities (in relative units) are as follows: 8.7; 9.8; 10.1; 11.3; 11.1; 8.3; 9.3; 10.3; 11.1; and 10.7. Estimate the mean value of this activity with (i) the standard deviation and (ii) the SE of the mean.

4 For the situation in Question 3, it is intended to expose these colonies to UVR to discover if the particular enzyme is affected. Are there sufficient samples to judge whether this form of exposure gives rise to a 10% change in enzyme activity, with a statistical power of 90%? What are the consequences of returning a null result in this experiment with 10 samples?

5 An investigator wishes to probe which part of the human brain become more (or less) active when exposed to RF similar to that from a phone handset. The method chosen is functional MRI (or fMRI), which uses a combination of a strong static magnetic field, a switched gradient field, and an RF field (usually around 120 MHz). Discuss the interpretation of results if significant changes were to be observed.

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3

Hazard Identification: Epidemiological Studies and Their Interpretation

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3.1 Introduction

Many of the most important, and often most controversial, studies of the health effects of nonionizing radiation are epidemiological studies. These vary from very simple descriptive surveys to large, complex, and very sophisticated studies. This chapter gives an introduction to epidemiological studies and their interpretation; full discussions are given in other texts (Elwood, 2017).

Epidemiology is the study of the distribution and causes of human disease; it studies the causes of disease in human free-living populations, in contrast to studying causal mechanisms in experimental animals or cell systems. Epidemiological studies have two main purposes. The first is descriptive, to measure the frequency of diseases or other health-related characteristics in populations and to see whether that frequency varies with other characteristics. The second, and much more interesting, purpose is to assess whether causal relationships exist between possible causative factors and health outcomes, for example, whether the use of mobile phones causes brain cancers, or exposure to electric and magnetic fields (EMFs) from power lines causes leukemia in children.

3.2 Causation

The definition of causation sounds very simple: a factor is a *cause* of an event if exposure to the factor increases the frequency of the event. Extreme forms of causation are *sufficient causation*, where the action of the factor always

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produces the outcome, and *necessary causation*, where the outcome can only occur after the action of the factor. These are very rare situations in health. Genetic conditions are the best examples of sufficient causation; the possession of a certain inherited genetic defect may be sufficient to produce breast cancer, but it is clearly not necessary, as the great majority of breast cancers will occur without the genetic predisposition. Necessary causation is often a result of the disease definition; the measles virus is necessary to produce measles, but only because the clinical entity is defined in terms of the effects of the virus. In our current state of knowledge, it is unlikely that common diseases such as heart disease or cancer have important causes that are sufficient or necessary.

Generally, a causal factor (such as use of mobile phones) has a *quantitative* relationship in increasing the frequency of the outcome (such as brain cancers), but the relationship is not absolute. So the issue is not whether all mobile phone users get brain cancer (sufficient), or whether all brain cancers are caused by mobile phones (necessary), but whether mobile phone use increases the risk of brain cancer.

3.3 Incidence and Prevalence

The prime measures of the frequency of a disease are incidence, prevalence, and mortality. The *incidence rate* is the frequency of new occurrences (incidents) of a disease over a defined time period and has units of inverse time. Thus, there are 305 million people living in the United States, and there were about 22,000 cases of brain cancer diagnosed and recorded in 2009, so the incidence rate is about 72 per million per year, or per million person-years. (This is one of the rarer cancers; the incidence rate for all cancers is nearly 5000 per million per year.)

The *death rate*, or *mortality rate*, is merely an incidence rate where the event is death; the mortality rate for brain cancers in about 42 per million per year in the US.

The *prevalence* is the frequency of a state at one point in time. It is a proportion, without units: thus, the prevalence of high blood pressure in a group of people may be 25%, and the prevalence of brain cancer (the proportion of the living population who has been diagnosed with a brain cancer) is about 400 per million or 1 in 2500 people.

In a stable state, the prevalence equals the average incidence rate multiplied by the average duration; $P = I \times D$. So, on the data given, the average time a person diagnosed with a brain cancer lives is given by $D = P/I = 400/72 = 5.5$ years.

3.4 Evidence for Causation

Very occasionally, where a particular causal agent is the only (or almost the only) cause of a specific disease and has a very clear and strong effect, a causal relationship can be established on the basis of one, or only a few, well-conducted studies. Important examples include the occupational studies which showed high rates of lung cancers after asbestos exposure, and the studies of the survivors of the atomic bombs in Japan in 1945, which showed, and measured quite precisely, the effects of that ionizing radiation. Much more commonly, however, the causes of a disease are established by the cumulative evidence provided by a large number of different studies, rather than by one particular study.

The first result of a study is to estimate the size of the *association* between the potential causal factor and the disease studied. To interpret that result, a careful assessment of the extent and quality of the study is needed. The conclusion may be that the association means there is likely to be a cause and effect relationship, or alternatively, that the association seen is more likely to be due to other reasons.

For example, suppose a study shows that people who use mobile phones get 50% more brain cancers than those who do not use mobile phones. There are four general reasons why such an association could occur.

- One explanation is that mobile phones cause brain cancer. What are the other three?
- First, if people who have brain cancer are more likely to report their use of mobile phones than people who do not have brain cancer, this association could also be produced; this is a type of *observation bias.*
- Second, if people who use mobile phones have some other characteristic that puts them at greater risk of brain cancer, for example, being older (in the study) than the people who do not use them, then this association could also be produced; this is *confounding.*
- Third, especially if the numbers in the study are small, this association could be produced purely by *chance variation.*

Studies in human populations, unlike experimental studies in a laboratory, are limited to what can be done ethically and logistically in free-living human subjects. Thus, the precision and detail of the data collected, and the ability to isolate the effects of one factor from those of other factors, are less controllable than they are in a laboratory situation. In contrast, epidemiological studies, unlike laboratory studies, are directly relevant to the causation of disease in human individuals and populations and can assess “real-life” exposures, which are often more complex than those used in the laboratory.

As with any science, the results of epidemiological studies, whether they show an association or not, will be affected by limitations of the study design or analysis. The results will be influenced by the design of the study, the selection of the participants, errors or bias in the data, the influence of other relevant factors, and chance variation. These all have to be assessed carefully before the study can be interpreted as showing a cause and effect relationship or giving good evidence against such a relationship.

The skills needed in epidemiology are the ability to design and conduct studies in people that recognize and take account of these problems; and the ability to interpret the results of studies in a rigorous and objective way, comparing these noncausal explanations of the results against a causal interpretation. There are well-established principles that assist in interpreting epidemiological data.

3.5 Types of Epidemiological Study

3.5.1 Intervention Trials

There are several major types of study, shown in Table 3.1. The strongest evidence to assess a cause and effect relationship, and the most direct test of causation, comes from an *intervention study* (also called an experimental study). In this study, subjects who are exposed to the factor being studied are compared to similar subjects not exposed. The best intervention studies are those in which eligible and consenting subjects are randomized to either the intervention or a comparison group; these are *randomized trials*. For example, in trials of immunization, consenting subjects can be randomly allocated to receive the immunization or not. This is the normal best method of assessing new medical treatments. They can be used to assess preventive actions; for example, promoting the use of sunscreens in a randomized study to assess if the frequency of skin cancers is reduced.

Obviously, the intervention design cannot be applied to potential hazards, and it is difficult, although not impossible, to use an intervention study when the outcome may only occur many years after the causal agent operates. Thus, it is impossible to do a human intervention study to assess whether mobile phones cause brain cancer, although such a study is possible on animals, and then the critical issue is whether the results of the study on animals also apply to humans. Of course, it is possible to do experimental studies on volunteer subjects to assess short-term effects; for example, randomized double-blind studies have been used to objectively assess reported electromagnetic hypersensitivity (Rubin, Munshi, and Wessely, 2005). Intervention studies can test causation by removing the agent, even without randomization: thus, in one study, the transmissions from a powerful Swiss radio transmitter were redirected and people living in the surrounding area were asked to keep diaries of their quality of sleep, to see if sleep quality was affected by the transmissions (Altpeter et al., 2006).

3.5.2 Analytical Studies: Cohort Studies

Usually, the best possible studies to assess potential hazards are studies in which *individuals* are selected for a study and specific information is collected on the suspected causal factor, the disease outcome, and (most importantly)

Table 3.1 Features of the three major study designs which can assess the relationship between an exposure and an outcome.

Design	Intervention trials	Cohort studies	Case–control studies
Question asked	What are the effects of this intervention?	What are the effects of this exposure?	What were the causes of this event?
Applicability	To evaluate interventions of likely benefit	To assess suspected hazardous or beneficial exposures	To find the causes of disease
Example	Randomized trials of new medical treatments; assessment of preventive programs	Assessment of cancer following radar exposures	Studies of causes of brain cancers
Major strengths	Intervention is controlled by the investigators Allows randomization and double-blind assessment Accepted as the most reliable method of assessment of causation	Allows multiple outcomes to be assessed Cause to effect time sequence is clear Relative and absolute risk can be measured Exposure is assessed prior to outcome, avoiding bias	Usually can be done with moderate numbers of subjects Retrospective method is rapid Multiple exposure factors and confounders can be assessed
Major weaknesses	Ethical limitations: beneficial exposures only; requires informed consent Often needs large, multicenter, study, often longtime scale High cost	Usually requires large numbers of subjects Often long time scale if prospective Information on confounders may be limited	Retrospective method limits exposure information and is open to bias Adequate control group may be difficult to define or obtain

Source: Adapted from Elwood (2017).

other relevant factors that could be related to the disease outcome. These are referred to as *analytic studies*, and are of two main types, defined by how the individuals included in the study are selected.

Studies comparing health outcomes in two or more groups *selected on the basis of their exposure* are *cohort* studies, for example, comparing mobile phone users with nonusers. If a causal relationship exists, mobile phone users will have an increased incidence of brain cancers as compared with nonusers, once other factors are taken into account. One cohort study assessed over 400,000 mobile phone subscribers in Denmark, comparing their cancer incidence with the national registry and finding no increased risk (Schuz et al., 2006): see also Chapter 15. Another study compared nearly 200,000 employees of Motorola with different levels of estimated RF exposure, with follow-up beyond 20 years for some workers, again finding no excess of cancer (Morgan et al., 2000).

Cohort studies have often been the way in which occupational hazards have been identified. Workplace studies have identified employees and used measurements or existing records to classify them in terms of their exposure; these records are linked to health information to discover for each employee whether they develop cancer or other diseases or what they die from. Summing the years of observation for each employee gives the total number of *person-years* of follow-up, and comparing this with the number of cancers gives the incidence rate. We will use a hypothetical example to show how epidemiological results appear.

In our example, we follow 100,000 employees and observe an incidence rate of 114.4 cancers per 100,000 person-years (Table 3.2). Comparing exposed and nonexposed employees, the incidence rate is higher in the exposed group, 168.8 per 100,000 person-years, than in the unexposed group, 60.0 per 100,000 person-years. The *relative risk*, that is the ratio of the incidence rate in the exposed group to that in the nonexposed group, which is the "reference group", is 2.81. It is a ratio and so has no units. We also assess the *risk difference*, the arithmetic difference in the rates, which is 108.8 per 100,000 person-years. The 95% confidence limits of the relative risk are 2.47–3.21, that is, they exclude the null hypothesis value of 1.0; the increased risk is statistically significant at the 5% level.

3.5.3 Case–Control Studies

There is another way we can assess the relationship between the incidence of cancer and chemical exposure in the employees. We can compare employees who have been diagnosed with cancer, to a control group chosen to be representative of employees who have not been diagnosed with cancer. We would then assess from interviews with the employees, or from work records, each person's past chemical exposure.

This is a case–control study; the essential point is that case–control studies compare subjects *selected on the basis of the outcome*. Let us assume (Table 3.3) that we do such a study and identify 57 employees who have had cancer diagnosed and 210 control subjects. The number of controls is arbitrary, although obviously the more we have, the more precise our estimate of exposure in the control group will be. Then we assess exposures. We cannot assess from a case–control study the incidence rate, so the measure of association we use is different. The measure is the *odds ratio*, which is the ratio of the odds of exposure in the cases ($42/15 = 2.8$) to the odds of exposure in the controls ($120/90 = 1.33$). We then take the ratio of these, which in our example gives a result of 2.10. The derivation of this measure is given in standard

Table 3.2 Results of a cohort study.

	Number of employees	Number of person-years of follow up	Number of cases of cancer	Incidence rate per 100,000 person-years	Relative risk	95% confidence limits	Risk difference per 100,000 person-years
Total study group	100,000	700,000	1,144	163.4	–	–	–
Chemical exposure	50,000	400,000	844	211.0	2.11	1.85–2.41	111.0
No exposure	50,000	300,000	300	100.0	1.0 (reference)	–	Reference

Confidence limits are calculated by the method described in Elwood (2017).

Table 3.3 Results of a case–control study.

	Cases	Controls
	Cancer diagnosed	Sample of those without cancer, or of total work force
Chemical exposure	42	120
No exposure	15	90
Total	57	210
Odds of exposure	2.8:1	1.33:1
Odds ratio	2.10	–
95% confidence limits	1.10–4.02	–

textbooks, but basically the odds ratio is in most circumstances a good estimate of the relative risk and can be interpreted in the same way. There are some circumstances in which this equivalence does not apply. A case–control study, because it does not measure incidence rates, does not directly give a value for the risk difference. The 95% confidence limits of the odds ratio are 1.10–4.02, excluding the null hypothesis value of 1.0.

The two examples in Tables 3.2 and 3.3 are in fact based on the same data. In Table 3.3, it is assumed that the cases are a representative sample of all the cases that occurred; here they account for 5% of the total. The controls are a small representative sample of all employees in proportion to their contribution to the number of person-years of follow-up. A study in which controls were drawn from employees who have not had cancer diagnosed would also be satisfactory, as relatively few employees developed cancer. With a study design that will give these characteristics, the odds ratio from the case–control study is almost identical to the relative risk obtained from the cohort study. Of course, working out how to do such a study and achieve the correct sampling of cases and controls is not easy.

Most of the studies of low frequency magnetic fields and childhood leukemia have been case–control studies; for example, the UK Childhood Cancer Study included all childhood cancer cases in England, Wales, and Scotland, each matched to a control child of the same age and sex; at-home and school measurements of EMF were assessed on 2226 cases and their controls (UK Childhood Cancer Study Investigators, 1999). This study gave no evidence that exposure to magnetic fields associated with the electricity supply in the United Kingdom increases risks for childhood leukemia, cancers of the central nervous system, or any other childhood cancer (see also Chapter 20). The Interphone studies were a series of international case–control studies of brain cancer and mobile phones, based on a common protocol, involving personal interviews with over 5000 patients with brain cancers and a similar number of matched controls, carried out in 13 countries (INTERPHONE Study Group, 2010); the combined analysis showed no overall increased risk, but an increase in the maximum use category (see Chapter 15).

3.5.4 Surveys

Studies can also be done on groups of people selected without reference to either possible causative factors or health outcomes; these are simply described as *surveys*. This may be an adequate design where both the factors to be assessed and the health outcomes to be assessed are common and easy to report objectively; for example, we could do a survey to find out if high blood pressure is associated with obesity in a population group. In an overly simple study, 530 people responded to a postal questionnaire about 18 nonspecific health symptoms and also reported on how close they lived to a mobile phone base station (Santini et al., 2002). There were more complaints recorded by subjects who reported living closer to a base station in most of the symptoms; but both the method of selection of the subjects and the subjective nature of the responses make this study open to severe biases. A later study showed a stronger association with the subject's estimated distance to a base station than with the actual distance (Baliatsas et al., 2011).

3.6 Time Dimensions – Prospective, Retrospective, or Cross Sectional

Epidemiological studies also differ in their *time relationships*. In a *prospective* study, individuals or communities are enrolled in the study and information on the possible causal factors and other factors is collected and then people are followed through time and information on outcomes, such as disease occurrences or deaths, collected as they occur. Some such studies can be short; for example, studies of exposures during pregnancy in which the health outcome is the birth of a baby with or without a congenital defect. However, where the time course of events may be very long, the study also has to be long, and epidemiological studies of heart disease and cancer may have to last 20 years or more. Indeed, many such studies have been done, including the studies of the effects of asbestos and of atomic bombs mentioned earlier.

In a *retrospective* study, the information is collected on events that have happened in the past. Case–control studies are all retrospective because cases have already developed the disease, and the other information collected relates to events and exposures even further in the past. A cohort study, based on identifying, for example, employees with chemical exposures and comparing them to employees without chemical exposures, can also be retrospective if records are available which adequately document the exposure.

Surveys are generally *cross sectional*, that is, they relate only to health outcomes and risk factors at the time the study is done, but they may have a retrospective component.

The distinction between cohort and case–control designs, based on the sampling schemes used for the studies, determines the methods of analysis that are appropriate and the types of results that can be produced. The time relationships affect the way data are collected and their quality and completeness.

3.7 Some Other Epidemiological Studies

Most causes of human cancer have been identified by analytical studies (such as smoking, asbestos, and ionizing radiation). Usually, a large number of such studies need to be completed before a consensus can be reached on a particular causal situation. All these types of studies are comparative studies, with control groups, of the exposure in free living human subjects. In general, studies of humans that lack an appropriate control group are weaker.

3.7.1 Ecological Studies

Another type of study is usually much weaker – that is, much harder to interpret clearly in terms of cause and effect. This is the *ecological study*, or *descriptive study*, where *population groups* instead of individuals are studied and a comparison is made of the frequencies of disease in populations with different exposure levels. Several of the studies of radiofrequency exposures fall into this category, for example, the studies of cancers in groups of people living at different distances from TV or radio transmitters (Dolk et al., 1997) or comparisons of the time trends in brain cancer deaths with the trends in use of mobile phones (Kim, Ioannides, and Elwood, 2015). This type of study is rarely regarded as definitive. However, with the mobile phone and brain cancer issue, the trend studies have shown that the increased risks within a few years of starting phone use, reported in some case–control studies, are unlikely to be valid as no increase in incidence rates was seen.

3.7.2 Clusters of Disease

Studies that are based on a presuspected group or "cluster" of cases of disease have particular weaknesses. They are best regarded only as preliminary observations that have to be reassessed by one of the study types described earlier. For example, a number of cases of a relatively infrequent disease such as childhood leukemia may occur in a community which is situated close to a television transmitter. Have these been caused by emissions from the transmitter? It is very difficult to know, as even if the frequency of the cases is many times the general population average, this may be caused simply by chance variation. The best way is to treat this as an observation that generates the hypothesis that leukemia could be caused by emissions from television transmitters and test that hypothesis in other studies. We could identify other transmitters with the same type of output and assess whether leukemia is also more common around them. This was done in the United Kingdom; after a cluster of cancer cases was reported near one large transmitter, all other similar transmitters in the United Kingdom were studied to see if high rates of cancer occurred near them, but no increase in risk was seen, showing that the first noted cluster was either a chance event or caused by something else (Dolk et al., 1997).

3.8 The Results of Epidemiological Studies: Relative Risk, Confidence Limits, and *P*-Values

The main result is usually expressed as a measure of association, the *relative risk*, which is the ratio of the risk (incidence rate) of disease in people exposed to the factor under consideration, to the risk in those people not exposed. For example, a relative risk of 1.5 means that people exposed to the factor under consideration have 1.5 times the disease risk of those not exposed; this can also be expressed as a 50% increase. A relative risk of 1.0 means that there is no association, and a relative risk of less than 1.0 equates to a protective effect. This result (the relative risk) is the *size of the association* provided by the study. As we have seen, case–control studies yield estimates of odds ratio, but these can be interpreted, and are often referred to, as estimates of relative risk.

The accuracy or statistical precision of the estimate of the relative risk is shown by *confidence limits*. These are usually expressed as "95% confidence limits", meaning that in statistical terms there is a 95% probability (95 chances in 100) that the true result will be within that range. A small study, because it is imprecise, will have wide confidence limits. A larger study will have narrower confidence limits, that is, the estimate is much more precise. Thus, although the studies in Tables 3.2 and 3.3 gave the same estimate of the relative risk, Table 3.2 uses more data and the confidence limits are narrower. If the confidence limits include the value of 1.0, the result is said to be "*not statistically significant*", in other words, it is compatible with no association and a relative risk of 1.0. If the confidence limits are all higher than 1.0, it means that the study shows an increased risk or a positive association, which in technical terms is "*statistically significant*".

If radiofrequencies do cause a disease like cancer, a good study will show this by giving a relative risk greater than 1. If the study is large enough, the 95% confidence limits will also be above 1: a hypothetical example would be a relative risk of 1.5, with limits of 1.2–1.8. This result would be described as a statistically significant increased risk. Even this result does not mean that a cause and effect relationship exists: that depends on whether the study is influenced by biases in the data used and whether the effects of other relevant factors have been taken into account.

If, on the other hand, radiofrequencies do not cause (or prevent) the disease, a good study will give a relative risk close to 1. However, it is unlikely that the relative risk will be precisely 1, because of the impossibility of collecting perfectly accurate data and having no influences of other factors, and also because of the effects of chance variation. The 95% confidence limits will usually include the value of 1.0: a hypothetical example would be a relative risk of 1.1, with limits of 0.8–1.3. This result would be described as showing no increased risk (or only a small increased risk), which is not statistically significant. A study with a relative risk of 3.0 with confidence limits of 0.5–18.0 is, however, difficult to interpret as it gives a nonsignificant result, but shows a substantial association; fundamentally, the study is very imprecise as it is too small.

The relative risk and its confidence limits depend on the association seen, the size of the study, and the statistical methods used. These results do not assess whether the observations have been collected without bias or whether the association is due to factors other than the one suspected, except where these have been dealt with in the study design or analysis. These issues have to be addressed by a careful review of the study. The result will also not tell us how relevant the results are, as that depends on the setting of the study, how the subjects were selected, and the definitions of the exposure and outcomes assessed.

The confidence limits around the relative risk estimates in Tables 3.2 and 3.3 can be calculated by simple methods that are described in epidemiological textbooks and are also available on many computer programs. However, in practice, the analysis of these results by simple statistical methods is not likely to be sufficient. Studies published in reputable journals would probably use more sophisticated analytical methods such as multivariate methods to take into account confounding factors and also aspects of the study design such as matching. However, the results will still be presented in terms of relative risk or odds ratio measurements and usually 95% confidence limits.

A less satisfactory way of assessing results is by statistical significance tests, which yield a probably or *P*-value that compares the results obtained with the null hypothesis result that equates to a relative risk of 1.0. In the examples of both Tables 3.2 and 3.3, the 95% confidence limits exclude this null hypothesis value of 1.0. A statistical significance test would yield a *P*-value of less than 0.05, so the results could be described as "statistically significant". However, this is much less informative than a calculation of confidence limits, particularly in the case where the results are not statistically significantly different from the null hypothesis value.

3.9 Assessing Causality: Identifying Noncausal Explanations

Criteria have been developed, which are generally accepted both for the assessment of an individual study and of the totality of evidence derived from a number of studies. The first process in assessing whether a particular study gives a valid cause and effect assessment is to see if alternative, noncausal, explanations can be reasonably excluded; this logic in fact applies to all science, including laboratory studies. These noncausal factors are as follows:

- *Observation bias.* For example, in a study based on an interview recall of exposures, people affected with cancer may be more ready to recall and report previous exposures (such as exposures to radiofrequency sources) than people who have not had cancer. If this bias occurs, even if there is no true relationship between the exposure and cancer, the study will show an incorrect positive association, which may well be statistically significant – statistical tests give no protection against observation bias.
- *The effects of other relevant factors,* known by the term "*confounding*". For example, if users of mobile phones smoked more than other people, a positive association between mobile phone use and lung cancer would result.
- Apparent associations may be due to *chance variation.* This is assessed by statistical methods, which should be applied once observation bias and confounding have been dealt with as far as possible.

3.9.1 Confounding

Of these three noncausal explanations, *confounding* is the most complex, and the major developments in epidemiological methods have been in methods of overcoming confounding in analytical studies. The effects can be subtle and often counterintuitive. Consider our cohort study assessing the association between chemical exposure and cancer (Table 3.2), this time dividing the employees into men and women. The results are shown in Table 3.4. In the men, the cancer incidence is just slightly greater in those with chemical exposure, giving a relative risk of 1.05. In the women, again those exposed have a slightly higher risk, with a relative risk of 1.20. The calculation of confidence limits shows that neither of these relative risks is statistically significant; they could be produced simply by chance variation. However, these data shown in Table 3.4 are in fact equivalent to the data previously shown in Table 3.2. If we combine the data for men and women to consider the whole of the employee group without subdivision by gender, we get the data shown in Table 3.2, which as we have previously seen, shows a relative risk which is statistically significant and apparently indicates an increase in cancer associated with the chemical exposure. The problem is that this is confounded by the gender difference in the employee group.

Further examination of Table 3.4 shows how the confounding has arisen. The majority of male employees were exposed to the chemical, whereas only a minority of women were exposed. There is therefore a positive association between male gender and exposure to the chemical. Furthermore, Table 3.4 shows that irrespective of exposure group, male employees have much higher cancer rates than female employees. This may indicate further confounding

Table 3.4 Results of a cohort study, stratified for men and women.

	Number of employees	**Number of person-years of follow up**	**Number of cases of cancer**	**Incidence rate per 100,000 person-years**	**Relative risk**	**95% confidence limits**	**Risk difference per 100,000 person-years**
Men							
Chemical exposure	30,000	300,000	820	273.3	1.05	0.91–1.21	13.3
No exposure	10,000	100,000	260	260.0	1.0 (reference)	–	–
Women							
Chemical exposure	20,000	100,000	24	24.0	1.20	0.72–1.99	4.0
No exposure	40,000	200,000	40	20.0	1.0 (reference)	–	–

factors such as age; note that the average follow up is longer for the men. As a result, there is a positive association between male gender and a higher cancer incidence rate. The simultaneous occurrence of these two associations, with men having more chemical exposure and independently having a higher rate of cancer, produces positive confounding. If this confounding is not taken into account, an erroneous positive association between chemical exposure and cancer will be seen, as shown in Table 3.2. Importantly, the finding that the association in Table 3.2 is statistically significant is no protection against confounding. Exactly the same logic would apply in the results previously shown in Table 3.3, representing a case–control study. Again these results will be misleading unless they are adjusted for the gender distribution.

Confounding can also disguise an association that may truly exist. A real example is that it is very likely that the use of sunscreens is an effective protection against skin cancer, by blocking out ultraviolet radiation. However, several epidemiological studies have shown that people who use sunscreens the most have a higher, not a lower, risk of skin cancer. This is probably because people who use sunscreens use them in order to stay out in the sun as long as possible without burning, so people who use sunscreens the most also have the highest exposure to the sun, and sun exposure causes skin cancer. This confounding effect of sun exposure may disguise a true protective association of sunscreens, replacing it with an apparent positive association. Direct evidence for this effect is given by randomized intervention studies that supplied volunteers over a summer period with either a very powerful sunscreen or a much less powerful sunscreen, without them having knowledge of which it was. It was shown that those given the more powerful sunscreen stayed out in the sun for longer, and therefore probably got, even with the partial protection of the sunscreen, a higher rather than a lower dose of carcinogenic ultraviolet radiation (Autier et al., 2000).

3.9.2 Positive Indicators of Causality: The Bradford-Hill Indicators

After excluding noncausal explanations, the next process is to look for specific features which would be expected if a biological cause and effect relationship exists. Such indicators are sometimes called the *Bradford Hill criteria* after Sir Austin Bradford Hill, a British statistician who did much to establish scientific methods in medicine (Hill, 1965). These indicators are generally accepted and used by many multidisciplinary international groups in the assessment of cause and effect in health studies; however, they are guidelines, not rigorous rules. They are as follows:

1) An appropriate *time relationship*, with the effect following the cause is logically essential.
2) A reasonable *strength* of the relationship, shown by the size of the relative risk.
3) A *dose-response relationship*. These three features are helpful mainly in making it easier to detect, and allow for, observation bias and confounding;

for example, if a study reports a small relative risk, for example, less than 1.5, it may be difficult to ensure that such biases can be excluded.

4) *Specificity* is the concept that the causal relationship applies only to certain exposures and/or only to certain outcomes. It can be useful in assessing bias or confounding; thus, the finding that a drug taken by pregnant mothers was associated with an increase in one particular type of congenital abnormality, but not in any others, would be easier to interpret than a situation in which an increase in many different types of abnormalities was observed, as this latter situation might suggest bias in the observations. However, the possibility of a true causal increase in multiple abnormalities cannot be ignored.
5) *Coherence* refers to the consistency of the association seen with the general distributional characteristics of the exposure and the outcome. Thus, an increase over time in both the use of mobile phones and the frequency of brain tumors would be coherent with observations of analytical studies showing a positive association. However, the absence of such equivalent trends would not strongly argue against the association, as many other factors may be operating.
6) *Plausibility* refers to the empirical associations seen in epidemiological studies being explicable by an established biological mechanism. While it may be helpful, the absence of a known biological mechanism may be misleading as epidemiological studies are often the first to show relationships, long before the mechanisms of the association are worked out. For example, the effect of smoking on cancers was demonstrated empirically in epidemiological studies long before the precise mechanism was clarified, and the way in which asbestos causes human cancer is still without a clear explanation. Bradford Hill also gave *analogy* as a separate concept, but this is really as aspect of plausibility: an association is more plausible if it is analogous to an established causal relationship. These concepts of specificity of effect, coherence, plausibility, and analogy were also given by Bradford Hill, but are much less critical than other factors.
7) *Consistency* is the most important criterion and is assessed in two ways: as consistency within a study, and, even more important, consistency among various studies. In the great majority of situations, the development of a consensus among the scientific community on whether a particular agent causes, for example, cancer is based on a consideration of the consistency of evidence from a large number of studies of different designs and in different populations, which overall produce a substantial body of evidence. This requires that all relevant studies be considered. This is made more difficult by *publication bias*, that is, not all studies have an equal chance of being published; studies that have negative results or results in accordance with conventional assumptions and therefore are not newsworthy, or in contrast give unexpected results that are not accepted by journal editors, may have difficulty being published.

Bradford Hill's often cited paper (Hill, 1965) listed nine items, which he referred to as "aspects of the association" and as "viewpoints". I have condensed "analogy" within plausibility in the text above. The other and very important aspect has been covered in the earlier discussion of the types of study: recognizing "*experiment*", that is, intervention studies, as likely to provide the best-quality evidence for or against a cause-and-effect relationship. Even where we are interpreting intervention studies, the principles above are useful.

These are not, however, criteria. Bradford Hill wrote (Hill, 1965): "What I do not believe – and this has been suggested – is that we can usefully lay down some hard-and-fast rules of evidence that must be obeyed before we accept cause and effect. None of my nine viewpoints can bring indisputable evidence for or against the cause-and-effect hypothesis and none can be required as a sine qua non. What they can do, with greater or less strength, is to help us to make up our minds on the fundamental question – is there any other way of explaining the set of facts before us, is there any other answer equally, or more, likely than cause and effect"?

3.9.3 Meta-Analysis

The comparison of the results of many studies, to search for consistency and to assess the best estimate of relative risk, based on all the available data, is referred to as *meta-analysis*. Subjectivity in the selection of studies is minimized by using explicit criteria, allied to computerized data bases of published literature worldwide; this gives some but not total protection against publication bias. Statistical methods have been developed for meta-analysis, which are in principle similar to the methods illustrated in Table 3.4; if there are, for instance, 20 available studies on a topic the 20 studies are used as 20 subsets of data, and the overall effect based on all the studies is calculated. Simple meta-analyses can be based on the reported results of studies, such as the relative risk and its confidence limits; a full meta-analysis (sometimes called a pooled analysis or IPD, individual patient data, analysis) requires the cooperation of the investigators of the various studies and uses the raw data from the various studies to allow a new analysis using all the data available. This type of analysis can be very powerful as it can be based on very large numbers of subjects and can yield conclusions that have not been shown in any of the individual studies. Such pooled meta-analyses have been done combining data from several case–control studies assessing magnetic field exposures and childhood leukemia, producing results which are in some ways different from those of the individual studies, but together provide strong evidence that an association exists (Greenland et al., 2000; Ahlbom et al., 2000). The Interphone studies of mobile phone use and brain cancer were designed from the outset to be pooled, and the main analyses are based on the pooled data (INTERPHONE Study Group, 2010). The interpretation remains open to debate; whether the epidemiological associations show a causal relationship or are due to observation bias, confounding, or chance variation.

3.9.4 Assessing if No Association Exists

These same issues have to be assessed to interpret studies that show no association, that is, the relative risk estimate is close to 1.0. Observation bias, or simple error, may disguise a true association. A confounding factor can disguise a true association: for instance, an increased risk due to an occupational hazard may be disguised by the generally better health of people selected for employment: the “healthy worker effect”; this bias can be dealt with by comparing the workers exposed to the suspected hazard with other workers in the same general situation but not exposed to that hazard. The size of the study is important; small studies can only show effects which are large. Another problem is the specification of the exposure; for example, if a hazardous effect of electromagnetic fields is restricted to a particular frequency range, a study in which exposure is defined as any EMF exposure will have reduced ability to detect an effect.

It is impossible to prove, with absolute certainty, the *absence* of an effect. To prove with certainty that nonionizing radiation, or any other aspect of the human environment, is completely safe is impossible; as to do so requires proof of the absence of any association between exposure to it and any one of an infinite number of health outcomes. This logical difficulty is expressed in the general approach of epidemiology, and science in general, which accepts as “fact” not something which has been proven with absolute certainty, but as the best current explanation of the available results of scientific studies. If the balance of the available evidence overall is that health effects have not been demonstrated, despite some studies of reasonable quality having been done, then the likelihood that the exposure is safe is increased. The evidence of the absence of risk may well be sufficient for the community to allow activities based on the assumption of safety.

It follows from this that a claim such as “electromagnetic fields may cause adverse health effects”, even if there is little or no objective evidence of such effects, will always be true. It cannot be disproved by scientific study, it can only be made less plausible if more studies are done and clear evidence of hazards does not emerge. But because it is always true, it is not very helpful. The claim that health effects may exist is of no value unless it is based on some objective evidence of either the existence of such effects or other scientific evidence which make such effects likely, rather than just possible.

3.10 Conclusion

This has been an extremely brief overview of the methods used in epidemiological studies, but should be sufficient to show the reader the main types of epidemiological study and the format in which their results are shown, and some of the key issues in interpreting them. Epidemiology is a complex science, and most contemporary epidemiological research studies use methods that, while based on the simple examples given here, are considerably more sophisticated. Further information can be gained from a wide range of epidemiology textbooks and internet sources.

Tutorial Problems

1 If a disease has an incidence of 200 per 100,000 per year, and the average duration to recovery or death is 12 years, what is the approximate prevalence, in what units?

2 Suppose that a study shows that people who use mobile phones have a relative risk of 5.0 for brain cancer incidence, compared to those who do not use mobile phones. There are four general reasons why such an association could occur. One of which is that mobile phones cause brain cancer, what are the other three?

3 What type of study do the following represent?

- **A** A group of naval personnel using radar are identified along with a comparison group of personnel not using radar, and their subsequent mortality from various diseases was studied.
- **B** Children with leukemia were identified, and measurements made in their home of magnetic field levels. Measurements were also made in the homes of normal children.
- **C** The blood pressure of volunteers was measured before and during exposure to radiofrequency emissions or sham exposures in a laboratory setting.
- **D** Employees in an electricity utility company were identified, and the job histories of those who had developed cancer were compared to the job histories of a sample of the rest of the workers, to ascertain likely electromagnetic field exposure from the job histories.

4 How would you interpret the following results?

- **A** RR = 2.8, 95% CI 1.5–5.2
- **B** OR = 0.7, 95% limits 0.3–1.6
- **C** RR = 2.5, 95% CL 0.3–20.8
- **D** RR = 2.5, $P > 0.05$
- **E** In result 4c, the limits extend much further above the RR estimate than they extend below it. Does this indicate an error?

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Part II

Ultraviolet (UV) Light

4

UVR and Short-Term Hazards to the Skin and Eyes

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4.1 Introduction

4.1.1 UV A, B, and C

Ultraviolet radiation (UVR) is part of the solar electromagnetic radiation spectrum, which includes visible radiation (wavelength range 400–770 nm) and infrared radiation (wavelengths >770 mm). The UVR region covers the wavelength range 100–400 nm and consists of three subregions, UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm) as defined by the International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) and the Commission International de l' Eclairage (IRPA/INIRC, 1985 and the CIE, 1998).

In general, only UVR in the range 200–400 nm can have a direct interaction with living organisms, since at wavelengths shorter than 200 nm, UVR is strongly absorbed by oxygen in the air. The penetration depth of UVR into human tissue is between 0.1 and 1 mm, so the organs at risk are the skin and the eyes. UVR has shorter wavelengths and thus more energetic photons than visible light and hence is capable of producing more damage when absorbed in biological tissue.

4.1.2 Action Spectra

The action spectrum is a measure of the effectiveness of different wavelengths of radiation in causing a photobiological process. The two most widely used action spectra are those for the skin and eyes (ICNIRP, 2004) and the skin (CIE, 1998), and these are shown in Figure 4.1. The biological effectiveness of UVR is very wavelength dependent with UVB being considerably more biologically effective

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

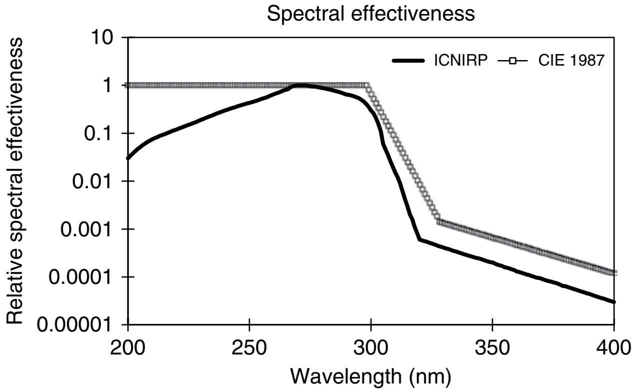


Figure 4.1 The relative spectral effectiveness of the CIE (-□-) for erythema compared with the ICNIRP (——) spectral effectiveness for eyes and skin. Both functions show a rapid decrease in effectiveness of several orders of magnitude for UVA wavelengths above 315 nm in comparison with UVB wavelengths. *Source:* Adapted from ICNIRP (2004), Health Physics.

than UVA radiation. Within the UVB, between 300 and 315 nm, the relative spectral effectiveness decreases by three orders of magnitude, which means that spectral measurements within this region must be very precise or large errors in the calculated effective radiation will result.

To determine the effective irradiance of a broadband source weighted against the peak of the spectral effectiveness curve (270 nm), the following weighting formula is used:

$$E_{\text{eff}} = \sum_{180}^{400} E_\lambda \, S_\lambda \, \Delta_\lambda \tag{4.1}$$

where

E_{eff} = effective irradiance in W/m^2 normalized to a monochromatic source at 270 nm
E_λ = spectral irradiance in W/m^2/nm
S_λ = relative spectral effectiveness (see Figure 4.1)
Δ_λ = bandwidth (nm)
λ = wavelength (nm)

The bandwidth is chosen to adequately capture the detail shown in Figure 4.1 and can vary according to which part of the spectrum is being evaluated.

For solar radiation, the CIE erythemal effectiveness function is generally used and the summation is from 280 to 400 nm. The technical name for sunburn is erythema and the minimum dose required to induce sunburn is defined as a minimal erythemal dose (or MED) and applies to previously unexposed skin. If the exposure is spectrally weighted by the CIE erythemal effectiveness curve, the MED corresponds to an effective radiant exposure expressed in standard erythemal dose (SED). One SED is an effective radiant exposure of 100 J/m^2 (CIE, 1998). Different people will have different skin types and also different MEDs. A pale-skinned person might have a MED of two SEDs, while a darker skinned person might have an MED of six SEDs (see Table 4.3). The ultraviolet index (UVI) is based on multiples of 25 mW/m^2, so for sunlight of UVI 12, the E_{eff} is 0.3 W/m^2, which is multiplied by 1000/25 = 40 to give a UV index of 12.

4.2 Sources of UVR: Natural and Artificial

4.2.1 Solar UVR and Latitude

A comparison between the extraterrestrial solar spectrum (Bird, Hulstrom, and Lewis, 1983; Frohlich and Wehrli, 1981; Iqbal, 1983) and one measured at the Earth's surface is shown in Figure 4.2 (Bird, Hulstrom, and Lewis, 1983). The effects due to absorption in the atmosphere can be clearly seen. While sunspot activity can increase the extraterrestrial intensity, this effect is more marked at wavelengths less than 290 nm, which are completely absorbed as they pass through the atmosphere and are not present in the solar spectrum at the Earth's surface. The intensity of the extraterrestrial spectrum generally has a yearly variation of less than 10%, but the intensity of solar radiation at the

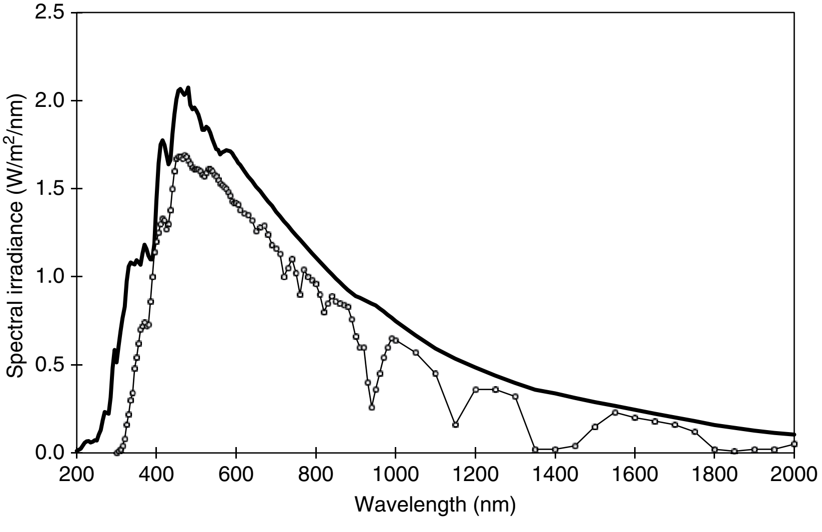


Figure 4.2 The extraterrestrial solar spectrum (solid line) incident at the top of the atmosphere and the solar spectrum measured at the Earth's surface (line with open circles). *Source:* Bird, 1983. Reproduced with permission of Elsevier.

Table 4.1 Distribution energy of the extraterrestrial solar spectrum (Thekaekara, 1973) and the solar spectrum measured at the Earth's surface.

	Extraterrestrial		Earth's surface	
Wavelength region	**Irradiance (W/m^2)**	**Percentage of total**	**Irradiance (W/m^2)**	**Percentage of total**
UVC	7.6	0.56	–	0
UVB	18.3	1.4	2.0	0.04
UVA	92.1	6.8	60	6.5
Visible	606	44.8	313	55
Infrared	629	46.5	355	38

Source: Bird, 1983. Reproduced with permission of Elsevier.

Earth's surface is subject to large variations due to numerous factors, mostly atmospheric, discussed later in this chapter. From Figure 4.2, the proportion of energy at wavelengths below 400 nm in solar UVR at the Earth's surface is very minor and is generally less than 7% with the UVB contributing just 0.04% (Table 4.1).

4.2.1.1 Factors Affecting Solar UVR

Ozone, although being only a minor constituent of the Earth's atmosphere, nevertheless plays a vital role in the absorption of incoming solar UVR, in particular, the lower wavelengths of the UVB. The absorption by ozone in most of the UVA region is virtually zero, but below about 340 nm, it increases rapidly with decreasing wavelength. The effect of this can be seen in Figure 4.3 and Table 4.1 as the difference between the extraterrestrial and surface solar spectra. Stratospheric ozone is responsible for preventing much of the UVR below 290 nm from reaching to the Earth's surface (molecular oxygen also plays a role). Concern about the effects of increased solar UVB as the result of stratospheric ozone depletion is not new but the discovery of the springtime Antarctic ozone hole by Farman, Gardiner, and Shanklin (1985) increased the general awareness and heightened concerns. The worry is that long-term ozone depletion will add significantly to the UVB levels (and hence the effective UVR, termed UVR$_{\mathrm{eff}}$) the population is exposed to, which in turn may ultimately result in increased skin cancer and melanoma rates. Over the past few years, the extent and size of the ozone hole over the Antarctic has started to stop increasing by starting to show signs of slowly decreasing in a number of measures (duration, area, depth, extent) and although the trend is now to decrease it is not at this stage a straight line downward (Klekociuk et al., 2014, 2015).

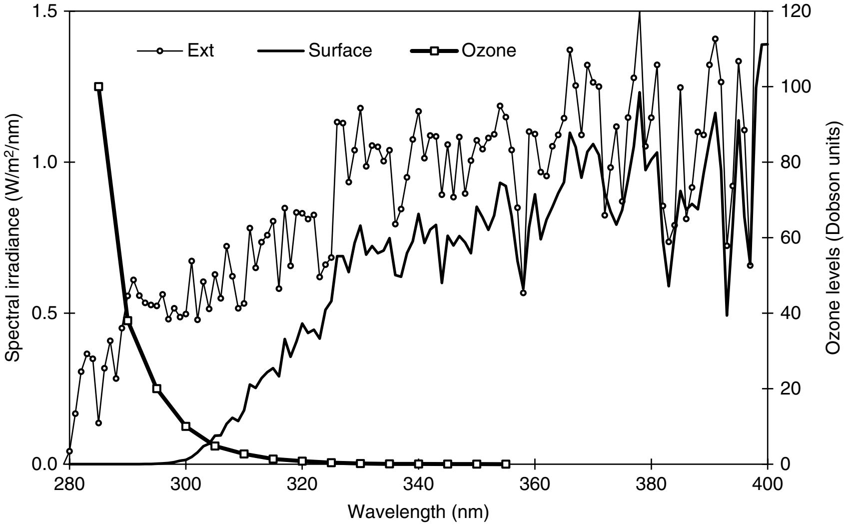


Figure 4.3 A comparison of the extraterrestrial solar spectrum with that measured at the Earth's surface (Melbourne, Australia, January) for the UVR wavelength range 280–400 nm. Also shown are the absorption coefficients of ozone (right axis), which increase sharply at wavelengths below 340 nm and are responsible for reducing the hazardous UVR below 300 nm.

The most recent UNEP Report's findings (UNEP, 2014) were that the levels of UVB at high latitudes will depend on the recovery of stratospheric ozone and changes in clouds and reflectivity of the surface of the Earth. In Antarctica, the mean noontime UV index (UVI) is projected to reduce by up to 40% by 2100 due to the continuing recovery of ozone. The UNEP Report also concluded that these reductions are comparable in magnitude with the increases in UVI that occurred in the past due to ozone depletion (UNEP, 2014).

The UNEP Report went on to say that with "continued effective implementation of the Montreal Protocol, future changes in UVB irradiance outside the Polar regions will likely be dominated by changes in factors other than ozone (UNEP, 2014)". The UNEP Report went on to say that "by the end of the twenty-first century, the effect of the recovery of ozone on UVB irradiance will be very small, leading to decreases in UVI of between 0 and 5. Additional decreases of up to 3% in the UVI are projected due to the anticipated increases in cloud cover" (UNEP, 2014). There will also be effects due to aerosols, "with the confidence in the size of the effects low due to substantial uncertainties in the projected amounts and optical properties of aerosols" (UNEP, 2014).

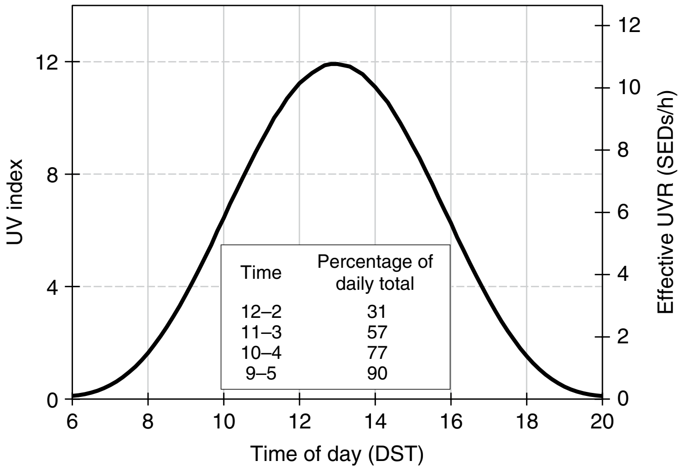
4.2.1.2 Solar Elevation

Geographical location, in particular latitude, is the important factor that determines the position of the sun in the sky and the sun can only be directly overhead for locations between the two tropics at latitudes 23.5°N and 23.5°S. The strength of the sun is at maximum for any particular location when it is directly overhead. For latitudes further from the equator, the sun will be at its highest at solar noon on December 21st or 22nd for the Southern Hemisphere and on 21st or 22nd June for the Northern Hemisphere. Another factor is that the Earth's orbit is elliptical and is at its closest to the Sun on January 3rd and at its furthest from the Sun on approximately July 4th (Iqbal, 1983). This results in about a 3% difference in distance and approximately a 7% higher intensity in January, during the Southern Hemisphere's summer. Coupled with clearer atmospheric conditions and the more significant ozone depletion observed over the Antarctic, this may result in measured ambient UVR, which is 12–15% higher for geographical locations in the Southern Hemisphere in comparison to similar locations in the Northern Hemisphere (McKenzie, 1991). Between September and March, the sun is over the Southern Hemisphere and is higher in the sky there, resulting in higher UVR levels than between March and September, when it is over the Northern Hemisphere.

The single most important factor affecting the amount of solar UVR (for clear skies) is the elevation of the sun in the sky: the higher the sun, the higher the levels of solar UVR. When the sun is low, the path of the radiation through the atmosphere is longer and more of the radiation is absorbed and scattered, as well as being spread over a larger area when it is incident on the surface. Radiation from the sun incident on the top of the atmosphere contains UVC, UVB, and UVA. However, due to absorption by oxygen and ozone in the upper atmosphere, no UVC and only a small fraction of the UVB reaches the Earth's surface. The height of the sun therefore determines how much UVB penetrates the atmosphere: the lower the sun the less UVB. In winter, the sun is low in the sky and contains proportionally less UVB due to absorption and scattering. The same process occurs daily, with the solar UVR around noon being more intense and containing more damaging UVB than early or late in the day.

Figure 4.4 shows the percentage of the daily total solar UVR within certain time periods. The hours 12 till 2 (1 hour either side of noon: 1 p.m. daylight savings time) have 31% of the daily total, while almost 60% of this daily total occurs within 2 hours of solar noon (11 a.m. till 3 p.m.). These percentages will vary for different latitude locations and for different times of year.

The yearly variation in solar elevation results in a maximum on December 21/22 and June 21/22 for the Southern and Northern Hemispheres, respectively. However, UVR levels are not necessarily a maximum on these days as other factors such as seasonal variations in ozone are also important. For locations inside the tropics, the sun will be directly overhead twice a year. Locations outside the tropics generally show a typical temperate variation in UVR, with solar UVR low in winter and high in summer. For example, at a UVI average of 10 for an hour, the time to two SEDs is 13.33 minutes, since two SEDs are equivalent to 200 J/m^2, which is equal to $10 \times 25 \times 10^{-3} \times 13.33 \times 60$.



Time	Percentage of daily total
12–2	31
11–3	57
10–4	77
9–5	90

Figure 4.4 The percentage of daily solar UVR within certain time periods. The hours 12 till 2 have 31% of the daily total, while almost 60% of the daily total occurs within 2 hours of solar noon (11 a.m. to 3 p.m.). These percentages will vary for different locations and for different times of the year.

4.2.1.3 Diffuse and Direct UVR

Solar UVR at the Earth's surface comes not only directly from the sun but also indirectly from the sky, due to atmospheric scattering and this is called diffuse radiation. Depending on the time of day, there can be as much UVR from the sky as there is from the direct sun. The higher the sun, the shorter the path-length through the atmosphere and the less diffuse and the more direct UVR there is. This means that the higher the sun is in the sky, the less atmosphere the incoming radiation has to pass through and as a result the highest UVI will occur when the sun is at its highest and absorption is at a minimum (for clear sky conditions).

Since UVB is scattered more readily than UVA, the diffuse UVB radiation from the sky exceeds the direct UVB from the sun, except for a few hours around solar noon. However, the direct component of UVA is greater than the diffuse for most of the day, with the exception of a few hours in the early morning and evening.

4.2.1.4 Effect of Ozone on UVR

Total ozone shows a fairly consistent annual cycle but daily variations can be up to 40% of the total. Therefore, while two consecutive days might have the same temperature and cloud cover, the UVR_{eff} hazard could be different by as much as 30% due to natural variation in ozone. Generally, ozone levels are lowest in late summer, which usually results in the highest measured UVR_{eff} levels in January (Southern Hemisphere) or July (Northern Hemisphere), even though the sun is higher in the sky in December and June for the respective hemispheres.

4.2.1.5 Effects Due to Clouds

Clouds significantly affect the level of solar radiation measured at the Earth's surface and the effects are wavelength dependent, in that the water vapor attenuates infrared much more than UVR. There is also a small wavelength dependence across the UVR, with UVB being transmitted more readily than UVA (Seckmeyer, Erb, and Abold, 1996). Heavy cloud cover can reduce the levels of UVR to almost zero. However, light cloud cover reduces the levels of UVB by approximately 10–50%, but it is very dependent on the type of cloud, its thickness, and areal coverage. In certain situations, reflected UVR from clouds can actually add to the ambient levels and for short time periods can result in higher UVR than on days with clear sky (Mims and Frederick, 1994).

4.2.1.6 Altitude

Solar UVR increases with altitude at a rate of approximately 4% increase in UVR_{eff} for every 300 m (Diffey, 1982). Spectral measurements (Blumthaler et al., 1994) of solar UVR at two sites in the European alps separated by 1 km in altitude showed that the increase in UVR with altitude has some wavelength dependence. Irradiances at the mountain site at a wavelength of 370 nm were 9% higher than the valley site, increasing to 11% at 320 nm. In the UVB, the increase was 24% at 300 nm, while the UVR_{eff} was 14% higher at the mountain site.

4.2.1.7 Typical Levels of Solar UVR and Effects of Latitude

For a mid-latitude location at solar noon, maximum levels of UVA and UVB are approximately 70 and 2.5 W/m^2, respectively, in summer and 25 and 0.6 W/m^2 in winter. The exact variation between summer and winter UVR levels will depend on the latitude of the location. Figure 4.5 shows the variation of solar UVR (annual SEDs measured at the Earth's surface) with latitude for locations in both the Northern and Southern Hemispheres (Driscoll, 1996 (UK); Gies et al., 2004 (Aust); Josefsson, 1996 (Swe); McKenzie, 1991 (NZ); Martinez-Lozana et al., 2002 (Spain); Ono, 1997 (Japan); Scotto et al., 1988 (USA); Jokela, Lezsczynski, and Visuri, 1993 (Arctic); Seckmeyer et al., 2008 (Germany); Utrillas et al., 2013 (Spain)). The latitude gradient is clearly evident. There is also a spread of values at the same latitudes due to other factors such as weather patterns, local topography, and altitude, where two of the locations have higher annual solar UVR due to high altitude (Mauna Loa at 4169 m at 20°N) and to a lesser extent Izana in Tenerife (at 2300 m at 28°N – Utrillas et al., 2013).

4.2.2 Artificial Sources of UVR

UVR is used widely in scientific, medical, industrial, and domestic fields. Uses include sterilization, photopolymerization, photoactivation processes, psoriasis phototherapy, and artificial suntanning. UVR is also inadvertently present in operations such as welding, metal smelting, glass processing, and all processes

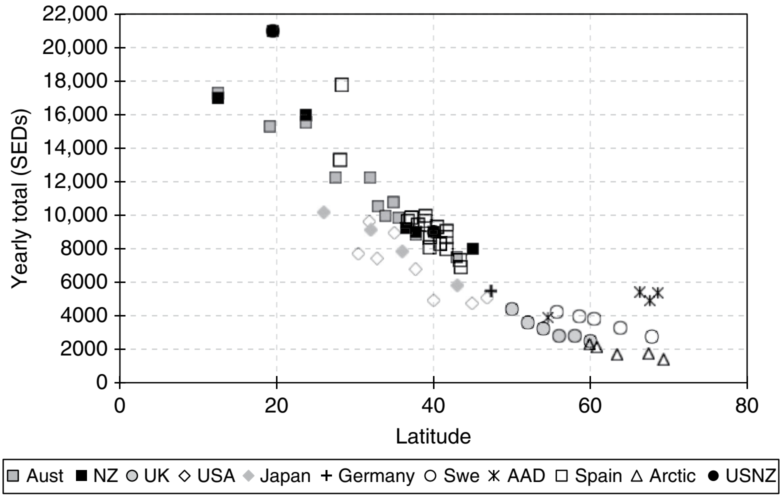


Figure 4.5 Variation of solar UVR with latitude for locations in both the Northern and Southern Hemispheres. Note that the Australian Antarctic Division (AAD) stations in the Antarctic (~60°S) points are higher due to higher solar UVB levels due to regular ozone depletion events, whereas the Macquarie Island AAD Station is unaffected by the ozone hole.

involving incandescent materials. These various sources emit a broad spectrum of UVR. Some artificial sources of UVR are described in the following.

4.2.2.1 Lamps

The general characteristics of lamps and pertinent technical characteristics will be briefly summarized.

4.2.2.1.1 Incandescent Filament Lamps

Solid-body incandescent materials such as iron and tungsten used in filament lamps seldom exceed black-body temperatures of 3000 K. Their spectral distributions peak in the red end of the spectrum with a relatively small fraction of visible (blue) and UVR. Such light sources present no problems from a safety standpoint.

Tungsten halogen (TH) lamps have been used for desk lighting and domestic and display downlighting. TH lamps consist of a small quartz bulb containing a tungsten filament and a halogen gas (usually iodine) and emit significant levels of UVR. The presence of the gas minimizes evaporation of tungsten from the filament, thereby prolonging the life of the lamp and allowing it to be operated at a higher temperature than a conventional lamp. The light produced is therefore brighter (for a lower power consumption), but because the operating temperature is higher, the envelope in TH lamps must be quartz. This combination of high filament temperature and quartz envelope (which transmits UVR) results in potentially hazardous levels of UVR emission from the lamp.

4.2.2.1.2 Low-Pressure Discharge Lamps

The mercury lamp in the various forms is one of the most important and widely utilized light and UVR sources. It is also potentially hazardous. The lamp consists of a UVR transmitting tube with an electrode at each end. The filling is not mercury alone, but a mixture of a single drop of mercury and an inert gas, usually argon, at a pressure of a few torrs. The pressure of mercury is just its vapor pressure (~1 Pa at the operating temperature, which is approximately 400 °C). The inert gas is therefore at a much higher pressure than the mercury, but contributes almost nothing to the spectral output. However, it plays a vital part in both the establishment and the maintenance of the discharge. When a lamp is first switched on, electrons are accelerated in the electric field. Because the vapor pressure of mercury is so low, most of the collisions that take place are between electrons and argon atoms. The lowest argon excited state is metastable (i.e., nonradiative) but on collision can cause ionization of a mercury atom.

Mercury emission occurs at a number of specific wavelengths including the UVR wavelengths of 189, 254, 297, 303, 313, and 365 nm. However, almost 90% of energy is emitted at 254 nm. The 254 nm radiation is a highly biologically active wavelength to the eyes and skin and extreme care must be taken in its use. Germicidal or UV-C lamps emit predominantly 254 nm radiation and are effective in destroying bacteria and molds and are used extensively in hospitals, cold-storage facilities, and food handling and processing rooms. These lamps are normally in either enclosed cabinets or mounted in a room in such a manner as to reduce the irradiances to personnel to an acceptable level.

4.2.2.1.3 Fluorescent Lamps

Most low-pressure mercury lamps are used for lighting, with a fluorescent powder coating on the inside wall, which converts the 185 and 254 nm radiation from the arc into visible radiation suitable for illumination. Fluorescent tubes are also used for purposes other than illumination with fluorescent coatings chosen to emit bands of radiation centering on wavelengths between about 300 and 450 nm. The most common emits a broad band of UVA, with peak emission at 360–370 nm. There are two versions of this lamp. One has a tube made from normal soda glass and the other a tube made from "Wood's" glass. Wood's glass contains oxides of nickel and cobalt and is opaque to visible radiation but transmits UV-A. Lamps having such phosphors or filters are called "blacklight" units. Blacklights are often used with fluorescent powders in many nondestructive testing applications as well as for special effects in entertainment.

Solaria (artificial suntanning establishments) typically used two different types of UV fluorescent tubes; UVB tubes found in "stand-up" tanning booths and UVA tubes that were used in sunbeds. Various national standards covered the artificial suntanning industry and only UVA lamps would meet the emission requirements. The main use of these lamps is in the medical (phototherapy) and recreational areas and would rarely be encountered in occupational situations. Many countries have now banned the use of solaria.

4.2.2.1.4 High-Intensity Discharge (HID) Lamps

The most common high-intensity discharge (HID) lamps are mercury, high-pressure sodium, and metal-halide lamps, where gas pressures are typically 2–4 atm. These lamps often present potential hazards and require evaluation. Most employ two envelopes – the inner envelope or arc tube is generally of quartz, while the outer envelope is typically of hard borosilicate glass. The outer envelope is to minimize ambient temperature and draft changes but it also plays an important role in filtering out UVB and UVC radiation. The lamps are sometimes operated with fluorescent phosphors in the outer envelope. In high-pressure mercury discharge lamps, the emission is no longer exclusively the atomic spectral lines of the low-pressure lamp, but is a continuum with the five principal visible emission lines (405, 436, 546, 557, and 559 nm) having much of the output energy.

High-pressure sodium lamps are used for both outdoor and indoor lighting. The lamp is constructed with two envelopes, with the inner of polycrystalline alumina that has a low transmittance for UVB and UVC. These lamps are not considered hazardous.

The metal halides lamps are very much like mercury lamps with a phosphor coating. These lamps contain mercury and mixtures of various metal halides (sodium, thallium, and indium).

4.2.2.1.5 Short Arc Lamps

Short, compact-arc lamps are the brightest continuous lamp sources available and are typically used for searchlights, movie projectors, and solar simulators. The short-arc lamps are generally direct current (DC) and specialized starting circuits and high-current, low-voltage power supplies are required. Xenon, mercury-xenon, and mercury are the most common. All of the short-arc lamp types employ quartz envelopes and therefore emit sufficient UVB and UVC radiation to present serious eye and skin hazards for direct exposure. The quartz envelopes are exceedingly hot and would cause burns of the skin if touched momentarily. In addition, the high-pressure lamps present an explosion hazard if not handled carefully.

4.2.2.1.6 Carbon Arcs

Carbon-arc sources were once widely used, but they have generally been replaced in projectors, spotlights, and searchlights by short-arc lamps. The arc is open, as in a welding arc and produces an emission rich in UVB and UVC as well as visible.

4.2.2.2 Welding Arcs

The largest number of personnel exposed to intense sources of optical radiation would be welders and their assistants. There are two broad categories of welding equipment – gas (acetylene) welding and electric-arc welding. The ultraviolet emission from a gas welding torch is quite small and is not considered a hazard. There are a variety of different arc welding and cutting processes and all vary in their UVR emission. Examples of welding processes include carbon-arc welding (CAW), shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and plasma arc welding (PAW). The most common shielding gases are argon, helium, and carbon dioxide. The irradiance depends on the type of process and the arc current. The structure in the spectrum is due to the metals involved and the shielding gases. In general, extremely high effective irradiances are calculated and full protection is required for the operators and nearby workers.

4.2.3 Medical Exposures

Medical exposures to UVR include phototherapy and photochemotherapy. In the treatment of psoriasis using either UVB or UVA plus psoralen, it is expected that the benefits for the patients will outweigh the risks associated with UVR exposures. Sometimes, as with the treatment of hyperbilirubinemia in newborn babies using blue light (usually 400–450 nm), UVR is a by-product of the lamp emission and must be eliminated by using specific plastic shielding that transmits the blue light but blocks the UVR below 400 nm (Gies and Roy, 1990). A more detailed discussion of medical exposures can be found in Moseley (1988).

4.2.4 Relative Exposure

The sources discussed above have quite different spectral emissions. A convenient way to illustrate the relative emissions is to calculate the time required to exceed the IRPA (1985) guidelines. The results of this analysis are given in Table 4.2. When the maximum allowed exposure time $T_{\max}$ is short, it is possible to easily exceed the ICNIRP limits in an 8-hour working day. Such sources are likely to be a UVR hazard and need to be controlled.

4.3 Short-Term Hazards to Skin and Eyes

The skin is composed of major tissue layers: the epidermis, dermis, and subcutaneous tissue. The epidermis is composed of:

- stratum corneum (8–16 μm thick) – 10–20 single-cell layers of dead keratinocytes
- stratum granulosum (3 μm)
- stratum malpighii (50–150 μm) – 10–20 cell layers of keratinocytes
- germinative layer (5–10 μm) – single-cell layer of basal cells that produce keratinocytes and melanocytes are also present, which produce melanin pigment granules.

Table 4.2 UVR hazards from various types of sources.

Lamp type	T_{max}
Fluorescent lighting	>8 h
Quartz halogen lamps	
No filter	10 min–5 h
Filter attached	>8 h
Standard lamps 1000 W (0.5 m)	20 min
Mercury discharge lamps	
UVC germicidal lamps	1–3 min
UVB sunlamps	30 s
UVA lamps	2–5 h
Sunlamps	3 min
Phototherapy lamps	
Filtered	7–400 h
Unfiltered	1 min–300 h
Blacklights	5–9 h
Arc lamps	
Xenon lamps (150 W)	5 h
Solar simulator	44 s
Deuterium lamps	6 min
Welding	1–5 min
Solar UVR	
Summer mid-latitude	6 min
Winter, mid-latitude	30–40 min

T_{max} is the time to exceed the IRPA (1985) UVR exposure guidelines.

The dermis (1–2 mm) – connective tissue, contains many capillaries, lymphatics, and nerves.

Skin: Penetration and interaction with dermis

For UVR to have an effect on skin, it must penetrate the different layers. Within each layer, a number of different processes may occur:

- reflection at the boundary
- scattering within the layer
- absorption that may lead to photochemical change
- transmission through the layer.

Skin is not very transparent to UVR. Some UVA may reach the subcutaneous tissues but generally UVR does not penetrate the dermis.

Table 4.3 Skin types and their response to solar UVR.

Skin type	Description and response to solar UVR	1 MED (J/m^2 erythemal)	Number of SEDs
I	Caucasian, fair skin, always burns easily, never tans	200	2
II	Caucasian, fair skin, usually burns easily, rarely tans	250	2.5
III	Caucasian, medium skin, burns rarely, tans gradually	300	3
IV	Caucasian, dark skin, burns rarely, tans readily	450	4.5
V	Middle Eastern, Indian, burns rarely, tans easily	600	6
VI	Dark-skinned, never burns, deeply pigmented	1000	10

Source: Adapted from Fitzpatrick (1988), JAMA Dermatology.

Tanning and erythema ("sunburn")

There are many factors affecting UVR-induced tanning and erythema, including:

- the source of radiation (in particular, the wavelengths of radiation involved)
- exposure conditions
- the skin (pigmentation, previous exposure, anatomical site, and the presence of sensitizing agent – see the following discussion).

Skin can be classified on the basis of its susceptibility to burn or its ability to tan following an exposure to UVR and this is given in Table 4.3. The MED is very skin type dependent. The use of the term SED provides a more meaningful concept of dose as it is independent of skin type. People with fair skin are much more susceptible to the effects of solar UVR and subsequent redness and sunburn than people with darker skin color and more melanin that helps absorb harmful UVR.

4.4 UVR Interaction with Biomolecules

UVR must be absorbed to produce a chemical change. Melanins are the major UVR absorbing entity in the skin, exhibiting a broad spectrum of absorption over the UVB, UVA, and visible ranges. There is some evidence that melanin may function as a photosensitizer of DNA damage.

The most important cellular target for UVR is DNA. Radiation in the UVB range is absorbed by DNA and leads to photochemical damage. Most of this damage is repaired by the cell; however, if the amount of damage is too great, some of the alterations to the DNA may remain as permanent mutations. DNA would certainly appear to be the primary entity and site of damage for most of the biological effects of short wavelength UVR. The peak absorption of DNA is dictated by its component nucleic acids and occurs at around 260 nm. There is a sharp drop in absorption through the UVB range and absorption is generally undetected at wavelengths much longer than 320 nm. DNA damage induced by UVB radiation is the key factor leading to sunlight-induced mutations in cancer-related genes and therefore in initiating the carcinogenic process.

4.4.1 Photosensitization

It has long been known that the presence in the skin of certain substances may result in an abnormally high reactivity to UVR. Chemical photosensitivity is often divided into phototoxicity (light-induced damage not dependent on an allergic reaction) and photoallergy (mediated by immunologic pathways). Common agents include antimicrobial agents (tetracyclines and sulfonamides), other drugs (phenothiazines and psoralens) and also sunscreens and cosmetics.

4.4.2 Psoralen Photochemotherapy (PUVA Therapy)

Psoralens have been extensively studied because of the beneficial effects of PUVA therapy. PUVA relates to the use of psoralen and UVA exposure. The therapy has been used for the treatment of a number of complaints including vitiligo, psoriasis, mycosis fungoides, and eczema. It has also been used to increase pigmentation. The primary mechanism is thought to be direct photochemical reaction of psoralen with DNA producing binding of psoralen and thymine and a subsequent inhibition of DNA synthesis.

4.5 Eye Transmission and Effects

The chronic exposure of the eye to solar UVR has long been suspected as a causative factor of cataracts, and a number of studies have attempted to demonstrate this. Research with rabbit and primate eyes has shown that acute exposures to UVR produce photokeratitis, temporary and permanent opacities (cataracts), and retinal injuries. UVR has also been shown to initiate photochemical changes in the eye.

UVR absorption processes in the eye show a marked wavelength dependence (Figure 4.6). The cornea absorbs strongly at wavelengths below 300 ran but has substantial transmission in the UVA. Absorption of UVB in the cornea produces short-term effects such as photokeratitis, which can occur at low exposure thresholds and become apparent within several hours of exposure. Damage is rarely permanent and discomfort usually disappears within 48 hours.

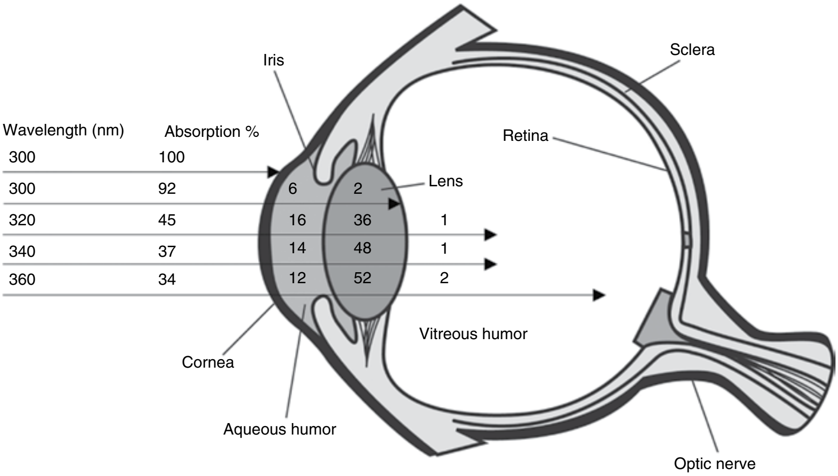


Figure 4.6 The spectral transmission of UVR through the eye. *Source:* Figures originates from Gies and Roy (1988) and is based on the data of Boettner and Wolter (1962).

The lens absorbs strongly at wavelengths between 320 and 400 nm. UVR damage to the lens is important in that lens cells, especially those in the nucleus have a very slow rate of repair. New tissue is continually added to the outside of the lens, but the interior tissues remain for the lifetime of the individual and any damage is therefore cumulative. Cataractogenesis in the lens results from high doses of UVR and develops very slowly. UVR damage to the retina is possible as approximately 1% of the UVA radiation incident on the eye reaches the retina.

Snow blindness or welder's flash: The absorption of UVB and UVC in the cornea and conjunctiva in sufficiently high doses will result in keratoconjunctivitis; a painful effect often called snow blindness or welder's flash. The initial effect of the exposure is damage to the outer epithelial cells of the cornea. Although painful, the damaged cells are generally replaced in 1–2 days. If the damage is deeper in the cornea, it can be permanent.

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5

Ultraviolet: Long-Term Risks and Benefits

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5.1 Hazards: General

The immediate hazards from UV exposure of the skin are erythema (reddening of the skin) and sunburn; and to the eyes, photokeratosis, such as snow blindness. These are discussed in Chapter 4. The action spectra for sunburn, cancer causation, and vitamin D production are very similar. Tanning is a protective response; immediate tanning results from oxidation of existing melanin, while tanning over a few days is due to the formation of new melanin, providing some protection against further UV damage. The action spectra show that there is no such thing as a safe tan; tanning results from exposure to carcinogenic UV.

Ultraviolet also causes skin aging or "photoaging", a loss of elasticity due to loss of interstitial collagens, showing as sagging cheeks, deeper facial wrinkles, and skin discoloration. UV also produces immunosuppression, which is likely important in the production of cancer and may also have other effects.

5.1.1 Hazards: Skin Cancers

Ultraviolet radiation was classified as a type 1 carcinogen (the most definite category) by the International Agency for Research on Cancer in 1992 (International Agency for Research on Cancer, 2012). UV directly damages DNA, characteristically forming pyrimidine dimers and other photoproducts. These affect several pathways that lead to carcinogenetic transformation of cells; also, UV induces immunosuppression and produces oxidative stress and DNA damage (Nishisgori, 2015). UVB (280–320 nm) is the most active, but UVA penetrates more deeply and also causes DNA damage. The peak of the action spectrum for the production of squamous cell carcinoma (SCC) in

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animals is at 293 nm; but the cancer-producing processes are complex and, for example, involve the production of reactive oxygen species, which are mainly produced by UVA. There are “signature mutations” in DNA that are characteristically produced by UV; these are a change from one pyrimidine (cytosine or thymine) to the other, a C–T or T–C transition, or the same with purines (guanine or adenine, G–A or A–G transitions). Such damage is normally repaired by DNA repair systems. In a rare genetic condition called xeroderma pigmentosum (XP), the DNA repair mechanisms are deficient and those affected need to be stringently protected from UV; otherwise, severe sunburn can occur soon after birth, and both keratinocyte cancers and melanomas can develop before 10 years of age (Balk and Section on Dermatology of American Academy of Pediatrics, 2011).

The most dangerous type of skin cancer, melanoma, arises in the pigment cells of the skin, the melanocytes. Other types of skin cancers are generally less serious but much more common; these arise in the keratinocytes that comprise about 95% of the cells of the epidermis, the common types being about 20–30% basal cell carcinoma (BCC), and about 70–80% SCC, these together being called nonmelanoma skin cancer, NMSC, or in more recent papers, keratinocyte cancers (Figure 5.1). There are many other rare types. SCC can be easily induced in experimental animals by UV, and there are some recently developed animal models for melanoma. All these skin cancers increase in incidence with age, with melanoma being more common in men than in women at ages above 50. These cancers are much more common in white-skinned people than in those with darker skin; more common in those who sunburn easily and tan poorly; and within white populations, are more common closer to the equator. Migrants to more sunny places, for example, moving from the United Kingdom to Australia, show the effects of early childhood exposures, with those moving before the age of 10 or 15 having much higher rates throughout life than those who migrated later. Thus, the highest incidence rates are in white populations living in sunny places, such as Australia, New Zealand, California, Hawaii, South Africa, and Zimbabwe and in some more unusual groups, for example, African people with albinism (a genetically controlled pigment deficiency) have about 1000 times the incidence of SCC as other Africans.

Ultraviolet causes almost all SCC and BCC and a high proportion of melanoma. There are also genetic factors involved and risks are increased in immunosuppressed patients such as transplant recipients and with some rare diseases. SCC and BCC are usually treated by surgical excision, a simple procedure except with larger lesions and those on difficult sites such as the face, where plastic surgery may be needed. Melanoma is usually detected when it is small and local excision is used, but this usually needs taking out the skin for 2–3 cm around the melanoma. However, if melanoma spreads (metastasizes) to lymph nodes and then to other parts of the body, further treatments are needed, and the disease may be fatal; overall, about 9% of melanoma patients die of their disease within 5 years after diagnosis.

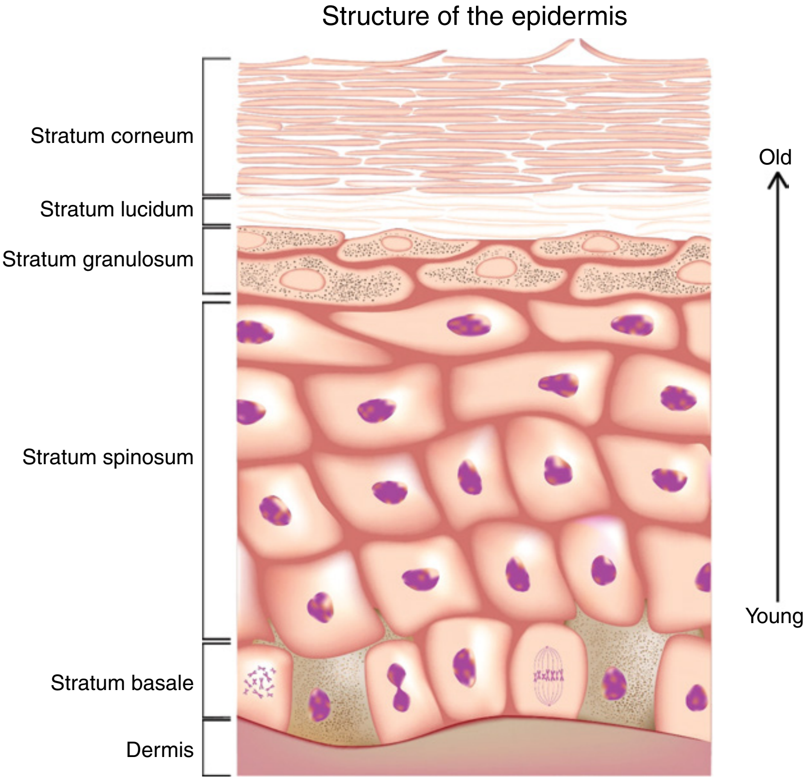


Figure 5.1 Structure of the epidermis. The keratinocytes start in the basal layer (stratum basale) and migrate toward the surface. The melanocytes are shown as colored cells in the basal layer: they produce melanin. Image from www.canstockphoto.com, with reproduction rights agreed.

The importance of sun exposure in melanoma was shown in large case–control studies, comparing representative series of people with recently diagnosed melanoma to unaffected subjects selected from the same communities, and using detailed face-to-face interviews to collect information on sun exposure and other features. Studies in Europe and Canada showed that intermittent-type exposure from recreational or holiday activities was more important than continued occupational exposure (Elwood and Jopson, 1997), while studies in Australia, with a higher intensity of UV, showed increased risks with both types of exposures. Childhood and adolescent exposure is particularly important. Incidence and death rates from melanoma have risen rapidly in white populations in most developed countries over the past few decades, stimulating educational campaigns to reduce excess sun exposure; there is now evidence that death rates are finally decreasing in adults under age 60 in high-risk countries such as Australia, although continuing to rise in older people whose experience as adolescents and young adults occurred before the attention being paid to reducing sun exposure.

SCC and BCC are the most common cancers in white populations, so common that they are not usually included in routine cancer statistics, and are among the most expensive cancers for health care systems. Based on a survey, the incidence of new treated NMSC in Australia in 2002 was more than five times the incidence of all other cancers combined (Staples et al., 2006). The estimated number of people treated for one or more NMSCs in Australia in 2008 was 434,000 (Cancer Council Australia, 2016), compared with about 11,000 cases of melanoma, with 70% being BCC. The cumulative risks to age 70 years of having at least one NMSC were 70% for men and 58% for women. People can have many lesions treated: so using Medicare data, the total number of NMSC treatments was over 700,000 in 2010, at a total cost of over \$500 million (Fransen et al., 2012).

In a recent analysis for Australia, 32% of all cancers (including melanoma but excluding keratinocyte cancers) were caused by modifiable factors, the most important being tobacco (13%), followed by a UV (6%), with dietary factors, obesity, infections, and many other causes each making a smaller contribution (Whiteman et al., 2015). Including keratinocyte cancers would make UV easily the most common identified and modifiable causal factor for cancer. In the United Kingdom, UV causes about 3.5% of cancers (excluding keratinocyte cancers), still a substantial factor. The US Surgeon-General issued a “call to action” on skin cancer in 2012 (U.S. Department of Health and Human Services, 2014), noting that each year in the United States nearly 5 million people are treated for all skin cancers combined, at an cost estimated at \$8.1 billion; with nearly 9000 deaths. Most of the costs are from keratinocyte cancers; most of the deaths are from melanoma.

How UV causes cancers is quite complicated. SCC has the most straightforward pattern, the risk being approximately dependent on lifetime cumulative exposure, being therefore more common in outdoor workers, and occurring most frequently on exposed body sites such as the face. Melanoma is more complex, and evidence suggests that at least two major pathways are involved, dependent on the individual’s propensity to develop nevi – the innocent pigmented spots common on the skin. The development of nevi is itself influenced by UV exposure and also by pigmentation and genetic factors. For individuals with many nevi, typically light-skinned Caucasians, further UV exposure acting on nevi produces melanoma particularly at intermittently sun-exposed sites such as the leg in women and the back in men, with the surrounding skin showing little solar damage. In people with a low propensity to nevi, more continuous sun exposure produces melanoma particularly at sun-exposed sites such as the face and neck, with the surrounding skin showing considerable solar damage (Whiteman, Pavan, and Bastian, 2011). This “divergent pathway” hypothesis explains many of the puzzling features of melanoma, for example, the higher rates per surface area of skin on partially exposed surfaces such as the back than on fully exposed sites such as the face, which has been a feature of the rapid increase in melanoma in recent decades in most white populations. Also, although research clearly indicates that long-term outdoor workers are at increased risk of BCC and SCC, they have no increased risk, or even a decreased risk of melanoma, in some studies, perhaps due to continuous exposure with consequent protection by tanning and skin thickening. However, short-term and new workers will not have this protection, and outdoor workers in UV-intense areas do appear to be at increased risk of melanoma, so outdoor workers need to be protected from the sun.

BCC has epidemiological features between those of SCC and melanoma, and its development may be more similar to that of melanoma.

5.1.2 Hazards: Effects on the Eyes

Acute exposure of the cornea to UV causes photokeratitis, such as snow blindness or welder's flash, discussed in Chapter 4. UV contributes to the development of cancer of the skin around the eye, corneal degenerative changes, and other conditions such as pterygium, known as surfer's eye. Normally, less than 1% of UV reaches the retina, but acute exposure such as looking at the sun during an eclipse can cause retinal burns (retinopathy). Melanoma can occur in the eye and is more common in those with light skin color, blonde hair, and blue eyes and is likely to be caused by UV. Melanoma of the eye is probably increased in welders. The most important effect of UV is the increased risk of cataracts, which are very common and a major cause of blindness in developing countries. Skin pigmentation does not protect against them, and they are a major problem in Australian aboriginal people, being more common closer to the equator.

5.2 Benefits: Vitamin D Synthesis

Vitamin D is essential for normal growth and skeletal development and its deficiency is shown most dramatically as rickets, a disease where children fail to develop normal bone strength. Ultraviolet converts 7-dehydrocholesterol in the skin to previtamin D_3 and then to vitamin D_3, which is then converted in the liver and kidneys to its active form, 1,25-dihydroxy vitamin D, also known as calcitriol. People with light-colored skin need only moderate UV exposure for adequate vitamin D production, so vitamin D deficiency has been noted in darker skinned individuals who have migrated to less sunny places such as the United Kingdom and also may tend to have little sun exposure. Vitamin D has dietary sources, such as oily fish and in some countries fortified milk and other products, but dietary vitamin D without supplementation is often limited. American pediatric authorities recommend that exclusively or partially breastfed infants should receive 400 international units (IU) per day

(10 mcg) of vitamin D from birth, and older children should take and vitamin D fortified milk or a 400 IU supplementary dose (Balk and Section on Dermatology of American Academy of Pediatrics, 2011).

In recent years, the potential benefits of vitamin D have received much attention, going well beyond the bone and joint effects. It has been claimed that increased vitamin D will prevent many cancers, heart disease, diabetes, autoimmune diseases, and many others and even reduce total mortality rates. Most of this work is based on observational studies, relating blood levels of 25-hydroxy vitamin D to disease outcomes in cohort or case–control studies. While many observational studies show lower disease risks associated with lower vitamin D levels, randomized trials of dietary supplements of vitamin D have generally shown only small effects or no clear effects, suggesting that the observational studies have not allowed for all confounding factors or that other factors produce both the diseases and, independently, the lower vitamin D levels. Thus, the potential benefits of increasing vitamin D by dietary supplements are uncertain, apart from its use with calcium in decreasing fractures in elderly people (Meyer, Holvik, and Lips, 2015). Increasing vitamin D by increasing sun exposure has to be weighed against the dangers of increasing skin cancers. In recent years, guidelines have been produced in countries such as Australia by experts in both skin cancer and vitamin D to present a balanced picture. The 2016 guideline (Cancer Council Australia, 2016) states that some protection to prevent skin cancer is required when the UV index is 3 or higher and that fairer skinned people can achieve adequate vitamin D levels by moderate exposure of the face, arms, and hands; however, in winter, more sunlight exposure is recommended to keep vitamin D levels, while people is naturally dark skin or of those who cover their skin for cultural reasons, and those who are confined indoors much of the time, may benefit from dietary vitamin D supplements.

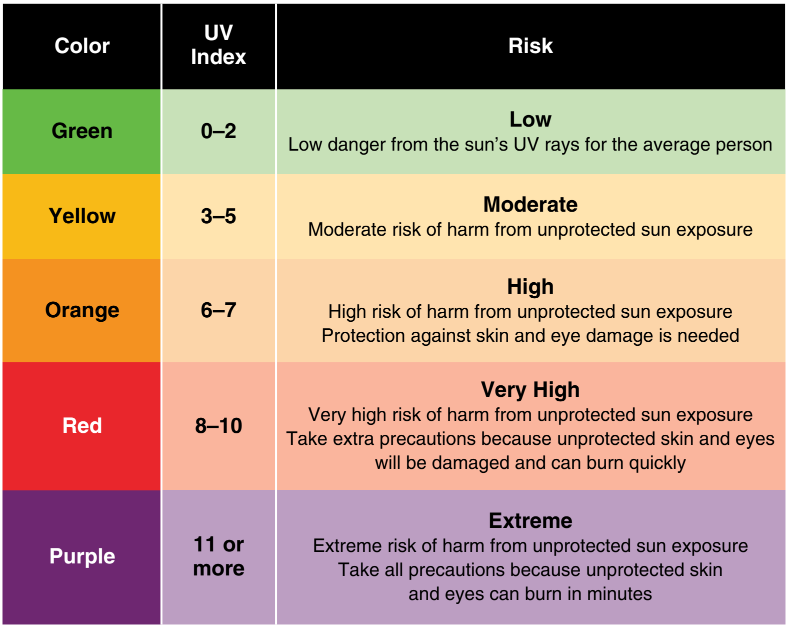
5.3 Reduction in Sun Exposure

Following the recognition of sun exposure as causing cancers, particularly melanoma, considerable preventive efforts have been undertaken in high-risk countries, particularly Australia. These have included programs in schools and workplaces, structural changes to increase the provision of shade in schools and public places, and educational campaigns such as "Sun Smart", with its message of:

- Slip (on a shirt, or clothing)
- Slop (on some sunscreen)
- Slap (on a hat)

now enhanced to

- Seek shade
- Slide on some sunglasses.



Color	UV Index	Risk
Green	0–2	**Low** Low danger from the sun's UV rays for the average person
Yellow	3–5	**Moderate** Moderate risk of harm from unprotected sun exposure
Orange	6–7	**High** High risk of harm from unprotected sun exposure Protection against skin and eye damage is needed
Red	8–10	**Very High** Very high risk of harm from unprotected sun exposure Take extra precautions because unprotected skin and eyes will be damaged and can burn quickly
Purple	11 or more	**Extreme** Extreme risk of harm from unprotected sun exposure Take all precautions because unprotected skin and eyes can burn in minutes

Figure 5.2 The UV index as used by the U.S. Environmental Protection Agency (U.S. Department of Health and Human Services, 2014).

Australian SunSmart programs are described further in Chapter 29. In parallel, sunscreens have been improved and assessed on the sun protection factor (SPF) scale, with an SPF 30 sunscreen blocking about 97% of UV if properly applied; although in practice, sunscreens are rarely applied optimally. Sunglasses can usually absorb over 97% of UV, and there are accepted standards for their manufacture, although these are voluntary. An internationally accepted standard for reporting UV exposure levels in weather forecasts, the UV index, has been developed. The index is defined as 40 times the erythemal solar UV in W/m^2, with a range of 0–12 (Figure 5.2). UV indexes are available through weather forecast services in most countries.

The evaluation of the effectiveness of sun exposure modification programmes is complex, and methods range from formal randomized trials of programmes for schools or work places, to community surveys (U.S. Department of Health and Human Services, 2014). Continued regular surveys have documented changes in population behavior in regard to sun exposure in Australia over many years (Dobbinson et al., 2013).

5.4 Control of Artificial Tanning

Australia banned commercial solariums marketing artificial tanning in 2015–2016 (Sinclair et al., 2014). Brazil also has a ban, and many other countries have partial bans, often for younger people, or have other limiting legislation. This is in response to concerns about risks of melanoma and other skin cancer; http://wiki.cancer.org.au. Epidemiological studies have shown that exposure to sunbeds increases the risk of both melanoma and NMSCs: a meta-analysis of 19 studies published before 2006 showed that ever-use of sunbeds increased melanoma risk, particularly if exposures were before 35 years of age. The most compelling evidence derives from a large cohort of Norwegian and Swedish women, which showed that melanoma risk increased regularly with increasing use of sunbeds (Dore and Chignol, 2012). An analysis of trends in Iceland, where sunbed use is high, showed increases in melanoma on the trunk of women younger than 50, suggesting an effect of sunbeds with a short latency period (Hery et al., 2010). An Australian survey of solariums found UVA emissions ranged from 98 to 438 W/m^2, more than six times the UVA content of mid-latitude summer sunshine (Gies et al., 2011).

Tutorial Problems

1 What are the three main skin cancers, and what cells do they originate in?

2 How common are skin cancers (all types) compared with other cancers?

3 Can cancer occur in the eye? Is it related to UV?

4 What is the main health benefit of UV exposure?

5 What does a UV index of 9 mean?

6 What are the two other Ss added to “Slip, Slop, Slap”?

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6

UV Guidelines and Protection Policies

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6.1 ICNIRP Guidelines and National Standards

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) produced guidelines on exposure to UVR in 2004 (ICNIRP, 2004). These guidelines are based on those of the American Congress of Governmental and Industrial Hygienists (ACGIH) brought out in the 1970s, which the International Radiation Protection Association's (IRPA) International Non-Ionizing Radiation Committee (IRPA/INIRC) adopted as guidelines in 1985 (IRPA/INIRC, 1985). The 2004 ICNIRP guidelines list exposure limits (ELs) for all of the different wavelengths of UVR that provide protection for both the skin and the eyes from acute effects of exposure. Subsequently, ICNIRP issued documents on protecting workers from Ultraviolet Radiation in 2007 and 2010 (ICNIRP, 2007, 2010). The ICNIRP spectral effectiveness, S_λ (see Figure 4.1), differs slightly from the International Lighting Commission (Commission International de l'Eclairage) CIE spectral effectiveness (CIE, 1998), which applies only to skin erythema. The ICNIRP effectiveness is for occupational UV exposures and applies to both the skin and the eyes.

Application of the ICNIRP (2004) guidelines allows quantification of the hazards associated with sources of UVR, in particular artificial sources and also for the Sun. For example, it is possible to calculate the biologically effective irradiance UVR_{eff} of a broadband source by using Eq. (6.1) with the ICNIRP (2004) spectral effectiveness curve for values of S_λ. The ICNIRP occupational EL is $30\,J/m^2$ in an 8-hour working day when weighted with the ICNIRP response.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

For determination of the erythemally effective irradiance of a broadband source weighted against the (CIE, 1998) erythemal spectral effectiveness curve, Eq. (6.1) can also be used with the CIE effectiveness for S_λ in Eq. (6.1); but in this case, the dose is 100 J/m^2 to relate it to standard erythemal doses (SEDs) (CIE, 1998). The relationship between SEDs and minimal erythemal doses (MEDs) is discussed in Chapter 4. In sunlight at a UV index 12, the occupational UV exposures limit $T_{\max}$ is exceeded in 6.6 minutes, while time to achieve erythema for people with fair skin (skin type 2 – see Chapter 4) is 11.1 minutes (a longer time period than the time to exceed to occupational EL $T_{\max}$, so an overexposure will not occur). At a UV index of 12, there are 10.8 SEDs in an hour (see Figure 4.4).

$$\mathrm{UVR_{eff}} = \sum_{\lambda_1}^{\lambda_2} E_\lambda \cdot S_\lambda \cdot \Delta_\lambda \tag{6.1}$$

where

$\mathrm{UVR_{eff}}$ = biologically effective irradiance in W/m^2, sometimes called “effective dose”
E_λ = spectral irradiance in W/m^2/nm
S_λ = relative spectral effectiveness (action spectra)
λ_1, λ_2 = are the lower and upper wavelength limits
Δ_λ = bandwidth in nanometers of the calculated or measurement intervals

The maximum allowed exposure dose of ICNIRP is 30 J/m^2 and the time to exceed this, called the maximum allowed exposure time $T_{\max}$, can be calculated using Eq. (6.2).

$$T_{\max}(\text{seconds}) = \frac{30\left(\mathrm{J/m^2}\right)}{\mathrm{UVR_{eff}}\left(\mathrm{W/m^2}\right)} \tag{6.2}$$

The more powerful the source of UVR, the higher is the effective irradiance $\mathrm{UVR_{eff}}$ and thus, the shorter will be the allowed exposure time. Exposure to UVR for a duration of less than $T_{\max}$ should not result in adverse short-term health effects. The UV index has been defined in a WHO publication (WHO, 2002) and generally has values ranging up to 12 or more depending on the location and the time of year. UV index values less than 3 are not considered hazardous and usually no protection is required, although recent evidence indicates that some cellular damage can occur (Rebel et al., 2005; Atillasoy et al., 1998; Byrne et al., 2002; Halliday and Lyons, 2008; Poon et al., 2005). Above a UV index of 3, protection is required and above a UV index of 8, extra protection is required (ICNIRP, 2012).

6.2 General Population versus Occupational Exposures

In a country like Australia, exposure of the general population to solar UVR during outdoor activities is high, whereas for European countries, the population will generally obtain most of their solar UVR exposures in an intermittent way during holidays to sunny places. Both situations can result in significant impacts regarding skin cancers in the populations. For Australia, the resultant nonmelanoma skin cancer (NMSC) burden is very large, with treatments increasing from 412,000 in 1997 to 767,000 in 2010 and costs of $511 million in 2010 rising to $730 million by 2015 (AIHW, 2008). In 2012, a worldwide systematic review of NMSC was carried out by bringing together 75 studies conducted over the past half century (Lomas et al., 2012) to look at geographical variations and trends of NMSC worldwide. Most of the studies focused on white populations in Europe, the United States, and Australia, but there was also limited data available for other skin types in regions such as Africa. The incidence for NMSC worldwide varies widely with the highest rates in Australia with more than 1000/100,000 person-years for basal cell carcinoma (BCC), while the lowest rates were in parts of Africa with less than 1/100,000 person-years for BCC. In England, the average incidence rates were 76.21/100,000 person-years for BCC and 22.65/100,000 person-years for squamous cell carcinoma (SCC), respectively. The incidence rates in the United Kingdom also appear to be increasing at a greater rate when compared with the rest of Europe (Lomas et al., 2012). The study concluded that NMSC is an increasing problem for health care services worldwide and called for prevention studies in this area and the issues caused by incomplete NMSC registrations in many countries.

Studies that have measured similar population groups (Diffey et al., 1996; Gies et al., 1998) found the UV exposures of primary schoolchildren in Australia and the United kingdom both followed a log normal distribution with UV exposures ranging from very low to very high depending on an individual's activities during the studies. For the Australian and UK groups, the mean of the log normal distributions for each group of students differed by a factor of 2, as did the measured ambient solar UVR at both locations, with Australia higher by a factor of 2. This difference of a factor of 2 was because the UK study took place in their summer and the Australian study took place in late spring and early summer (to avoid school holidays) when solar UVR was not at its maximum. This meant some school students in the United Kingdom at the higher end of UK UV exposures had higher UV exposures than some students in Australia, although overall the Australian students had higher UV exposures on average (see Figure 6.1; Diffey and Gies, 1998; Gies et al., 1998).

UVR exposures of the general population have also been measured in numerous studies, and these generally find that the UV exposures of any

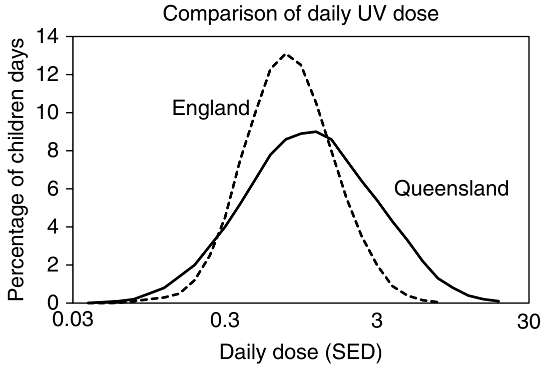

Figure 6.1 A comparison of the distributions of UV exposures for school children in Queensland compared to school children in England. The UV exposure distribution for the Queensland schoolchildren has its median centered, so it is approximately twice that of the UK schoolchildren, given that the UV exposure levels in Queensland were approximately twice those of the UK schoolchildren (Diffey and Gies, 1998; Gies et al., 1998). *Source:* Diffey and Gies (1998) and Gies et al. (1998). Reproduced with permission of Springer.

subject group are approximately proportional to ambient solar UVR (Herlihy et al., 1994; Neale et al., 2010).

6.3 Occupational Exposures to UVR

There are now numerous countries around the world that have in place basic legal requirements for occupational safety and health in workplaces and require the employer to do an assessment of risks in the workplace and design preventative measures and procedures. Occupational hazards may by physical hazards, chemical hazards, biological hazards, or radiation hazards. This last hazard, radiation, is also particularly the case with UVR exposures of workers, whether they are exposed to artificial sources of UVR at their workplace or to outdoor workers exposed to UVR in sunlight. Nowadays, most workplaces will have Workplace Policies covering the following:

- Risk management process
- Control prioritization
- Training and supervision
- Provision of information to employees
- Post incident exposure management

and this is also the case with radiation and in particular UV radiation.

As mentioned, the first UVR exposure standards were issued by the IRPA (IRPA/INIRC, 1985). Subsequently, a number of countries adopted these limits soon after, for example, in Australia (NHMRC RHS 29, 1989). Subsequently, the (ICNIRP, 2004) issued an occupational EL of a maximum personal dose of 30 J/m^2 of UVR, weighted against the ICNIRP spectral response and the spectral characteristics of the radiation emissions. Occupational exposure not only includes exposure to artificial sources of UVR but also applies to exposures of outdoor workers to solar UVR.

In 2002, the UK National Radiological Protection Bureau (NRPB, 2002 – now known as *Public Health England* or PHE) – issued a document on advice on UVR protection, where it was recommended that for artificial sources of UVR, which can be controlled, the ICNIRP ELs should apply. Given the uncontrolled nature of exposures to solar UVR, it was felt that strict application of ELs was impractical. However, they felt that it was important to limit the UVR exposures by using engineering and administrative controls and personal protective measures such as clothing, sunscreens, hats, and sunglasses.

In 2006, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA, 2006) produced a Radiation Protection Standard RPS 12 "Occupational Exposure to Ultraviolet Radiation," which applied UVR ELs to both artificial sources of UVR and solar UVR (ARPANSA RPS12). RPS12 also listed Employers duties and responsibilities as well as those of the workers and also introduced managing risk in occupational UVR exposures with a workplace policy and a risk management process and included control prioritization and training and supervision. Annex 3 of RPS 12 addressed protective measures including engineering and administrative controls, use of appropriate personal protective equipment (PPE), and training and supervision as well as a plan for post incident exposure management. Subsequently, the Australian Cancer Councils introduced a "Sample Sun Protection Policy for outdoor workers" which looked at controlling UVR exposures for outdoor workers. The Australian Safety and Compensation Council has a "Guidance Note for the Protection of Workers from the Ultraviolet radiation in Sunlight" (2008) that refers to RPS12. RPS 12 can be found at http://www.arpansa.gov.au/Publications/Codes/rps12.cfm.

In the United States, the National Institute for Occupational Safety and Health (NIOSH) has information on sun exposure (see http://www.cdc.gov/niosh/topics/sunexposure/). The American Industrial Hygiene Association also has a position statement on ultraviolet radiation (see https://www.aiha.org/…/PositionStatements/position06_UltravioletRaditation) as does the Canadian Centre for Occupational Health and Safety (see https://www.ccohs.ca/oshanswers/phys_agents/ultravioletradiation.html).

In Europe, many of the countries have authorities whose task is to enforce the basic legal requirements for occupational safety and health in workplaces and require the employer to do an assessment of risks in the workplace and design preventative measures and procedures (see the European Agency for Safety and Health at Work and their publication "New and emerging risks in Occupational Safety and Health" with a section on exposure to ultraviolet radiation).

6.4 Measured Occupational Exposures to UVR

One group of people who are definitely at risk from exposure to solar UVR is outdoor workers, and this is the case in numerous countries around the world. Measurement studies of UV exposures of outdoor workers around the world have generally found their UV exposures to be very high, certainly in comparison to other population groups due to the large amount of time spent outdoors exposed to the sun. In Denmark (Thieden et al., 2004), outdoor workers such as gardeners were found to have higher UV exposures (224 SEDs/year) than other population groups such as children (147 SEDs/year) and adolescents (189 SEDs/year) as well as for indoor workers (132 SEDs/year). A New Zealand study (Hammond, Reeder, and Gray, 2009) found that workers received 20% of total available daily ambient UVR. Studies measuring the UV exposures of outdoor workers in Australia have found substantial UV exposures. For example, a study that looked at the solar UVR exposures of three groups of outdoor workers on Australia's Sunshine Coast using UV-sensitive polysulfone (PS) badges (Gies et al., 1995) and found that the PE teachers, ground staff, and lifeguards received 36%, 27%, and 28% of available ambient solar UVR and estimated UV doses of 6–10 SEDs on unprotected skin. Subsequently, Gies and Wright (2003) looked at 493 workers doing 19 different occupations in the building and construction industry in Queensland, Australia. In this study, again using PS film badges, 90% of the outdoor workers had measured solar UVR exposures that were in excess of the occupational UVR EL, with 50% of the workers exceeding the occupational EL by more than four times. There was little use of higher-level controls evident in any of the workplaces visited. Even when a control was available, it was not used. Use of PPE was *ad hoc* with no planned approach to controlling the risk. The very high measured UVR exposures were especially alarming when considered together with the lack of controls for minimizing exposure and the skin types of the workers as assessed in this study. These results suggest that solar UVR exposure is not being taken seriously as a hazard in construction workplaces and that there is a significant risk to the health of outdoor workers in Queensland from occupational UVR exposure.

Numerous studies looking at outdoor workers in Europe and North America have also found significantly high UV exposures. Siani et al. (2011) found that during summer, vineyard workers received between 36% and 77% of ambient exposure on their backs and between 19% and 43% of ambient exposure on the arm. In addition, the results of the study indicate that both the arm and the neck of vineyard workers received regular UV doses in excess of the occupational threshold limit value (TLV) in all seasons. Serrano et al. (2009) looked at outdoor workers (gardeners and beach lifeguards) in Valencia, Spain, in June and July 2008, for a period of 4 and 6 days. The gardeners' mean UV exposure was 4.13 ± 0.60 SED day, whereas the lifeguards received 11.43 ± 2.15 SED day. The mean exposure ratio (ER) relative to ambient of gardeners was 9% and for lifeguards was 27% of ambient solar UVR, respectively. A study looking at the

UV exposures of mountaineers, tennis players, and runners (Serrano et al., 2011) took place in Valencia, Spain, from May to July 2010. The mountaineers received a mean daily UV exposure of 9.48 SEDs, the tennis players received a mean of 10.65 SEDs every 2 days, and the runners received 7.62 SEDs for every 5 days of training.

In the Australian state of Queensland, occupational exposure to UVR, whether from artificial or solar sources, is a risk that employers and self-employed persons are legally obliged to control. Outdoor workers are a group that receives regular and significant solar UVR exposures (Gies and Wright, 2003; Gies et al., 2009; Sianni et al., 2011). However, measures to help reduce the UVR exposures of outdoor workers using PPE such as hats, clothing, sunscreens, and sunglasses (often provided by employers) have not initially been well adopted in the building and construction industry. The Australian Tax Office (ATO) allows workers to claim a deduction for the cost of buying and cleaning occupation-specific clothing, protective clothing, and unique, distinctive uniforms. The ATO also allows workers to claim for clothing and footwear that they wear to protect themselves from the risk of illness or injury posed by their income-earning activities or the environment in which you are required to carry them out. To be considered protective, the items must provide a sufficient degree of protection against that risk. In particular, the protective clothing includes fire-resistant and sun protection clothing.

6.5 Awareness Campaigns

Awareness campaigns to alert the general population to the hazards of solar UVR have usually taken the form of urging the use of protective measures and awareness of when the UVR levels are high. In Australia, these “SunSmart” programs have been run by the state Cancer Councils (Dobbinson et al., 2008, 2013 and see Chapter 29) and they have been effective in raising awareness and promoting the use of personal UVR-protective items such as sun-protective clothing, hats, sunscreens, and sunglasses as well as beach tents and other shade structures and have even led to a decrease in melanoma mortality rates (see Chapter 29). The World Health Organization has also made considerable effort worldwide to raise awareness of the WHO’s UV index as a measure of the solar UVR levels to assist in promoting further changes to the population’s sun exposure behavior (WHO, 2002).

To put the size and scale of the issues into context, in terms of the whole world, the global burden of disease (GBD) due to skin conditions each year is 36.9 million DALY’s (disability adjusted life years) worldwide (ranked 18th) and 33.7 million YLD’s (years lost due to disability) for skin conditions (ranked fourth) worldwide (Hay et al., 2014). The NMSC disability combined BCC and SCC disabilities. BCC was considered to have negligible fatality, and disfigurement was the associated disability. SCC produced fatalities and was associated with disability due to cancer treatment, remission, and metastases. Deaths due to cancer were 8 million worldwide in 2010 and 38% higher than in 1990 (Lozano et al., 2012). Deaths due to malignant melanoma were 31.0 thousand worldwide in 1990 and 49.1 thousand in 2010, while nonmelanoma skin cancer deaths worldwide were 20.5 thousand in 1990 and 30.6 thousand in 2010 (Lozano et al., 2012), both significant increases.

Educational campaigns run by the various Australian state Cancer Councils have attempted to change the sun exposure behavior of the population and have had considerable success in raising awareness of the hazards and affecting behavior (Dobbinson et al., 2002; Dobbinson, 2008, 2014). Prevention campaigns in Australia have proved to be very cost-effective programs in which every dollar invested in SunSmart will return an estimated 2.3 times this amount (Shih et al., 2009).

6.6 Protection Measures

6.6.1 Sunscreens and SPF

Numerous countries around the world have had existing sunscreen standards for many years. Generally, these standards use the term sun protection factor (SPF) to denote the amount of protection provided by the sunscreen when it is applied at the recommended thickness. A sunscreen with an SPF of 30 would reduce the amount of solar UVR incident on the skin by a factor of 30 if applied at the same level as during when the sunscreen was tested. However, sunscreens should be used to reduce UVR exposures rather than extend the amount of time that can be spent outside. The SPF of sunscreens is usually measured by exposing human subjects with and without sunscreen to controlled amounts of artificially produced UVR from a solar simulator. Such testing under laboratory conditions rather than with sunlight is easier to control and provides reasonable correlation with sunlight exposures (e.g., AS/NZS 2604, 2012 – note that the standard is currently being updated). Factors that can affect the SPF of a sunscreen include the following:

- The thickness of application
- Method of application
- Concentration of the active components
- Whether the shelf life has expired and by how long
- Contact with water, sand, and sweat and the effect of toweling, and so on.

A number of studies around the world have shown that sunscreens are generally applied at about half to a third of their recommended application rates, which means that the sunscreens rarely attain their stated SPFs when used by the public compared to when they are tested by manufacturers at a thickness of 2 mg/cm^2 (Bech-Thomsen and Wulf, 1992; Wulf et al., 1997; Azurdia et al., 1999; Hart et al., 2000; Diffey and Taylor, 2004). This is because the amount of sunscreen that is applied is much less for the consumers, who generally apply amounts they feel comfortable with. An alternative that has been suggested is that consumers could purchase high SPF sunscreens (30+ or higher) and apply them at the levels they feel appropriate and yet still have SPFs of 15–20 (Diffey and Taylor, 2004).

6.6.2 Broad Spectrum Protection

Sunscreens are designed, primarily, to provide protection against sunburn and they do this by strongly absorbing UVB wavelengths. It is possible for sunscreens to achieve high SPF ratings by absorbing UVB strongly, while not absorbing much UVA. UVA, which penetrates deeply into the skin, has been implicated in melanoma risk and there has been considerable concern recently about UVA exposure. If sunscreens do not absorb UVA, that is, they are not broad spectrum, then people using such sunscreens can sustain very large exposures to UVA without getting sunburnt (Diffey, 2009). The implications of this for the development of skin cancer or melanoma, years later, are at this stage unknown but could be serious (Moan et al., 1999). The ideal form of sunscreen is one that absorbs all harmful wavelengths of UVR proportionally, from the UVB through to the UVA. In practice, however, this is more difficult to achieve.

Consequently, there have been efforts recently by standards organizations around the world to address the question of broad spectrum protection and to get sunscreens that provide better UVA absorption. There are a number of issues, including how the UVA absorption is to be reliably tested and how to inform the public about the test results. Standards currently use *in vivo* (irradiation of human volunteers) for UVB testing. However, using a similar test for UVA is difficult and an *in vitro* test method that provides consistent test results in the UVA has been developed: for example, the 2012 Australian and New Zealand Sunscreen Standard (AS/NZS 2604, 2012) introduced an *in vitro* test method to determine whether sunscreens provided broad spectrum protection including the UVA. The concept of a critical wavelength was introduced, where the critical wavelength is that where 90% of the cumulative area under the sunscreen total absorbance curve from 290 to 400 nm occurs. The higher the measured critical wavelength, the more UVA is blocked.

The 2012 sunscreen standard also introduced the concept of primary and secondary products, where a primary product is a sunscreen and a secondary product is defined as a product having a primary function other than sun protection while providing some protection of the skin from UVR.

6.6.3 Sun-Protective Clothing

Australia introduced the world's first standard on sun-protective clothing (AS/NZS 4399) in 1996. This standard covers both recreational wear and clothing for occupational purposes. Clothing for outdoor workers can be tested against this standard to ensure that it has a sufficiently high ultraviolet protection factor (UPF) (Gies et al., 1994) for use all days in the sun in Australia. For clothing, the effectiveness depends on the color, weave, design, condition, and type of material of the garment (CIE, 2006; Gies, 2007). Lightly colored and thin materials allow more UVR to pass through, as do wet or stretched materials. Sun-protective clothing has become the first line of defense against solar UVR exposures for young children at the beach. This is due to the fact that UVR exposures in early life are very important in the induction of skin cancer and melanoma in later life.

In 2012, ARPANSA initiated an update of the sun-protective clothing standard with the aim of reducing the number of protection categories, mainly due to measurement uncertainties above UPF 50 but also to restrict the claims of sun protection and UPF 50 to garments that provided body coverage such as sleeves for shirts and increased leg coverage for shorts. Given hats (Gies et al., 2006) are also tested for their UPFs, they were also introduced into the new standard, which is expected to be issued in 2017.

6.6.4 Sunglasses and Their Effectiveness

Sunglasses are used principally to reduce sunglare. In 1970, the first standard on sunglasses was introduced in Australia, and in 1985, this standard was made mandatory and to this date is still one of the few sunglass standards in the world that is mandatory. All sunglasses sold in Australia must comply with the standard and UVR protection provided by sunglasses is thus generally of a high order. This standard and subsequent standards introduced around the world require a range of sunglass characteristics to be tested. These include the spectral transmittance across the wavelength range from 280 nm in the UVR region through the visible and into the infra red region, the same spectral regions as present in sunlight. The ratio of transmittance in the UVR is compared to the visible to ensure that the eye is subjected to less solar UVR than if no sunglasses were worn. Also tested are various coloration limits, to ensure that the sunglasses do not affect visibility of traffic lights and brake lights if used while driving (color blindness is 8% in men and 0.4% in women – Spalding, 1999).

The latest sunglass standard (AS/NZS 1067, 2003) makes a clear distinction between sunglasses, which provide high levels of UVR protection as well as reduction of visible light, compared with fashion spectacles where the requirements are less demanding. Interestingly, while US and European standards for sunglasses set the upper UV wavelength limits at 380 nm, all three of the Southern Hemisphere Sunglass Standards (Australia, South Africa, and Brazil) set the upper UV wavelength limit at 400 nm (as defined by ICNIRP for the boundary between the UV region and the visible), in an effort to provide increased UVR protection (Masili et al., 2015) against the higher levels of solar UVR in the Southern Hemisphere (McKenzie et al., 1991; Gies et al., 2004).

Testing of sunglasses in the United States (Anderson and Gebel, 1977) found high transmittances in the UV part of the spectrum in comparison to the low transmittances in the central visible region, actually a disadvantage to the eye response, making the eye open wider to try and compensate for the low visible light levels and thereby letting in more UVR. The Australian sunglass standard was revised to exclude these types of sunglasses. Figure 6.2 shows the results of testing the optical transmittance requirements of some sunglasses in the 1980s, which lead to the standard being made mandatory in Australia in 1985, as well as some testing from the 1990s. Figure 6.3 shows recent testing, and all of these sunglasses comply with the standard. However, numerous sunglasses that were examined failed because the standard has a mandatory requirement that all sunglasses must indicate, either with a swing tag or a label which standard they comply with (e.g., AS/NZS 1067, 2003; sunglasses). If there is no label, they immediately fail. Testing in Australia of imported sunglasses from Europe has found up to 20% noncompliance with EN 1836, the European sunglass standard (Dain et al., 2010) with lens defects and excessive UV transmittance.

Eyewear used in industrial and occupational situations also provides high levels of protection but are covered by the industrial eyewear standard. In a Queensland study (Gies and Wright, 2003) looking at outdoor workers in the building industry, nearly 50% of workers wore wrap around sunglasses that gave excellent UVR protection. Even though the reason for wearing sunglasses

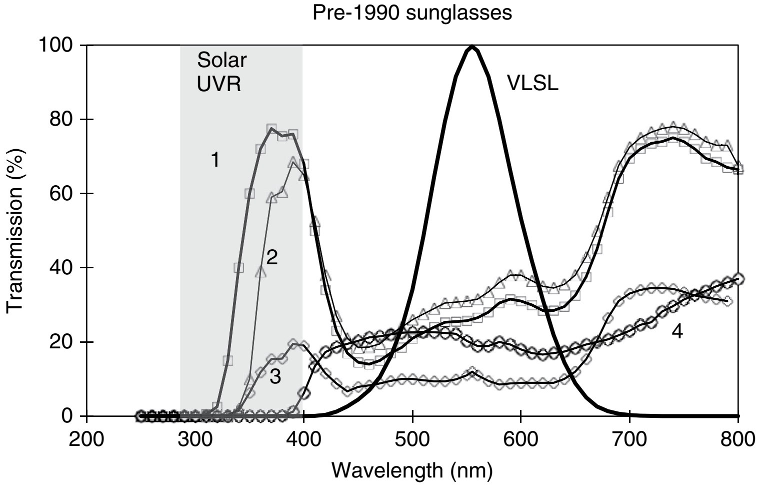

Figure 6.2 The spectral transmittance of four pre-1990 sunglasses as well as the eye response to visible light (VLSL). Sunglasses numbered 1, 2, and 3 all fail the UV transmittance requirements of AS/NZS Sunglasses and Fashion Spectacles because of their transmittance in the UVR region. Sunglass number 4 is the only pair of sunglasses shown that passes the standard.

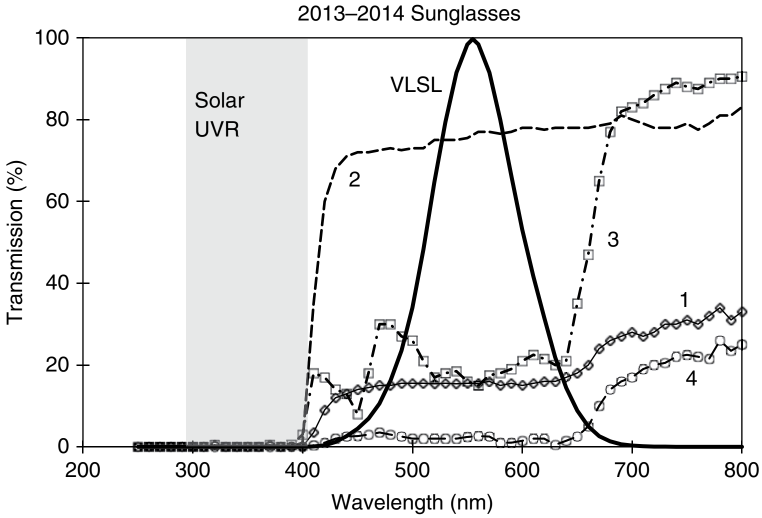

Figure 6.3 Sunglasses tested in 2013–2014 with only sunglass number 1 passing the mandatory Sunglass Standard AS/NZS 1067, while sunglass 2 transmits too much visible to qualify as a sunglass and sunglass 4 transmits too little to qualify.

is more likely to be to reduce the glare of visible light, protection from UVR exposure to the eyes also results.

6.6.5 Solaria Around the World

Solaria have been a worldwide health issue for a considerable time, as shown by the evidence from numerous research studies that link solaria to melanoma induction in solaria users. In 2007, the International Agency for Research on Cancer (IARC, 2007) reviewed the scientific literature and found first exposure to sunbeds before 35 years of age significantly increased the risk of melanoma, based on seven informative studies. The evidence does not support a protective effect of the use of sunbeds against damage to the skin from subsequent sun exposure. Young adults should be discouraged from using indoor tanning equipment and restricted access to sunbeds by minors should be strongly considered. In 2009, IARC raised the classification of the use of UV-emitting tanning devices from Group 2A to Group 1, “carcinogenic to humans” (IARC, 2009) (solar UV had been in the Group 1 category since 1992). Recently, Nilsen et al. (2016) summarized all of the published papers from around the world that have made measurements of the UV emissions from solaria. They found that compliance with irradiance limits was reported in nine studies. Erythema-weighted irradiances were highest in the most recent studies, and most studies had mean values higher than from natural sun and with large variations between devices (Nilsen et al., 2016). They also found that all studies except two had mean-unweighted UVB irradiances lower than from natural summer sun (at latitudes from 37°S to 35°N), while mean-unweighted UVA irradiances were, with one exception, substantially higher than from natural sun. The high values of UVA exposure from modern tanning devices were alarming in light of the increased focus on UVA irradiance as a carcinogen and as UVA exposure confers little protection against subsequent UV exposure (Nilsen et al., 2016).

Subsequently, two large studies looked at solarium use and melanoma. Lazovich et al. (2010) in a US study concluded as follows: "In a highly exposed population, frequent indoor tanning increased melanoma risk, regardless of age when indoor tanning began. Elevated risks were observed across devices." The same year Cust et al. (2011) did a study in Australia as part of the Australian Melanoma Family Study looking at young people and found that those who had ever used a sunbed and were diagnosed with melanoma between 18 and 29 years of age, three quarters (76%) of melanomas were attributable to sunbed use. Sunbed use is associated with increased risk of early-onset melanoma, with risk increasing with greater use, an earlier age at first use and for earlier onset of disease. Gordon et al. (2008) estimated the number of melanomas in Australia due to UV exposures in solaria at 281 and the number of deaths at 43 each year.

In November 2009, Brazil banned solaria (Resolution – RDC no. 56, dated November 9, 2009, which states "Prohibits, within the whole Brazilian territory, the use of artificial tanning devices, for cosmetic purposes, based on the emission of ultraviolet (UV) radiation.") Brazil was thus the first country to ban solaria, citing the publication from IARC (2009) that there was enough evidence that exposure to ultraviolet radiation is carcinogenic to humans.

6.6.6 Solaria in Australia

The Australian Solaria Standard AS/NZS 2635 (2008) provides for a maximum intensity of solaria of 0.9 W/m^2 of erythemally effective UVR (UV index of 36), down from the 1.5 W/m^2 (UV index of 60) of the 2002 Solaria Standard, when maximum typical values in sunlight in Australia are UV index 12! That is, the levels are now down to three times the intensity of solar radiation instead of five. The standard relied on solarium emission data gathered by ARPANSA and subsequently published as shown in Figure 6.4 (Gies et al., 2011). The standard does not allow the use of UVC emissions in solaria, nor the exposure of people with fair skin (skin phototype I – who cannot tan) to solaria. For repeat exposures, the standard requires at least 48 hours between exposures and such exposures cannot exceed three MEDs per week. The 2008 standard requires the use of protective goggles at all times. The standard prohibits the use of solaria by persons under the age of 18 and requires a signed and dated client consent form for all eligible users. The standard does not allow claims of noncosmetic health benefit of solaria to be used in their promotion. The standard requires supervision of users by trained operators at all times. To that end, ARPANSA developed an online training course so that solaria operators could

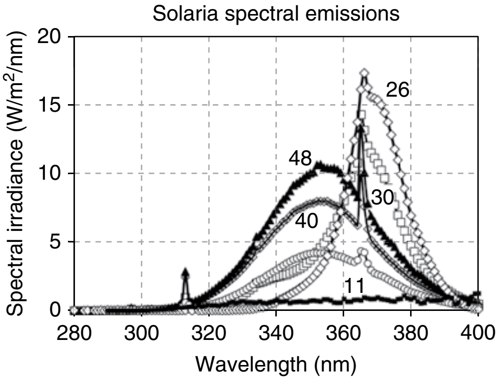

Figure 6.4 The spectral emissions from solaria in Australia, showing the various distributions versus wavelength. The solaria with higher emissions toward the UVB and lower wavelength UVA have the highest resulting UV index, which is shown near each of the respective spectral distribution curves.

receive training and education from an independent organization (rather than the solarium industry as had been the case in the past) and obtain a certificate to say they had successfully completed the course.

The relevant ARPANSA committee considered that the provisions of the standard should be presented in a manner that the standard could be implemented by persons without specialized technical knowledge of ultraviolet protection. A skin type chart showing photographs of people with different skin types and summarizing their responses to UVR is available on the ARPANSA web site at http://www.arpansa.gov.au/pubs/RadiationProtection/FitzpatrickSkinType.pdf.

Given the health effects of solaria, this committee was concerned about the findings of a survey of solarium operators by a state Department of Human Services in 2002. The department found that the level of awareness of and compliance with the standard by solarium operators was below acceptable levels. Subsequent surveys in another state initially found in 2009 that compliance by solaria operators was poor with over 200 noncompliances and in 2010 found some improvement with 41 of 73 solaria meeting the requirements. However, there were still many difficulties and noncompliances. While ARPANSA recommended that all solaria operators comply fully with the Australian/New Zealand Standard on Solaria for Cosmetic Purposes AS/NZS 2635, 2002, this was rarely the case. In addition to deaths due to solaria in Australia mentioned earlier, they are also associated with over 2500 new cases of SCC (Gordon et al., 2008).

Given the technical difficulties of measurement of solaria along with the example of Brazil banning them, all of the Australian states and territories decided to introduce bans on solaria at the beginning of 2015, a process which is now complete.

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7

UV Measurements

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Everybody is exposed to solar ultraviolet radiation (UVR) from the sun. In addition, an increasing number of the population are exposed to artificial sources of UVR that are used in industry, commerce, and in recreational and domestic situations. There is a clear link between exposure (both acute and chronic) to UVR and a range of adverse health effects.

For the general public, it is not possible to control exposure to solar UVR; however, programs to encourage appropriate outdoor behavior are important. However, for outdoor workers, a duty of care by employers requires that appropriate advice is provided and good protection measures are in place. Many companies have Workplace Health and Safety Requirements and Plans in place (see Chapter 6).

The measurement of UVR from either the sun or artificial sources requires extreme care. Measurement fundamentals are discussed briefly.

7.1 Radiometry and Spectroradiometry

Radiometry is the measurement of optical radiation for the purpose of characterizing a radiation source, a detecting system, or the optical properties of materials. Ultraviolet radiometry involves measurements, with relatively broad wavelength bands – typically 50–200 nm, within the wavelength range 200–400 nm in air. The types of measurement include the following:

- Irradiance – the flux density of radiation incident at a point in a particular plane, typical units: W/m^2, mW/cm^2.
- Radiance – the flux density per unit solid angle of radiation emitted at a point in a surface in a particular direction, typical units: $W/m^2/sr^1$.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

(Note: sr is the abbreviation for steradian and is the SI unit for solid angle as used in three-dimensional geometry and is comparable to the radian in 2D planar geometry.)

- Radiant response – the broadband spectral sensitivity of a detector.
- Transmittance and reflectance – ratios of transmitted or reflected radiation to broadband radiation incident on a material (dimensionless units) for a particular optical geometry.

Spectroradiometry is the measurement of the spectral concentration of source radiance or irradiance, that is, radiance or irradiance per unit wavelength interval. Spectral responsivity and spectral transmittance and reflectance are not measures of spectral concentration, but of the quantities, defined above, applying to a particular wavelength or narrow band of wavelengths. In spectroradiometry, the wavelength band is selected by a dispersing system (a monochromator) or narrow band filters, with a spectral bandwidth somewhere between some fraction of a nanometer up to about 10 nm, depending on the instrument and the resolution required. Ideally, the measurement should be made at wavelength intervals equal to the spectral bandwidth in order to include and weight equally all spectral components. If the property being measured varies smoothly and gradually with respect to wavelength, sampling at broader intervals is satisfactory and values at intermediate wavelengths can be interpolated if required. Typical units for spectral irradiance and spectral radiance are milliwatts per square centimeter per nanometer and milliwatts per square centimeter per nanometer per steradian, respectively. A typical spectroradiometric setup is shown in Figure 7.1.

The spectroradiometric system is made up of three basic elements:

- source with power supplies and electrical measuring equipment;
- monochromator, with optical coupling to the source (sun and lamps) and detector;
- detector, with power supply, electronics for measuring detector output quantity and recording equipment.

Normally, the measurement process involves the comparison of the test source with a standard source (usually a tungsten filament lamp) having a known spectral power distribution. In all cases, the exact conditions of calibration must be stated so that they can be reproduced when the source is operated on subsequent occasions.

In the case of irradiance, the quantity to be measured is the radiation from the source in a given direction reaching an area at a specified distance. When an absolute measurement is required, it is essential to define exactly the distance from the source to the plane of the irradiated surface. It is preferable to accept radiation from the whole of the source area, although with large sources, a mask might be used to isolate a representative sample in order to prevent light entering the spectroradiometer at large off-axis angles.

To reduce errors due to the nonlinearity of the measuring system, the signals from the test source and the standard should be as nearly equal as possible. To this end, the distances of the two sources may be adjusted appropriately. Where sources having dissimilar spectra as, for example, a fluorescent and a tungsten lamp are to be compared, then there are bound to be considerable, unavoidable differences in the signal levels in some regions of the spectrum and the demands on the linearity of the system are correspondingly greater.

In the case of irradiance measurement, direct irradiance of the entrance slit of the monochromator by the sources is best avoided because of the resultant variation in the irradiance distribution in the monochromator and also over the photocathode of the detector. The use of a transmitting diffuser in front of the slit is unlikely to solve the problem and cannot be recommended. The degree of diffusion produced varies with wavelength and is, in many cases, almost zero at the red end of the spectrum.

The most accurate methods of spectral irradiance measurement use an integrating sphere before the entrance slit of the monochromator (see Figure 7.1). An entrance aperture is located on the sphere wall at 90° to the optical axis of the monochromator. The sphere may conveniently be rotated about a diametrical axis coincident with the optical axis of the monochromator into the two symmetrical positions where the entrance aperture is in a vertical plane. In one position, radiation from a standard source may enter the aperture, in the other

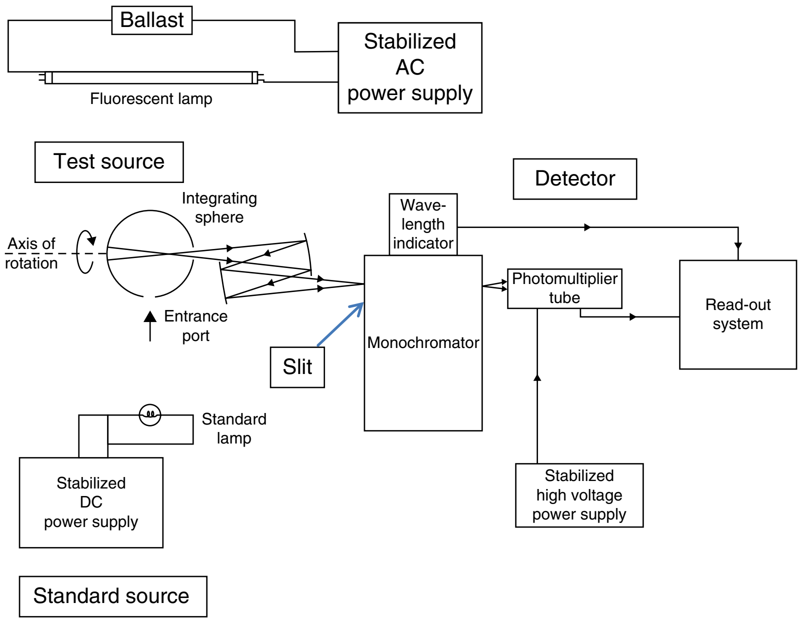

Figure 7.1 Typical spectroradiometric setup including a light source to be evaluated (a fluorescent lamp in this case).

radiation from the test source. Alternatively, the sphere may be fixed in position and the sources moved so as to permit first one and then the other to irradiate the entrance port. It should be noted that perfect diffusion is not always essential, although it is important that radiation from both sources is treated in a similar manner. This condition is more difficult to satisfy when the sources to be compared differ markedly in size or shape. The directly irradiated area of the sphere wall should preferably be identical for the test and standard sources, but where this cannot be achieved, it will normally be sufficient to ensure that the area of the sphere surface seen by the monochromator does not overlap the areas directly irradiated by either source. That is, radiation should enter the monochromator only after undergoing two or more reflections. Care should be taken to ensure that excessive stray radiation is not introduced by overfilling the monochromator with radiation from the sphere. Adequate screening must be provided to prevent radiation from sources other than the one being measured entering the sphere.

7.1.1 Band Radiometry

The irradiance from a source within a particular band bounded by wavelength limits λ_1 and λ_2 is equal to the integral of the spectral irradiances over this wavelength range.

$$E_{\lambda_1,\lambda_2} = \int_{\lambda_1}^{\lambda_2} E_\lambda \, d\lambda \tag{7.1}$$

As no practical radiometer can be made with response matching precisely a particular wavelength distribution, a compromise must be made between adequate band coverage and the detection of some out-of-band radiation. With the provision of adequate spectral data for both source and detector, reasonably accurate field measurements of irradiance for various spectral bands are possible.

If a given radiometer gives an output represented by S_{λ_n} spectral responsivity units per unit irradiance at wavelength λ_n ($W^{-1} m^2$), then for monochromatic radiation at that wavelength, the reading R and irradiance E will be related by

$$R = E \cdot S_{\lambda_n} \tag{7.2}$$

If the irradiances form a continuum between wavelengths λ_1 and λ_2 within which the spectral irradiances (i.e., irradiance per unit bandwidth) are represented by E_λ then the emission band may be divided into small intervals, $\Delta\lambda$ and the radiometer reading is given by the sum

$$R = \sum_{\lambda_1}^{\lambda_2} E_\lambda \cdot S_{\lambda_n} \cdot S(\lambda) \cdot \Delta\lambda \tag{7.3}$$

The radiometer calibration usually required is a relationship between display readings and the source irradiance for a particular rectangular wavelength band. The responsivity, S, for the band bounded by wavelength limits λ_1 and λ_2 will be given by

$$S = R / \int_{\lambda_1}^{\lambda_2} E_\lambda \, d\lambda \tag{7.4}$$

A correction multiplying factor S, to be applied to the radiometer spectral responsivity at the wavelength λ_n to give the response to a broad wavelength range λ_1 to λ_2 of radiation from a particular type of source, can more practically be obtained from the following ratio of two summations:

$$S = S_{\lambda_n} \, \Sigma E(\lambda) \cdot S(\lambda) \cdot \Delta\lambda / \sum_{\lambda_1}^{\lambda_2} E(\lambda) \cdot \Delta\lambda \tag{7.5}$$

7.1.2 UVR Measurements

When making and interpreting UVR measurements, there are important factors that need to be taken into account:

- the UVR source and in particular the dimensions and spectral power distribution;
- the detection system including the input optics, the dispersing optics (if present), and the full characteristics of the detector;
- the biological or physical effect being evaluated including the action spectrum and dose effect.

Most detectors in general use are based on the photoelectric effect, which is the direct conversion of UVR into an electric current. The detector must meet a number of important criteria including the following:

- a linear or known response;
- a stable and low dark current;
- a uniform response over its surface;
- suitable response time for the source being evaluated;
- a known spectral responsivity.

For spectral measurements where low levels of UVR are measured, it is necessary to have a high gain detector, and hence, the most common detector is the photomultiplier tube (PMT). The PMT consists of a photocathode in which incident radiation is converted into a current, which is then amplified through a series of electrodes (or dynodes) each of which is at a progressively higher potential. The wavelength response is determined by the composition of the cathode and the tube window. For the measurement of UVR, a quartz window is required. PMTs are approximately 10^5 times more sensitive than photodiodes and have a gain between 10^5 and 10^8.

Photodiodes are used when broadband measurements are being made, these are often incorporated into portable detectors for field measurements. In general, more radiation is being measured so the detector can be less sensitive. Vacuum photodiodes are often used in the UVB region and have similar spectral responsivities to PMTs. The photodiode consists of a photocathode and anode – a bias voltage of about 50 V is applied across the diode. UVR incident on the cathode results in the emission of electrons that are collected at the anode. For broadband measurements in the UVA region, it is also possible to use a silicon photodiode. This is a solid-state device in which a voltage is generated across a PN junction when exposed to UVR.

7.2 Solar UVR

If it is assumed that the sun radiates as a blackbody, it can be calculated that the effective temperature of its surface is approximately 6000 °K. As the temperature of the blackbody, in this case the sun, increases the peak wavelength shifts to shorter wavelengths (Wiens displacement law) and appreciable UVR is emitted. The extraterrestrial solar radiation (solar constant) is approximately 1351 W/m^2 of which about 900 W/m^2 reaches the earth's surface. About 45 W/m^2 is UVA and 2 W/m^2 is UVB. Typical solar UVR spectral irradiances are shown in Figure 7.2 for different solar zenith angles (SZA). The smaller the SZA the higher the sun is in the sky, the greater is the total UVR and the relative amount of UVB.

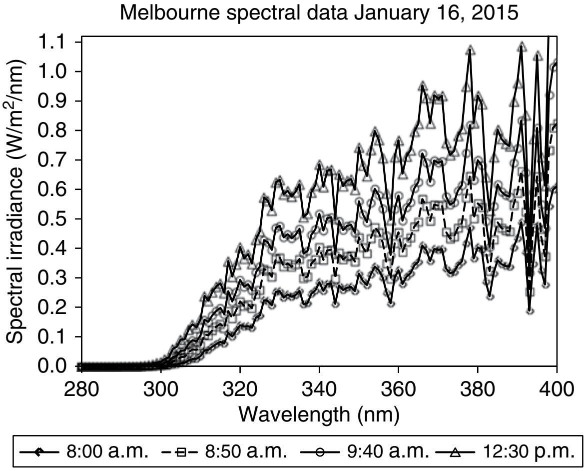

Figure 7.2 Solar UVR spectral irradiance at the earth's surface for different solar zenith angles and different times of the day.

7.3 Solar UVR Broadband Measurements

The establishment of a solar UVR measurement network using spectroradiometer systems is an expensive operation. In a number of countries, broadband instruments such as the Solar Light 501 UV-Biometer (Figure 7.3) are used for continuous monitoring of erythemally weighted solar UVR. Details of the Solar Light UV Biometer can be found at the following link: http://solarlight.com/header/uvb-biometer-model-501-radiometer/.

The principle of UV Biometer UVR measurement is as follows. The solar radiation passes through the input filter, and this eliminates the visible component. Then the partially filtered light, containing the whole UVR spectrum excites the phosphor. The visible light emitted by the phosphor is detected by the GaAs diode. The diode and the phosphor are contained in a metal enclosure that is thermostated by the Peltier element. The current produced by the GaAs diode is amplified and converted to frequency inside the detector. The temperature of the detector is converted to frequency also. The frequency signal from the detector is transmitted to the recorder. The biometer needs regular calibration against a traceable absolute spectral irradiance reference to

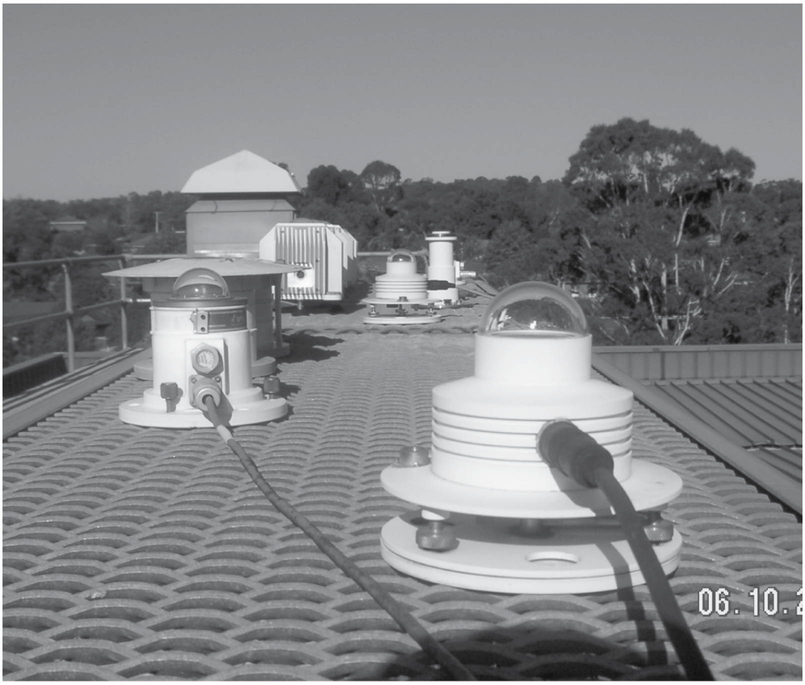

Figure 7.3 Solar Light 501 UV-Biometers on the roof of the ARPANSA Laboratory for calibration.

account for the difference between the detector spectral response and the theoretical CIE erythemal effectiveness spectrum (CIE, 1998).

Solar Light biometers are used in numerous UV monitoring networks around the world including the ARPANSA UV network in Australia (Melbourne, Canberra, Sydney, Brisbane, Townsville, Adelaide, Hobart, Alice Springs, Darwin, Perth, and Townsville) and the Antarctic (Casey, Davis, and Mawson stations + Macquarie Island), where the UV data is updated every minute. South Africa also has a number of stations run by the Weather Service to monitor ambient solar erythemal UVR levels at six stations in South Africa: Pretoria, Durban, Cape Town, Cape Point, De Aar, and Port Elizabeth (Wright et al., 2013). Cape Point and Durban have Solar Light UV Biometers. The Cape Point Laboratory is part of the World Meteorological Organization's Global Atmosphere Watch network of stations to monitor the chemical composition of the Earth's atmosphere.

7.4 Solar UVR Spectral Measurements

Spectral measurements of solar UVR are made at numerous countries and locations around the world.

7.4.1 Europe

Europe has many spectral systems operational and an overview paper (Seckmeyer et al., 2008) presented solar UV data from 28 locations across Europe ranging in latitude from 32.6°N (Portugal) to 69.3°N (Norway) and in longitude from −16.9°E to +26.6°E. Monthly mean erythemally weighted doses ranged from 1395 J/m^2 (13.95 SEDs) in Norway to 4566 J/m^2 (45.66 SEDs) in Italy (see Table 4.3).

7.4.2 North America

In Canada, there are 14 sites that operate Canadian designed Brewer spectrophotometers (see http://exp-studies.tor.ec.gc.ca/e/ozone/ozonecanada.htm) operated by Environment Canada. Long-term decline in column ozone over northern midlatitudes is about 2% in summer and 4% in winter-spring, yielding a 2.5% and 5% increase in UV index, respectively (Fioletov, Kerr, and Fergusson, 2010). Long-term changes in cloud cover can also affect UV index values. In the United States, there are two spectral systems provided under contract by the New Zealand National Institute of Water and Atmospheres (NIWA), one at Boulder, Colorado (40.015°N, 105.27°W, 1655 m) and the other at Mauno Loa (19.47°N, 155.59°W, 4169 m) in Hawaii.

7.4.3 South America

Zaratti et al. (2014) used a spectral system (Brewer Spectrophotometer at the Laboratory for Atmospheric Physics (LFA-UMSA), La Paz Bolivia (16.5°S, 68.1°W, alt: 3420 m a.s.l.)) to measure cumulative distribution of peak daily UVI values showing that the UVI daily maximum exceeds 10 in 2 days out of every 3. UVI measurements were available on 95% of the days. They argued strongly for the UV index scale to be modified from that introduced at the two previous UV index meetings organized by ICNIRP and WHO (McKinlay A, 2006; Allinson S et al., 2011) both held in Europe where levels rarely exceed UV index 6 to 8. Also in South America, Corrêa (2015) presented solar UVR measurements from three locations in Brazil, Ilhéus (14.79°S, 39.05°W), Itajubá (22.42°S, 45.46°W), and São Paulo (23.55°S, 46.63°W). In 5% of these measurements, the cumulative solar UVR doses surpass 6000 J/m^2 or 60 SEDs per day. These levels are similar to those measured in Australia (Gies et al., 2004) and South Africa (Wright et al., 2013).

7.4.4 New Zealand

The National Institute of Water and Atmosphere (NIWA) in New Zealand has spectral measurements systems that accurately measure the incoming solar spectral irradiance. Their systems have been in operation for many years and have been utilized by a number of overseas organizations including NOAA/ESRL Global Monitoring, Boulder, Colorado, USA, Research Center for Advanced Science and Technology, University of Tokyo, Japan, and the Bureau of Meteorology in Australia, with NIWA systems in place in Boulder, Colorado, USA (40.0°N, 1650 m altitude); Tokyo, Japan (35.7°N 57 m altitude); Mauna Loa Observatory, Hawaii, USA (19.5°N 3400 m altitude); and Lauder, New Zealand (45.05°S, 169.67°E, 370 m altitude). NIWA spectral systems are also used by the Australian Bureau of Meteorology at Darwin (12.4°N, 130.844°E) and Melbourne (−37.81°N, 144.96°E).

7.4.5 Australia

As well as its broadband network covering the major population centers in Australia, ARPANSA runs a Bentham DTM 300 spectral system on the roof of its Melbourne Laboratory making spectral measurements of solar UVR and providing calibrations for the Solar Light Biometers that are placed in the Australian capital cities to measure solar UVR levels there. The Bentham spectroradiometer also made the spectral measurements shown in Figure 7.2.

7.4.6 South Africa

South Africa has a Bentham DTM-300F UV spectrometer at Saint Denis, Reunion Island (20.9°S, 55.5°E), in the Observatory of Atmospheric Physics to measure ambient solar UVR levels (Wright et al., 2013). The input optics are a Teflon diffuser under a quartz dome with an optical fiber connecting the optics to the monochromator. The instrument is regularly calibrated with a reference lamp traceable to NIST (National Institute of Standards and Technology) in the United States.

7.5 Personal Dosimetry

In order to determine appropriate protection practices against UVR, it is often necessary to have detailed information on the actual UVR exposure of people and personnel. Measurement programs provide information on the level of UVR received on a horizontal surface, but in order to accurately assess personal exposure, it is necessary to get people to wear some form of UV dosimeter, worn at specific location such as the wrist or at various other anatomical sites. In this way, the UV exposures at those sites can be determined and quantified.

7.5.1 Film Dosimeters

One of the earliest forms of dosimetry of UVR was polysulfone (PS) film, where PS badges have been used in a numerous to studies to quantify the solar UVR exposure received by different subjects undertaking various activities (Diffey and Gies, 1998; Gies et al., 1995, 1998, 2009; Herlihy et al., 1994). PS undergoes a change in absorbance following exposure to UVR, and the response curve, shown in Figure 7.4, can be used to quantify the exposure of a badge worn by a subject. Care needs to be taken with exposures of PS badges as at very high levels of solar UVR, the badges can saturate if left exposed for too long, that is, into the flat part of the PS dose–response curve at absorbances of greater than 0.6 as shown in Figure 7.6. Shoulder and chest badges indicate that unprotected outdoor workers in Queensland can receive up to 20% of the daily total

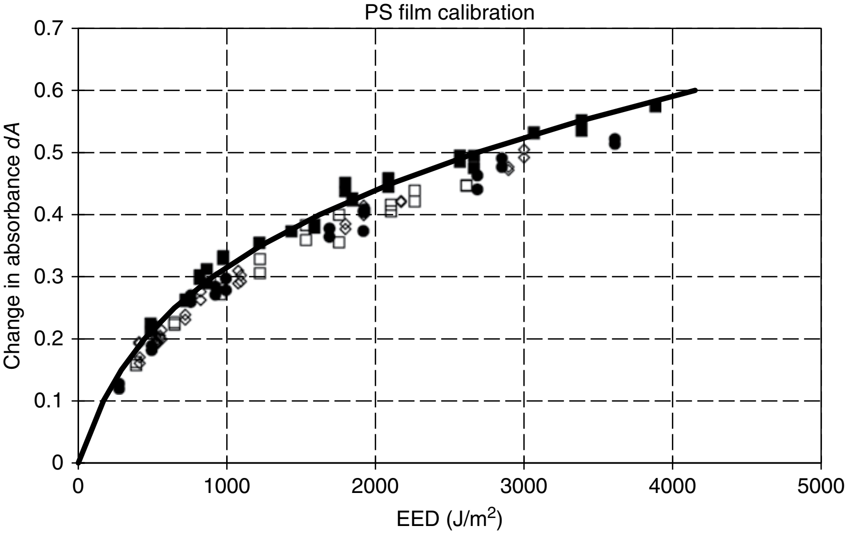

Figure 7.4 The dose–response curve of polysulfone film showing the change in absorbance as a function of the erythemal effective dose (EED).

ambient UVR (Gies and Wright, 2003). One of the advantages of PS film dosimeters is that individual PS badges are not very expensive and if some are lost by study participants, the cost of the losses are not substantial. However, if a study uses electronic UV dosimeters and these are lost or damaged, the costs can be quite substantial.

7.5.2 Electronic Dosimeters

Over the past 10 years or so, small electronic dosimeters that can be worn by subjects in order to measure their solar UVR exposures while outdoors have become available (Figure 7.5). These measure both the incident UVR and the time when it was received and in this way build up a picture of when a particular subject receives most of their solar UVR. The dosimeters can run for days or weeks depending on their memory allocation and the frequency of the measurements, for example, every 10 seconds or every minute or every 5 minutes, depending on how detailed the researchers are trying to be.

A number of different types of UV sensors have been utilized. Thieden, Philipsen, and Wulf (2006) used a "SunSaver" to measure the UV exposures in a number of studies. This unit has a silicon carbide photodiode which only responds in the wavelength range 200–400 nm. The sensor has a built-in diffuser and has a cosine response as well as a spectral response that is similar to the CIE erythema action spectrum. The data logger controls the sensor which was set to measure at every 8 seconds and to store an average of the last 75 measurements every 10 minutes along with the time. The measurement range of the dosimeter is 0.1–23 SED hours. The UV dosimeter has battery and can run for 145 days without maintenance, and the data can be downloaded to a personal computer.

Other electronic UV dosimeters have been developed in New Zealand and Germany. The New Zealand electronic UV dosimeters were developed by Scienterra Ltd and have been utilized for a number of studies of UV exposures of different groups of subjects (Allen and McKenzie, 2005; Sherman, 2014). A number of these UV dosimeters are shown being tested on the roof of the ARPANSA Laboratory in Figure 7.5.

An overview paper (Wright and Reeder, 2005) looked at youth UV exposure and found measurement duration and unit of UV exposure varied in most studies, but a method common to 15 UV exposure studies was found to be measured UV exposure as a percentage of ambient UV (Figure 7.6).

One advantage of electronic UV dosimeters is that they provide detailed UV exposure data for individual subjects, and in many cases, clear patterns of exposure can be seen. Figure 7.7 shows the UV exposures of a worker at an alpine ski field in Australia in spring, part of a study carried out by ARPANSA and the Cancer Council Victoria. In this case, the exposures are occupational, so the pattern is determined by work requirements and also by how much sun there is each day, which at the ski fields can vary dramatically with the weather.

Figure 7.5 A WMC GmbH electronic UV dosimeter that can be worn on the wrist or the lapel.

Figure 7.6 A large batch of personal UV Dosimeters on the roof of the ARPANSA Laboratory undergoing calibration against the calibrated ARPANSA traceable Bentham spectral system.

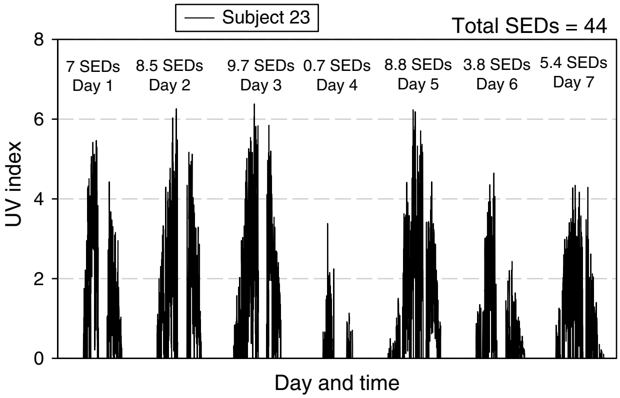

Figure 7.7 Measurement results for a subject that wore an electronic UV dosimeter while working at the ski fields in Australia in winter. The UV doses vary slightly from day to day depending on the levels of ambient solar UVR. The regular breaks for lunch inside are also clearly evident.

The worker obviously had a substantial break for lunch on most but not all days and went inside where there was no ambient solar UVR as shown by the gaps with zero UV readings.

7.6 Chemical Dosimeters

Chemical dosimeters have also been used to measure solar UVR. A new UV dosimeter (Mills, Grosshans, and McFarlane, 2009) made up of a tetrazolium dye, neotetrazolium chloride (NTC), which had been dissolved in a film of polymer, polyvinyl alcohol (PVA), was detailed. The dosimeter is pale yellow/colorless in the absence of UV light but upon exposure to UVR turns red. This chapter provides details of the spectral characteristics of a typical UV dosimeter film as well as the mechanism through which the color change occurs. The dosimeter also has a response that is independent of temperature over the range 20–40 °C. The UV dosimeter also exhibits a cosine-like response dependence on irradiance angle. The NTC UV dosimeter films exhibit a response to UV that is related to the intensity and duration of UV exposure as well as the amount of dye present in the films and the film thickness. A layer of a UV-screening compound which slows the rate at which the dosimeter responds to UVR enables the dosimeter response to be tailored to different UV doses. The dosimeters provide a direct indication that solar UV levels are high, which is useful for people wanting to reduce exposures. However, the dosimeters almost certainly respond to UVA as well as UVB, so the color change is probably not a good indicator of the hazard.

7.7 Biological Dosimeters

Given the difficulties that some electronic dosimeters have with water proofing and the intense cold in the Arctic and Antarctic, other dosimeter types have been utilized there. Cockel et al. (2001) used biofilm UV dosimeters developed by the German Aerospace Centre (Deutsche Lebens Raum or DLR Centrum) in Germany to measure UV exposure of Arctic and Antarctic expeditioners at the Haughton impact structure in the Canadian high Arctic (75°N) and the Rothera Station (UK) (67°S) in the Antarctic. The mean exposure ratio in the Antarctic was 0.20 ± 0.09, while in the Arctic, it was 0.27 ± 0.09. The exposure ratios can be used to translate measurements of incoming solar UV radiation onto a horizontal surface into estimates of the mean exposures expected in populations at polar latitudes.

As solar UV radiation has harmful effects on the DNA molecule, it was not surprising that the development of a reliable biological monitoring system based on using elements of DNA to quantify the harmful effect of exposure to UV radiation was developed by Schuch et al. They based their system on the exposure of plasmid DNA to artificial UV lamps and sunlight. Their results confirmed the genotoxic potential of sunlight and revealed that UVA may also produce changes directly in naked DNA. Schuch et al. (2009) went on to demonstrate the applicability of a DNA-dosimeter system for monitoring the biological effects of solar-UV radiation.

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Part III

Visible and Infrared (IR) Light

8

Laser and Visible Radiation Hazards to the Eye and Skin

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8.1 Intense Sources of Optical Radiation

The ultraviolet (UV), visible, and infrared parts of the electromagnetic spectrum are termed *optical light*. The different wavelength regions are demonstrated in Figure 8.1.

The UV wavelength region extends from below 100 nm to around 400 nm. This region is subdivided into three subregions, UVC (100–280 nm), UVB (280–315 nm) and UVA (315–400 nm), as shown in Figure 8.1. Light below approximately 180 nm is strongly absorbed in air and is therefore called vacuum ultraviolet (VUV) radiation. Because of its strong absorption in air, this wavelength region is not normally considered from a safety perspective. The wavelength region visible to the human eye is relatively small: between 380 and 780 nm. The relative sensitivity of the eye varies largely as a function of wavelength as can be seen in Figure 8.1. It reaches its maximum around 555 nm where green light can be seen. In the blue wavelength region, close to the UV limit, the sensitivity is very low and this explains the overlap in the definition of UVA light and visible light between 380 and 400 nm. From a safety perspective, wavelengths below 400 nm are often classified as UV. This classification will be adopted in this text. The infrared region is often divided into IRA (780–1400 nm), IRB (1400–3000 nm), and IRC (3000 nm–1 mm).

Most sources of optical light will produce emissions in a wide band of wavelengths, whereas one of the characteristics of lasers is that the emission is monochromatic (single wavelength).

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

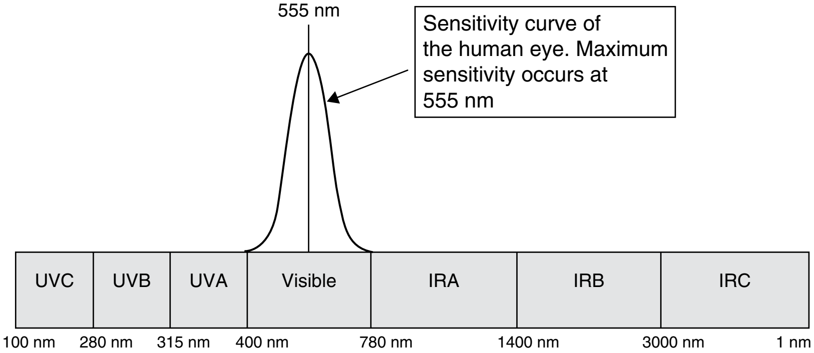


Figure 8.1 Optical light region of the electromagnetic spectrum showing the relative sensitivity of the human eye.

8.1.1 Solar Radiation

Solar radiation spans a large wavelength region, from the UV, through the visible to the IR region. The UV and infrared part of the solar spectrum is discussed in Chapters 4 and 9. The visible light range spans from 400 to 780 nm. This is also the strongest output range of the sun's total irradiance.

8.1.2 Laser Radiation

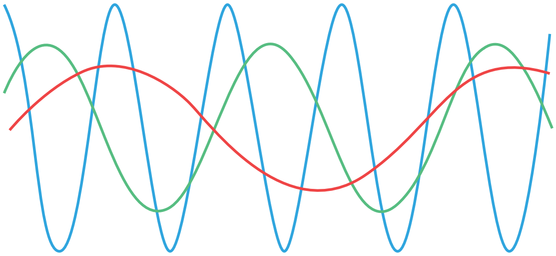
Although both lasers and conventional sources emit electromagnetic waves that are fundamentally the same, the properties of the resulting beams differ markedly. From a radiation safety point of view, there are two main differences. Firstly, as the laser beam is generally collimated (light traveling in the same direction), a large amount of energy can be transported long distances. Secondly, depending on the wavelength of the laser, the radiation can be focused onto a small spot, which means that very high power densities can be reached. Generally, injury to the eye is of concern from lasers. Skin damage can also result from lasers depending on their power density.

8.1.3 High-Power Light-Emitting Diodes

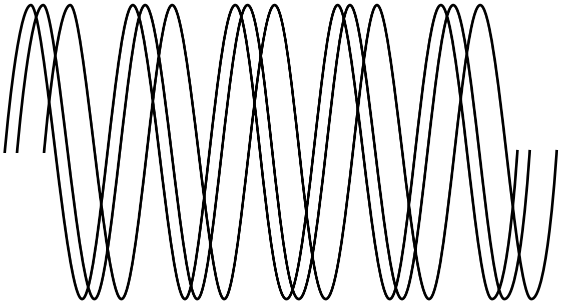
Unlike lasers, light-emitting diodes (LEDs) produce radiation which is not limited to a single wavelength but is spread over a wavelength range. The light from LEDs can be focused onto a small area in the same way that laser light can. This can result in eye injury even though the output from the LED is moderate.

8.1.4 Intense Pulsed Light Sources

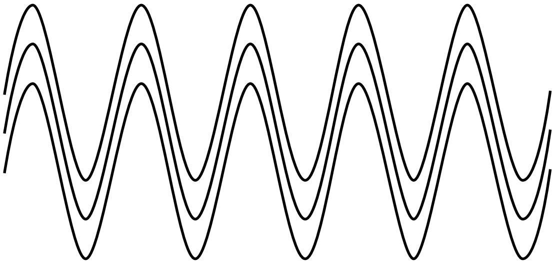
Intense pulsed light (IPL) sources emit, as the name implies, intense pulses of noncoherent light, that is light that is not in phase (see Figure 8.2). IPL sources typically employ xenon flashlamps that emit broad spectrum electromagnetic



Many different wavelengths which are non-coherent, for example, sunlight and florescent light tubes



One wavelength (monochromatic) but waves not in phase (non-coherent), for example, some LEDs



One wavelength (monochromatic with waves in phase (coherent) as found in lasers

Figure 8.2 Diagram showing the difference between noncoherent forms of light and coherent light from a laser.

radiation in the wavelength range from 240 to 2000 nm. Filters are often used to cut-off lower wavelengths or narrow the spectrum of the emitted light to suit the application of the IPL source. The high intensity and broad spectrum of the light emitted mean that IPLs present hazards to both the skin and eyes.

8.2 Basic Principles of a Laser

8.2.1 Properties of Laser Light

Laser light differs from conventional light in a number of ways.

- It is *directional* which means that it can travel long distances with small divergence.
- It is *monochromatic*, that is, it is concentrated at a single wavelength.
- It is *coherent*. This means that the electromagnetic waves remain in phase as they propagate as shown in Figure 8.2.

By contrast, conventional sources such as incandescent or more recently compact fluorescent bulbs emit light with random phase in a number of directions. The light is also emitted at different wavelengths.

From a safety point of view, the resulting hazard presented by a laser is based on the irradiance (power per unit area, normally specified in W/m^2) that reaches the surface of a tissue.

There are two important properties that contribute to the irradiance that can reach a surface:

- *The directionality* Since lasers are capable of producing very concentrated light in a narrow beam with very small divergence, this means that a large amount of energy can be contained within a very small area and can be transferred to a surface a large distance from the source. The divergence of a beam is measured in milliradians (mrad), where a milliradian is a thousandth of a radian. A beam with a divergence of 1 mrad will expand 1 mm for every meter of propagation.
- *The source size* Lasers are considered to be a point source. Although a laser beam can have a large diameter, the rays can be made parallel and a point image is created when focused with a lens such as in the eye. However, an extended source, like an incandescent light bulb, emits light from a finite area. When the light from an extended source is focused, an image will be formed of the source. As the laser light is focused into a much smaller area, the irradiance will be correspondingly higher. In addition, only part of the light emitted from the light bulb will be collected by the lens and focused, whereas all the light in the laser beam can be collected by the lens and focused onto a small spot. Figure 8.3 shows how light is focused onto the retina by the lens of the eye.

8.2.2 Understanding the Laser

The word LASER is an acronym for light amplification by stimulated emission of radiation. To understand how a laser works, it is necessary to understand the concept of stimulated emission.

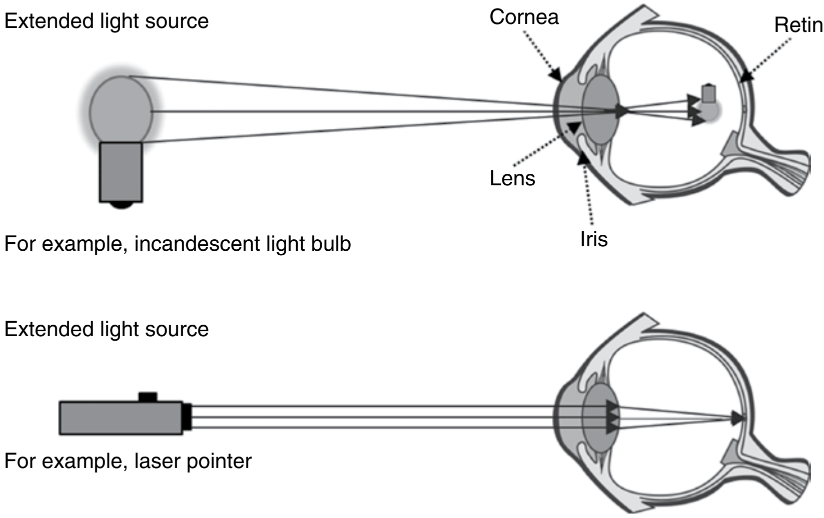


Figure 8.3 Light from an extended source and a point source being focused by the lens of the eye.

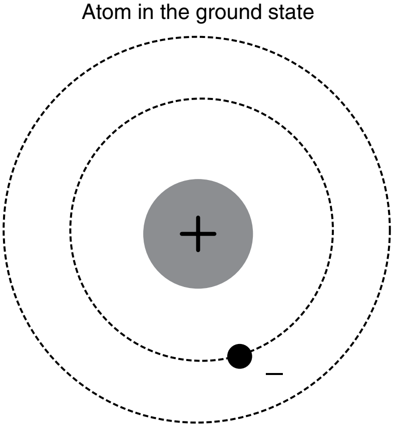


Figure 8.4 Pictorial representation of the atom showing the energy levels (orbitals) in the energetic ground state.

Electrons in atoms occupy discrete energy levels called orbitals as shown in Figure 8.4. Electrons can occupy any of these fixed orbitals but cannot exist between them. If light (a photon) with a specific energy is absorbed by an atom, an electron can jump to a higher energy level (excited state). If an electron drops from an excited state to a lower energy level, a photon will be emitted. The energy of the emitted photon is equal to the energy difference between the two orbitals. In general, this process will occur spontaneously. However, if a

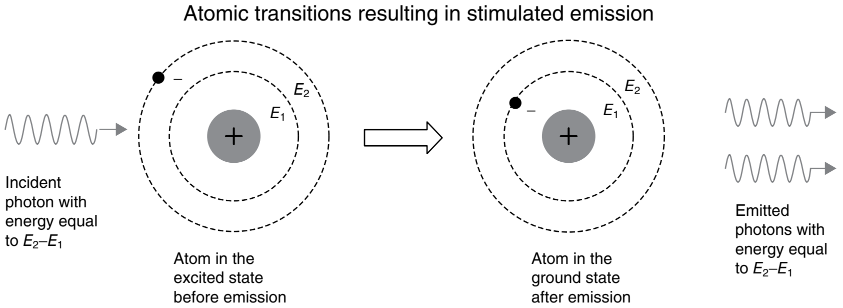


Figure 8.5 An incoming photon with energy $E2–E1$ (equal to the difference in energy between the excited and ground state in the atom) interacts with an excited atom. Stimulated emission occurs and two photons result with the same direction and phase, that is, they are coherent.

photon with the same energy passes by the electron at the excited state, there is a certain probability that the electron will decay to the lower energy level and emit a photon with equal energy and in the same direction as the incident photon. This process is called *stimulated emission* and forms the basis for a laser. This process is shown in Figure 8.5. Most materials will only contain a small number of atoms with electrons in excited states. In order to increase the probability of the stimulation and the number of emissions, it is necessary to artificially excite a larger number of atoms within the material to this higher energy state. This process results in a state called a *population inversion*. Photons entering the material in this state will be amplified and the number of photons emitted will increase exponentially.

A laser consists of three main components as shown in Figure 8.6. These components function to stimulate and amplify the emission of light:

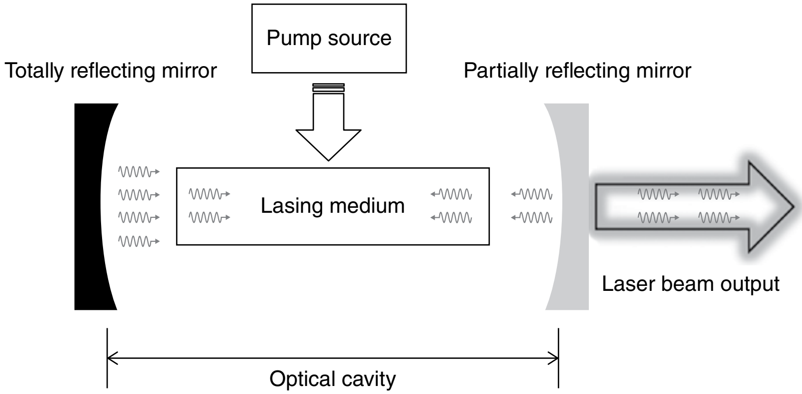


Figure 8.6 Example of the main components of an optically pumped laser.

- The *lasing medium* is the material in which the population inversion is created. It can consist of a gas, liquid, or solid through which an incident photon is amplified with each passage through the material. The laser wavelength is characteristic of the lasing medium and lasers are often categorized by the type of lasing material used. The lasing material for one of the first lasers ever developed is the common ruby. A ruby consists of aluminum oxide with some of the aluminum being replaced with chromium ions that provide the crystal's pink color.
- The *pump source* raises electrons to a higher state in the lasing medium and creates the required inversion population for stimulated emission to occur. There are various ways to pump energy in the system – optical pumping (xenon flashlamps used in solid-state lasers) and high-voltage electrical input to create collision pumping (such as in helium–neon or CO_2 lasers where the gas molecules collide to provide the excitation energy necessary for lasing) are most common.
- The *optical cavity* is composed of two opposing mirrors at each end of the lasing medium. The light beam is reflected from one mirror to the other. These mirrors are aligned so that the incident photon beam retraces its path through the lasing medium. One of these mirrors is partially transparent. This allows some of the amplified light to escape from the cavity and results in the laser beam output. The beam can also be stored and then emitted from the cavity (in the case of a Q-switching laser) once the power has reached the desired level.

8.2.3 Different Types of Lasers

8.2.3.1 Pulsed versus Continuous Lasers

The output of a laser may be either continuous wave (CW), where the power is constant over time, or it can be pulsed. Pulsed lasers are characterized by the pulse repetition rate (the number of pulses the laser produces in a given time – typically given as the number of pulses per second, i.e., Hz), pulse length (the length in time of each individual pulse), average power, and peak power. Lasers producing pulses with a very short pulse length can achieve very high peak powers even though the average power might be very low. There are two main techniques for achieving extremely short pulses:

- *Q-switching* results in short high-intensity pulses with a duration in the order of nanoseconds (10^{-9} s)
- *Mode locking* results in very short pulses in the order of picoseconds (10^{-12} s) and femtoseconds (10^{-15} s). These pulses have the potential to reach extremely high peak power outputs.

When excited energy levels have a relatively long lifetime (the length of time the electrons in the cavity remain in an excited state), energy can be stored within the optical cavity preventing laser oscillation until external energy is

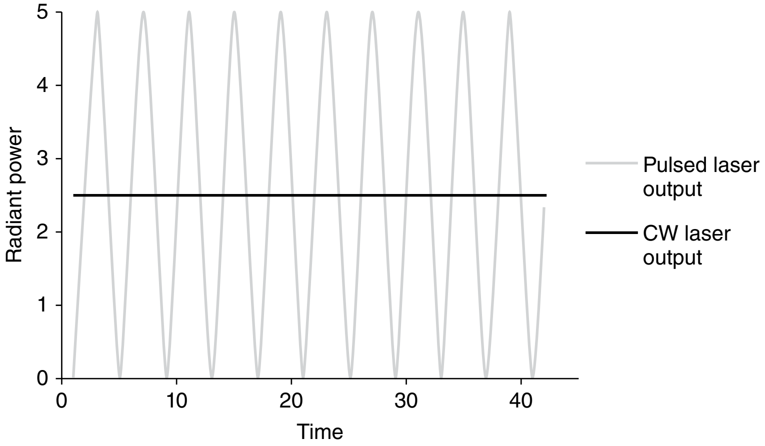


Figure 8.7 Energy output difference between a continuous wave laser and a pulsed laser.

applied. In Q-switching lasers when the barrier (i.e., chopper and rotating mirror) blocking the path of light is removed, the output of the pulse can have a peak power significantly greater than the average CW power. From a hazard perspective, the mechanisms of interaction with tissue can be quite different in these types of lasers and the associated health effects need to be considered. Figure 8.7 illustrates how the peak energy of a pulsed laser can be much higher than that of a CW output laser.

8.2.3.2 Common Laser Types and Their Uses

As mentioned earlier, lasers are often characterized by the lasing medium used in the cavity. A brief description of the most common laser types, their characteristics, and common uses is given in the following paragraphs.

- *Solid-state lasers* have the lasing medium distributed in a solid material like ruby, mentioned earlier. This is achieved by doping a solid material with ions that offer the required energy states for light amplification. A common dopant is neodymium (Nd) that can be used in a number of host materials including yttrium aluminum garnet (Nd:YAG), yttrium orthovanadate (Nd:YVO_4), and yttrium lithium fluoride (Nd:YLF). These solid-state lasers can produce very high powers in the infrared. The most common is the Nd:YAG laser that emits at 1064 nm. This type of laser can also be made to produce visible light at 532 nm (green) and UV light at 355 and 266 nm. These lasers have many applications including surgery, tattoo and hair removal, research, pumping (energizing) other lasers, laser pointers, and light shows in the entertainment industry.

  Another common solid-state laser is the titanium doped sapphire (Ti:Sapphire) laser. This laser is tunable over the wavelength range 650–1100 nm. It also has the ability to generate ultra-short pulses (in the order of femtoseconds). These properties make this type of laser useful in scientific research.

- *Gas lasers* use an electric current to create an inversion population in a gas. There are a few common types of gas lasers. The most widely used type is the helium–neon laser, which is a cheap, compact laser producing a beam of high quality. The most common output wavelength is at 633 nm, but other wavelengths are available. There are many applications for this type of laser including barcode scanning, laser pointers, holography, and optical demonstrations.

  Argon-ion lasers are also available with very high CW outputs in a range of UV and visible wavelengths. They are commonly used in research applications and retinal phototherapy.

  Carbon dioxide (CO_2) lasers have the capacity to produce very high powers and can be used in CW or pulsed mode. With the high-power levels available and relatively low cost, it is a suitable laser for cutting and welding in industrial applications. The most common wavelength of 10.6 μm is readily absorbed in water. Since tissue largely consists of water, the CO_2 laser is useful as a cutting tool in surgical procedures.
- *Excimer (short for excited dimer) lasers* utilize a liquid- or a gas-phase lasing medium. An excimer is a short-lived molecule formed from two identical or structurally similar species, where at least one species has electrons in an excited state. The energy contained within the excimer is released by the emission of a photon. Excimer lasers produce intense pulsed radiation in the UV region of the spectrum. The use of the shorter wavelengths in this region allows the output to be focused into a smaller spot than a corresponding laser with longer wavelength. The short wavelength also means that the excimer laser can ablate unwanted tissue without thermal damage to the surrounding area. This is because ablation of the tissue occurs as a result of breaking molecules apart rather than heating the tissue such as in the case of an infrared laser. This property makes it useful for laser surgery including laser vision correction.
- *Semiconductor* lasers, also called *diode lasers or laser diodes*, have become more common as they are efficient, cheap, and reliable, emitting light in a large range of wavelengths. Population inversion is achieved through the application of an electrical current. A wide variety of applications has been found in telecommunications and the printing industry. Diode lasers are often found in CD/DVD players. They are also useful as a pump for other types of lasers.
- *Dye lasers* use an organic dye suspended in a liquid as the lasing medium. Depending on the dye used, the emission can cover a wide range of wavelengths. These lasers are tunable which makes them suitable for applications in spectroscopy and for the generation of ultra-short pulses. The limited lifetime of the dyes used and the toxic nature of the dyes mean that dye lasers are not always a convenient or safe to use and have to a large extent been replaced by other lasers.

8.3 Intense Nonlaser Sources of Visible Light

8.3.1 Light-Emitting Diodes

LEDs have become increasingly popular as they are a cheap, reliable, and efficient source of light. An LED is a semiconductor diode that emits light when placed in an electric circuit. Its construction is similar to the laser diode in some ways, but the light emitted does not exhibit the characteristics of laser light (coherent, directional, and monochromatic). The light emitted is due to spontaneous emission and not to stimulated emission. LEDs are inherently divergent, compared to lasers, but by using focusing optics the beam can be made reasonably collimated. LEDs produce radiation, which is not limited to a single wavelength but is spread over a wavelength range. The wavelength depends on the material used and can be UV, visible or infrared. LEDs can also be used to produce high-intensity white light. There are two methods for doing this. The first is to mix differently colored lights, the most common being red, green, and blue light, to produce white light. The second method is to use a blue LED coated with a phosphor compound. The combination of the blue light and the fluorescence from the phosphor produces white light. Due to its simplicity, this is the most common way of producing high-power LEDs. The use of an array of LEDs forms the basis of LED screens displays. These displays typically use a matrix of red-, green-, and blue-emitting diodes to generate full color images. Devices such as smart phones, digital cameras, and tablets use AMOLED (active-matrix organic light-emitting diode) technology to generate images. In these devices, organic compounds form the luminescent material that it coated onto an array of transistors for generating color images.

The small size of the light-emitting section of the LED means that it can be considered a point source and the eye can focus the light into a small image on the retina. High-power densities are possible which can cause damage to the retina. From a hazard evaluation point of view, LEDs can be treated similarly to lasers, and in the following sections, the discussions regarding laser hazards are also applicable to high-power LEDs.

8.3.2 Intense Pulse Light Sources

IPL devices utilize a high-output flashlamp to produce a broad wavelength output of non-coherent light. Xenon lamps emit from the UV to the IR (185–2000 nm) similar to sunlight. They have high-output intensity, tend to be highly stable, and have a long life expectancy. The most common method of generating the light pulses in IPL devices is through the application of electrical current bursts through a chamber containing xenon gas. This input of energy excites the electrons in the xenon atoms to a higher energy state. When the electrons return to their ground state, light is emitted. The output from this lamp is then directed toward an aperture where it is released and focused through a sapphire or quartz block (the conduction crystal) onto the surface of the skin.

Control of the light pulses can be achieved by setting the duration, intensity, and spectral distribution of the emission. IPL devices can have their emissions limited at the lower end of the spectrum by using "cut-off" filters to more selectively target cellular or structural elements. These cut-off filters can be made to restrict damaging UV light and some visible light that is not required for the treatment process. The filters function by blocking the emission of shorter wavelength light. IPLs emit light over a larger surface area than most lasers. IPL devices also incorporate cooling systems to protect the skin in contact with the light from burns due to heat build up.

IPL devices are used in dermatology to facilitate selective photothermolysis by targeting chromophores (parts of a molecule that are responsible for color). In this process, hemoglobin, water, and melanin in the skin absorb light at a range of wavelengths, leading to thermal radiation damage of the selected cells. The broad wavelength range discharged from an IPL device allows the various chromophores to be targeted simultaneously.

IPL devices can pose a health hazard when they are used inappropriately by users with little or no training. This is due to high intensity and wide spectrum of the emitted light pulses. Unlike pulsed lasers that can deliver picosecond and femtosecond pulses, the duration of a pulse from IPL devices are in the order of milliseconds, resulting in inherently longer exposure times. There is also potential for eye injuries if skin treatment is in close proximity to the eye.

8.3.3 Solar Radiation

Solar radiation consists of optical radiation in the UV, visible, and infrared regions of the electromagnetic spectrum. The solar spectrum output closely approximates the irradiance from a black body at 5778 °C (*Wikimedia Commons*, 2016). The strongest output is in the visible region from 400 to 780 nm. Figure 8.8 demonstrates how the atmosphere reduces a considerable fraction of the irradiance from solar radiation. UV light is attenuated due to absorption and scattering by ozone while the irradiance of infrared light is reduced due to absorption by other atmospheric molecules including water and carbon dioxide. Visible light is also attenuated by the atmosphere. Consequently, at the top of the atmosphere, the irradiance is approximately 50% more intense than the irradiance at the earth's surface, with an average irradiance of 1353 and 730 W/m^2, respectively (Gies, Roy, and Udelhofen, 2004). However, the intensity is still high enough at sea level to cause injuries to the skin and eyes in the UV region, solar retinitis in the visible region, and thermal injury in the infrared. Hazards are also posed by reflections of the light from highly reflective surfaces such as snow.

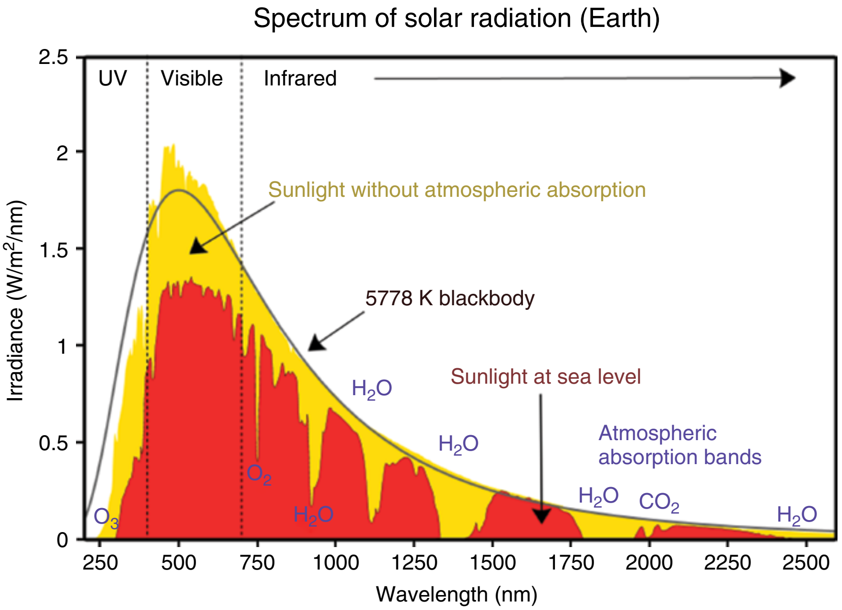


Figure 8.8 Spectral irradiance of the solar radiation spectrum at the top of the atmosphere and at sea level. *Source:* https://en.wikipedia.org/wiki/Sunlight#/media/File:Solar_spectrum_en.svg. Used under CC-BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/.

8.4 Biological Effects

8.4.1 Anatomy of the Eye

The eye is the organ most sensitive to optical light and the hazard is related to the amount of energy absorbed in the tissues. The absorption in the tissues varies strongly depending on wavelength and so different wavelengths will cause harm to different parts of the eye. To understand the tissue–light interaction, it is useful to review the anatomy of the eye. A picture of the eye is depicted in Figure 8.9.

The first tissue that light interacts with is the cornea. The cornea is transparent and together with the lens acts to focus the incoming light onto the retina. Most of the focusing power can be attributed to the shape of the cornea. The shape of the cornea does not change in response to the light being transmitted through it. However, the thickness of the lens automatically adjusts to fine-tune the focus onto the retina (this is called accommodation). As the eye looks at a close by object, the lens thickens which increases its optical power so that the image formed on the retina is sharp.

The fovea is an area on the retina responsible for sharp central vision. It is located opposite the lens and is the portion of the retina that is used when

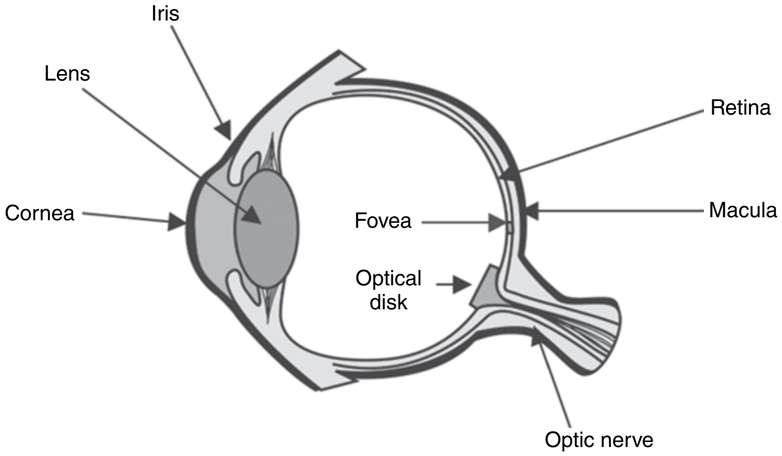


Figure 8.9 Structure of the eye.

looking straight at an object. As the eye observes the object, the area of interest is focused onto the area around the fovea, the macula region. This relatively small part of the retina delivers images of high resolution. Areas of the retina further away from the macula region are responsible for peripheral vision and provide images of low resolution. Photoreceptors, located in this region, give the retina-specific characteristics and are responsible for absorbing photons from the visual field translating the information to a change in electrical potential difference in the cell membrane. Photoreceptors exist in two forms with different functions, rods, and cones. The rods are located at the outer region of the retina responsible for peripheral vision. They are more sensitive to light than cones and therefore facilitate night time vision. They only provide images in black-and-white. Cones, on the other hand, are responsible for high acuity vision and are concentrated in the macula region. They are able to perceive finer detail, are less sensitive to light, and are responsible for color vision. The point on the retina where blood vessels and nerves exit the eye is called the optic disk. This area is also known as the "blind spot" as there are no cones or rods in this area. The viewer is normally unaware of this area as the brain fills in the details with information from the other eye.

8.4.2 Hazards to the Eye

The hazard of optical light is related to the amount of energy absorbed in the tissue. The extent of the damage depends on a number of parameters, the most important being wavelength (for lasers in particular), irradiance, duration of interaction, image size, and radiant exposure. The two main mechanisms by which light induces damage are thermal and photochemical. Both these mechanisms are wavelength specific and therefore the damage to the absorbing tissue will be strongly wavelength dependent. A third mechanism of interaction is thermomechanical, which becomes important when very short pulses interact with tissue.

Thermal effects are caused by increased vibration of molecules due to the absorption of light. This results in a temperature increase in the tissue and if the temperature increases above a critical level damage occurs. If the exposure time is long, as in a CW laser or a long-pulse laser, the affected area will increase as heat is conducted to the surrounding areas. Similarly, if the spot size is large, the possibility for cooling through heat diffusion will be diminished and more cells will experience a temperature above their thermal tolerance.

The absorption of light at a given wavelength can lead to chemical reactions such as excitation of atoms or breaking of bonds in molecules. These photochemical effects can occur at irradiances that are not sufficient to cause thermal damage in the tissue. The molecules will undergo a chemical reaction due to the absorbed photon rather than the temperature increase. Photons in the UV wavelength region contain enough energy to induce photochemical effects, whereas photons in the visible and infrared region are mainly responsible for thermal effects. Photochemical effects will typically depend on the total amount of absorbed photons but not on the timescale within which they are absorbed. A long low-intensity exposure will have the same effect as a short more intense one, as long as the total number of photons absorbed is the same. There is also no dependence on spot size, as there is for thermal effects, due to thermal diffusion not playing a part in the interaction mechanism.

Thermomechanical effects can occur for very short pulses, typically nanosecond pulses or shorter. The energy delivered to the tissue causes the temperature to rise so rapidly that the cells rupture and mechanical shockwaves propagate through the tissue, causing damage.

The absorption properties of the eye are shown in Figure 8.10. As can be seen from the figure, the cornea and lens are at risk from UV radiation as it is absorbed in that region. The retina is at risk primarily from visible light, as the design of the eye means that these wavelengths are optimally imaged onto the retina. Near infrared light is partially absorbed by the cornea and the retina. Far infrared light is absorbed by the cornea.

Light in the UV-C region (180–280 nm) and UVB region (280–315 nm) is strongly absorbed in the cornea and exposure can lead to photokeratitis. This condition is known as welder's flash or snow blindness and the feeling is often likened to having sand in the eyes. Although being very painful, in most cases, the injury is temporary and the repair mechanisms of the cornea mean that full recovery is possible. Some light in the UVB region can penetrate to the lens and a cataract can result, sometimes referred to as a clouding of the lens. Damage can be permanent as the lens is less capable of repair than the cornea. UVA radiation is also predominantly absorbed in the lens, but eye damage is less likely from this exposure.

Visible (400–780 nm) and near infrared (780–1400 nm) radiation is focused onto the retina. Due to focusing mechanisms in the eye, the intensity of the

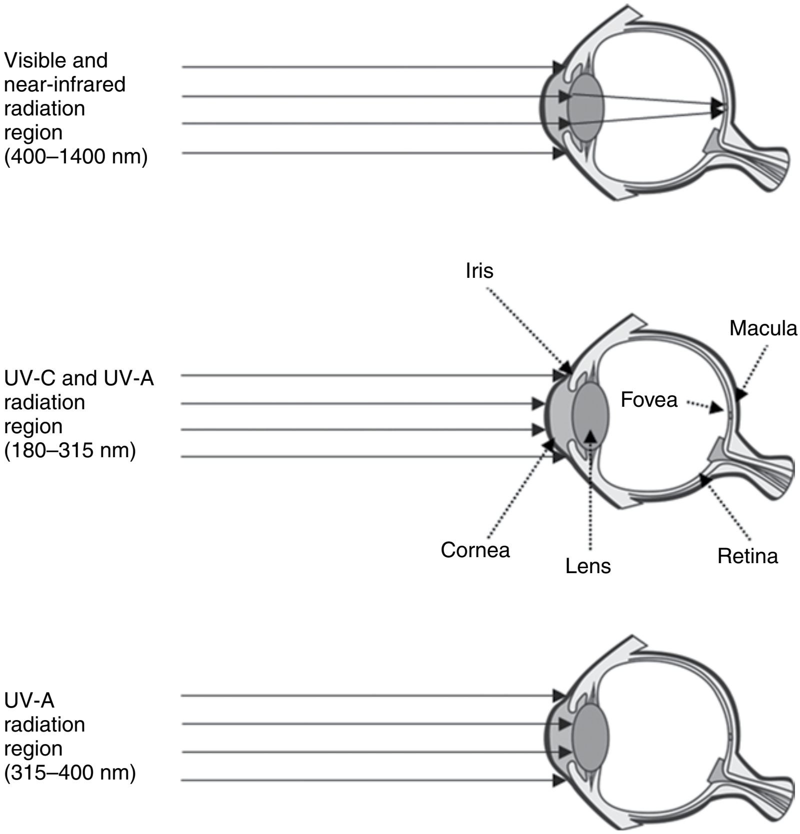


Figure 8.10 Absorption properties of the eye.

light being focused onto the retina from the lens may increase by many orders of magnitude (IEC, 2014). Consequently, lower intensities of light in this wavelength region may cause injury. Damage to the retina is generally permanent, but there are some repair mechanisms that can improve vision after an accident.

Damage to the cornea and lens can result from exposure to infrared wavelengths between 1400 nm and 1 mm, with the cornea being the most susceptible to injury. The biological effects can cause infrared cataracts (or otherwise known as glass blowers cataract) and flash burns to the cornea. The mechanism is largely thermal for infrared above 1400 nm since this region is absorbed by the cornea and lens. The injury threshold depends on the penetration depth for the specific wavelength. A longer penetration depth means that the energy is absorbed in a larger volume; thus, the exposure limits are higher in this situation. Corneal burns will heal if the damage is minor, but not if the exposure is well above the damage threshold.

8.4.2.1 Infrared Wavelengths and Eyesafe Lasers

The wavelength region from about 1.4 to 1.6 μm is often termed the "eye-safe region". This is because light in this wavelength range is strongly absorbed in the eye's cornea and lens and therefore is not focused onto the retina. At these longer wavelengths, although the light does not reach the retina, the absorption length in the cornea can become very short and therefore the energy is deposited in a small region causing damage to the cornea. This is particularly the case around 3 and 10 μm (close to the wavelength of CO_2 lasers). Obviously, how eye-safe a laser is depends not only on the wavelength but on the power that interacts with the cornea and lens. At sufficiently high power, eye damage will occur even in the eye-safe region.

8.4.2.2 Aversion Response and Eye Movements

The human aversion response for visible light is the blink reflex, normally taken as being 0.25 seconds. This is the time taken to close the eye after unexpectedly being exposed to bright light. Obviously, the aversion response mechanism can only be relied on in the visible light region. It is possible to intentionally stare into the beam for longer and thus emission levels judged to be safe based on the aversion response can become hazardous. The aversion response can also be impaired if a person is under the influence of alcohol or drugs.

8.4.3 Hazards to the Skin

Injury to the skin from optical sources is much less likely than injury to the eye, even when working with high-power optical sources and lasers. The skin can tolerate higher levels of radiation than the eye and also there is no focusing mechanism in the wavelength region 400–1400 nm. This means that the injury threshold for the skin is much higher compared to the injury threshold for the eye. As with the eye, the absorption properties of the skin are strongly wavelength dependent. UV radiation is absorbed in the outermost layer. As the wavelength increases, the radiation penetrates further into the tissue. A maximum is reached at 800 nm where the penetration depth is around 1 cm. As the wavelength increases, the penetration depth decreases again. The sensitivity of the skin can be increased by photo-sensitizing agents, for example, medication and certain chemicals.

As with the eye, the interaction between radiation and tissue can be categorized as being photochemically induced or thermally induced. Exposure to UV radiation can give rise to "photochemically induced erythema" (e.g., sunburn). For long-term or repeated exposure to levels above the exposure limit for UV light, there is a risk of developing skin cancer (see Chapters 4 and 5). The likelihood for this type of exposure with lasers is generally small, but it can occur if there is frequent exposure to stray light from high-power UV lasers.

Thermal injury to the skin is similar to injury caused by contact with hot surfaces. A reddening of the skin, blisters, and charring can result from the exposure. For wavelengths with a large penetration depth, a large volume of tissue is affected and can result in necrosis. In effect, the tissue has been boiled due to the absorbed heat.

8.5 Laser Radiation Safety

8.5.1 Intrabeam Viewing

In intrabeam viewing, the eye is exposed to the laser beam through either direct viewing or specular reflections. Specular reflections are reflections from reflective surfaces such as mirrors or glossy surfaces. The surface merely redirects the beam and the properties of the laser beam are kept intact. This differs from diffuse reflections, where the beam is scattered in many directions by a diffusive surface or medium. Due to this scattering, the power in the beam and the incident irradiance on the eye is much lower. Figure 8.11 illustrates the difference between specular reflection intrabeam viewing and viewing of diffuse reflections. In intrabeam viewing, the beam is incident onto the eye, but the eye is not necessarily looking into the laser beam.

8.5.2 Maximal Permissible Exposure

The maximum permissible exposure (MPE) is the highest exposure to the naked eye that is considered safe. This is a theoretical limit, with some uncertainty inherent in its derivation, and individual variations exist. In all circumstances, the aim should be to minimize exposure to laser radiation as much as possible. MPE levels are determined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and are published in the international

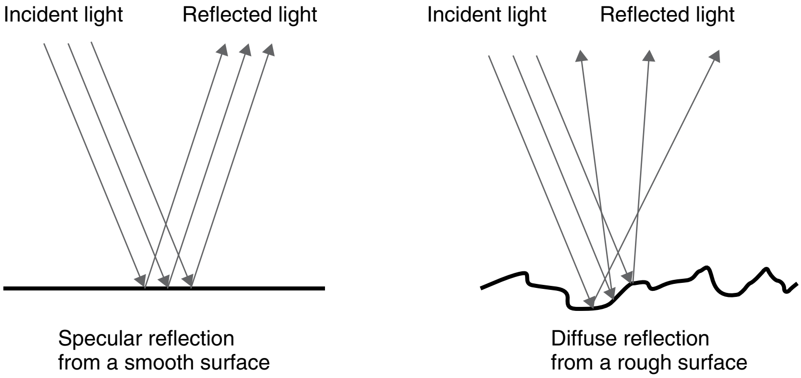


Figure 8.11 Light reflections showing the difference between specular reflection from a smooth surface and diffuse reflections from a rough surface.

standard (IEC, 2014). The MPE limits are given as radiant exposure (J/m^2) or irradiance (W/m^2) at the cornea or the skin for a given wavelength and exposure time. The MPE is based on experimental data and is usually set at 10% of the dose at which 50% of the exposures lead to damage (Schröder, 2000). At exposures below this, the risk of injury is considered low enough to not require eye protection (see Chapter 11).

The MPE values are based on biological effects described in the abovementioned sections and have a complex dependence on wavelength, pulse length, and, in some cases, spot size on the retina. In some cases, there are two limits, one where photochemical interaction dominates (e.g., in the UV and where the exposure time is long) and one where thermal interaction dominates (where sufficient energy has been absorbed in the system to cause heating). In these cases, the MPE should be chosen as the most restrictive one of the two limits.

It should be noted that the MPE refers to the exposure that is considered safe from the point of view that no permanent injury results. This does not take into account the possibility of a person being dazzled or temporarily blinded by a visible laser beam where the exposure level is below the MPE.

8.5.3 Nominal Ocular Hazard Distance

In assessing the hazard of a laser, the concept of nominal ocular hazard distance (NOHD) is useful. It is defined as the distance from the laser at which the exposure equals the MPE for the eye. Within this distance, the exposure exceeds the MPE and eye protection is necessary. Outside this distance viewing is safe for the unprotected eye.

In some cases, it is useful to speak of the extended nominal ocular hazard distance (ENOHD), which takes into account the possibility of viewing through optical instruments such as magnifying lenses or binoculars. This is of particular interest for lasers that are safe only for viewing with the naked eye.

The nominal ocular hazard area (NOHA) is the area within which the exposure exceeds the MPE for the eye. Again, if the possibility of viewing with optical instruments is taken into account, this area is called the extended nominal ocular hazard area (ENOHA).

8.5.4 Laser Hazard Classification

Lasers have four classes and a few subclasses according to their level of hazard, with Class 1 being the least and Class 4 the most hazardous. The international laser safety standard IEC 60825-1 classification of a laser product is based on the radiation emitted during normal operation and any reasonably foreseeable fault condition. This document has been internationally adopted and the national standards in many countries are based on this document.

The limits used for classification are called accessible emission limits (AELs). The AELs are based on the MPE's using limiting apertures and are expressed in power (W), energy (J), irradiance (W/m^2), radiant exposure (J/m^2), or a combination of these. These limits apply to lasers in the higher risk category from Class 3R to Class 4 lasers. Class 1 and 2 lasers do not have a defined boundary separating their classes in terms of AELs. Rather, they are separated by other factors including accessibility to the beam and specific applications.

The classes according to the classification in IEC 60825-1 are summarized in the following paragraphs.

Class 1: A Class 1 laser does not emit levels above the MPE and is safe under all conditions of normal use. Class 1 includes lasers that are completely enclosed and although the laser emission in this case can be of high power, it is not accessible. This type of laser is called an embedded laser. Examples of class one lasers can be found in laser range finders.

Class 1C: A Class 1C classification applies when a laser is intended to be in contact with the intended target of the emission. The C in this case refers to the use of the laser in contact-mode. Class 1C lasers need to have engineering controls such that exposure to the eyes is not reasonably foreseeable and that any leakage of laser radiation does not exceed the AEL of a Class 1 laser. These lasers can be found in cosmetic devices used for hair removal.

Class 1M: A Class 1M laser is safe under normal conditions of use, provided that it is not viewed with magnifying optics (e.g., binoculars or eye loupes). The M denotes *m*agnifying optical viewing instruments. Class 1M lasers have a diverging beam or a beam with a large diameter. If the beam is refocused the hazard increases and the laser may have to be reclassified. These lasers are commonly used in research applications.

Class 2: Class 2 lasers are safe provided that the blink reflex limits the exposure time to 0.25 s. It only applies to lasers emitting in the visible wavelengths (400–700 nm). The output power is higher than for Class 1 lasers, but as the aversion response limits the exposure of the retina, they can be considered safe as long as there is no intentional staring into the laser beam. Barcode scanners and laser pointers are common examples of Class 2 lasers. Class 2 lasers are restricted to an AEL of less than 1 mW.

Class 2M: A Class 2M laser emits visible light and is safe as long as it is not viewed through optical instruments. As for Class 2 lasers, the aversion response ensures that exposure levels are not exceeded. Again, the M denotes *m*agnifying optics and eye injury can occur if exposure is through optical instruments. These lasers are commonly used in research applications.

Class 3R: A Class 3R laser is of low risk to the eye if handled carefully and of no risk to the skin. The MPE can be exceeded under direct intrabeam viewing, but the risk of injury is low because the AEL for Class 3R is only five times the AEL for Class 2 (for visible beams) and five times the AEL Class 1 (for nonvisible beams). This class is intended for trained personnel and fewer manufacturing requirements and control measures apply than for Class 3B. The R denotes *r*educed or *r*elaxed requirements. CD players commonly use lasers that fall into this class. Class 3R lasers have AELs that are higher than 1 mW but no more than 5 mW.

Class 3B: Diffuse reflections are generally safe, but direct intrabeam viewing is hazardous. Powerful Class 3B lasers can produce skin injuries when focused or when the beam diameter is small. Generally, serious skin injury is prevented due to the aversion response when heating of the tissue occurs. These lasers are commonly used in CD and DVD burners. Lasers within this class have AELs between 5 and 500 mW.

Class 4: This is the most hazardous laser class and there is no upper limit on power. Intrabeam viewing and skin exposure is hazardous, as well as viewing of diffuse reflections. Class 4 lasers are able to cut and burn skin. In addition, these lasers may ignite combustible materials and often represent a fire hazard. These lasers are used in a wide variety of applications depending on their power output. Examples include laser cutters, surgical lasers, and certain cosmetic lasers (tattoo removal). Class 4 lasers have accessible energies above 500 mW.

Further details on guidelines and standards can be found in Chapter 11.

Tutorial Problems

1 Briefly describe how a laser works to amplifies light.

2 How does laser light differ from other light sources such as IPL devices, LEDs, and sunlight?

3 Describe the way in which optical radiation interacts to cause damage to the retina and the cornea of the eye.

4 Which classes of laser emit light:
  i) in the visible spectrum only;
  ii) at levels that are is safe under all conditions of normal use;
  iii) that is hazardous by intrabeam viewing, skin exposure, and diffuse reflections?

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9

Infrared Radiation and Biological Hazards

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9.1 Introduction

In this chapter, we will look at electromagnetic radiation in the infrared part of the spectrum, the way it interacts with the human body, and the potential exposure hazards it presents.

However, before doing so, it is useful to understand what infrared radiation is, how it is produced, and where it sits in the electromagnetic spectrum.

Infrared radiation is nonionizing electromagnetic radiation. Table 1.1 shows that infrared radiation has a longer wavelength than visible light, but a shorter wavelength than radio waves.

In physics, the amount of energy electromagnetic radiation possesses is described by the equation $E = h\nu$, where h is Planck's constant and ν the reciprocal of the wavelength of the electromagnetic radiation.

Therefore, in broad terms, we can say that infrared radiation is less energetic than visible light, but more energetic than radio waves.

Interestingly, the proximity of infrared radiation to visible light in the electromagnetic spectrum means that infrared radiation behaves in a similar manner to visible light. For instance, lenses made from certain materials can focus infrared radiation. It can also be attenuated, filtered, diffracted, reflected, and refracted.

9.2 Black Body Radiation

All objects at temperatures above absolute zero (0° K) emit electromagnetic radiation.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

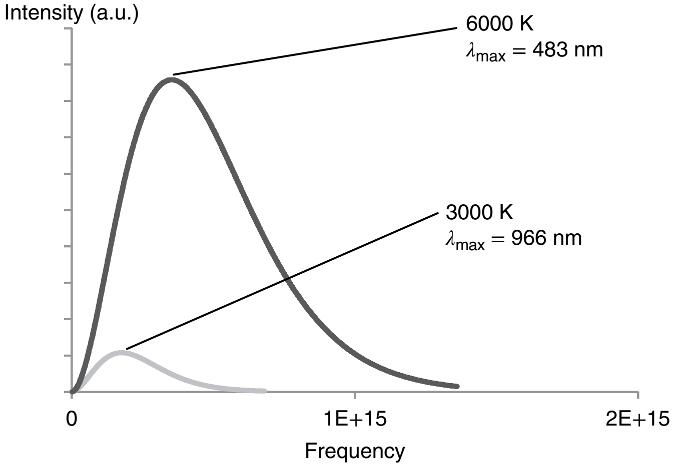

Figure 9.1 Blackbody radiation intensity as a function of wavelength/frequency for two different blackbody temperatures.

Radiation produced in this manner can be described by the black body radiation curve shown in Figure 9.1, and it is a general property of black body radiation that the emissions will have a maximum or peak at a particular wavelength.

This peak is directly proportional to the temperature of the black body and is described by Wien's displacement law.

$$\lambda_{\max} T = b$$

$\lambda_{\max}$ is defined as the wavelength at maximum radiant emittance, that is, the wavelength for which the black body radiator produces its maximum output of radiation; b is Wien's constant of 2898 (for $\lambda_{\max}$ in micrometers); and T the temperature of the object in degrees Kelvin.

Wien's displacement law basically states that hot objects produce electromagnetic radiation at shorter wavelengths than cold objects.

Figure 9.1 shows black body radiation curves for a 6000 K black body and a 3000 K black body. Note not only the change in intensity but also the change in wavelength for the maximum radiant emittance.

The International Commission on Illumination (CIE, 1987) has categorized infrared radiation on the basis of its wavelength into IR-A, IR-B, and IR-C covering the wavelength ranges 0.78–1.4, 1.4–3, and 3–1000 μm (1 mm), respectively.

If we apply Wien's displacement law to the CIE categories for IR-A, IR-B, and IR-C, we see that the temperature range for the peak emissions from a black body is around 3400 °C for 0.78 μm and approximately −270 °C for 1000 μm.

9.3 Absorption of Infrared Radiation

Like other forms of electromagnetic radiation, infrared radiation can interact with matter. For instance, it can reflect from surfaces, be transmitted through material, and in doing so deposit some or all of its energy in the material. The process of electromagnetic radiation depositing energy in material is referred to as absorption, and the absorption per unit mass can be expressed as joules per kilogram, while the rate of energy incident on any particular object is given in joules per second (Watts).

Given a large component of the human body is water, we will first look at the way infrared radiation interacts with water before we examine how infrared is absorbed and reflected by the human body.

9.3.1 Absorption by Water

Atoms and molecules can absorb electromagnetic radiation. Electromagnetic radiation possessing sufficient energy can elevate electrons to higher energy states within the atom. This is certainly true for the ultraviolet and X-ray parts of the electromagnetic spectrum. Infrared radiation has less energy than either ultraviolet or X-rays and as a result cannot excite electrons in atoms to higher energy states. However, infrared radiation can excite vibrations in molecules. These vibrations can be visualized in terms of spheres (the atoms) connected by springs (the bonds) oscillating under the influence of the infrared radiation.

Figure 9.2 provides a simple model of this.

What this absorption mechanism allows is for the energy ($E = h\nu$ in joules) of the incident infrared radiation to be "transmitted" into the vibrational

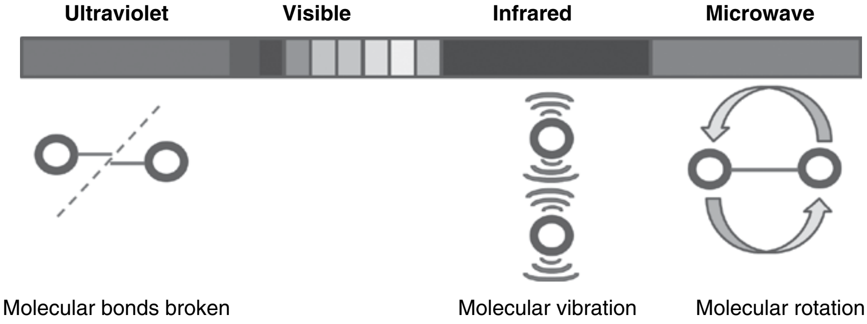

Figure 9.2 Modes of energy absorption by molecules from electromagnetic radiation from UV through to microwave, showing that molecular vibrations predominate in the infrared region. *Source:* Adapted from Pecsok and Shields, 1968 and Schwartz, 1994. Reproduced with permission of Elsevier and Wiley.

motion of a molecule. This vibrational motion leads to frictional interactions in the bulk material, which in turn lead to temperature increases in the bulk material.

This analogy is not strictly true in that the mechanical model presented will vibrate at a wide range of frequencies in response to a wide range of infrared energies. Molecules on the other hand will only vibrate at certain quantized (discrete) frequencies.

Looking in more detail at the absorption of infrared radiation by water, Figure 9.3 shows that the absorption coefficient for water is a function of wavelength.

We can see that in the visible part of the spectrum water is almost completely transparent with absorption coefficients ranging from 10^{-2} to $10^{-1}\,\mathrm{m}^{-1}$, that is for every meter of water, the visible light passes through, only 1–10% of its incident energy is absorbed.

However, in the infrared part of the spectrum (780 nm to 1 mm), the absorption coefficient is many orders of magnitude higher. For example, at 3 μm, it is around $10^3\,\mathrm{mm}^{-1}$ or simply put for every millimeter of water infrared radiation at 3 μm passes through only 1/1000 of its incident energy is transmitted (i.e., 99.9% is absorbed).

At very long infrared wavelengths near 1 mm and extending into the microwave region of the spectrum, water is almost totally transparent (an absorption coefficient of $10\,\mathrm{mm}^{-1}$).

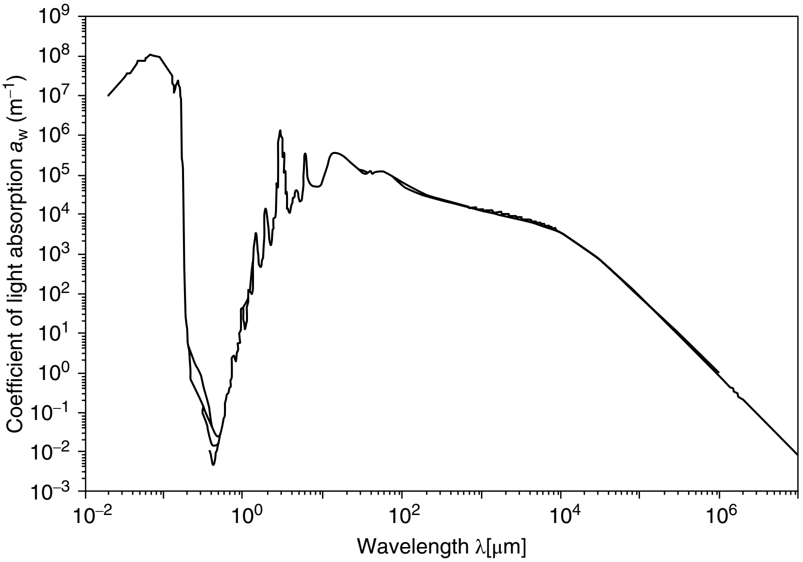

Figure 9.3 Absorption of infrared radiation by pure water as reported by numerous authors. Wozniak and Dera, 2007. Reproduced with permission of Springer.

9.4 Interaction of Infrared Radiation with the Human Body

The two main organs of the body that can be affected by infrared radiation are the eyes and the skin.

While the human eye is not capable of directly detecting images produced by infrared radiation, it can nevertheless be exposed. In the case of the skin, it is possible to detect infrared radiation through "feeling warm".

9.4.1 Skin

In Figure 9.4, it can be seen that the depth of penetration of various wavelengths of light in the human skin depends on the wavelength of the incident light. In the visible part of the spectrum (390–700 nm), the penetration depth increases with increasing wavelength. However, the penetration depth of infrared radiation in our skin, while also being dependent on wavelength exhibits a different variation with wavelength. IR-A (0.78–1.4 μm) is the most penetrating and reaches some millimeters, IR-B (1.4–3 μm) penetrates into the dermis, which is about 1 mm in depth, and IR-C (3 μm to 1 mm) is mostly absorbed in the external layer of the epidermis (stratum corneum).

The rate at which infrared energy is deposited (Watts) can lead to temperature increases in the skin, and depending on the ability for this energy to be transported away from the exposed area by the vascular system, or other thermal conducting mechanisms, there can be effects of varying severity.

For example, if the infrared energy is deposited at moderate exposure rates, and effectively conducted away from the exposure area, then the exposed area

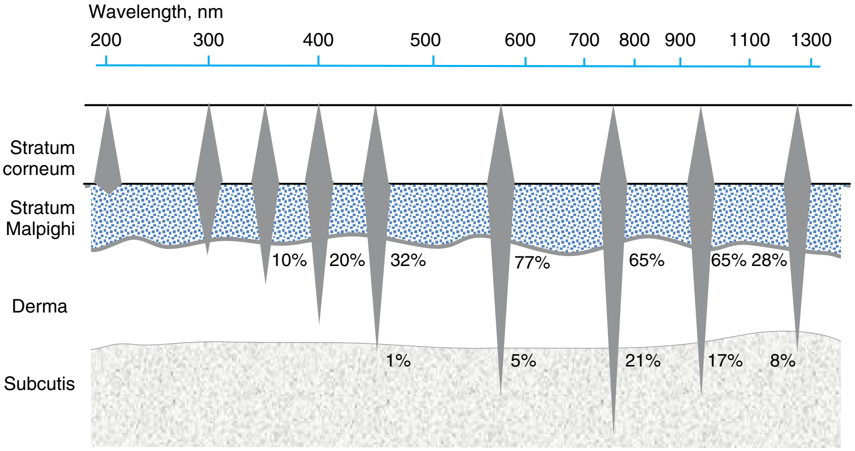

Figure 9.4 Absorption properties of the human skin, as a function of wavelength. *Source:* Adapted from Urbach, 1985, The University of Chicago Press.

may only experience a sensation of warming. However, long exposures at moderate exposure rates may lead to a whole body temperature increase for an individual, and this may cause heat stress.

If the rate of infrared energy being deposited greatly exceeds the ability of the body to transport the heat away from the exposed area, then severe localized heating or even burning may result.

9.4.2 Eye

The eye has evolved some abilities to protect itself from optical radiation and in particular sunlight. For example, the aversion or blink response of the eye, which is of the order of 1/4 of a second, protects the eye from bright naturally occurring optical sources. However, infrared radiation does not trigger the blink response in the same way as a bright optical source since it is "invisible", and exposure to these wavelengths can result in acute and chronic effects for the eye.

Figure 9.5 shows a cross section through the human eye, and in conjunction with Figure 9.3 (absorption by water), we can see how the different infrared wavelengths are transmitted and absorbed by the structures of the eye, which can essentially be thought of as being composed of water (vitreous is approximately 99% water and 1% collagen.

The shorter infrared wavelengths (IRA) mainly affect the retina because the preceding structures of the eye absorb relatively small amounts of energy at these wavelengths.

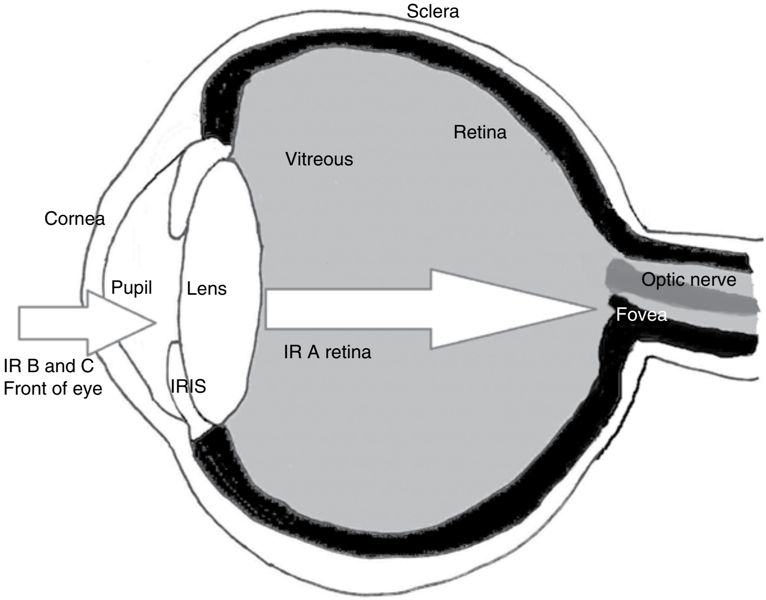

Figure 9.5 A cross section through the human eye.

At the longer infrared wavelengths (IRB and IRC), we have previously seen in Figure 9.3 that water is a strong absorber. Since the aqueous just behind the cornea at the front of the eye is essentially water, IRB and IRC absorbed in this region may lead to general increases in temperature in the eye.

However, the penetration of IRA to the retina is of importance with respect to damaging vision. IRA could lead to localized heating to the fovea, which could result in severe visual handicap. Injuries peripheral to the retina may also occur from IRA exposure but could go unnoticed by the person sustaining the injury.

9.5 Traditional Sources of Infrared Radiation

Traditional sources of infrared radiation are furnaces that behave essentially as "black body" radiation sources. Newer technologies such as lamps, lasers, and laser diodes, all producing infrared radiation, may be thought of as extended sources, point sources, or coherent sources of infrared radiation. Small lamps and other physically small incoherent sources of infrared are characterized by the intensity of the radiation decreasing approximately with the inverse of the distance squared from the source ($1/d^2$), while lasers (coherent radiation) maintain nearly the same intensity of radiation irrespective of the distance from the source. These two factors are important when any risk assessment calculation for the eyes is carried out.

9.5.1 Hazards from "Traditional Sources of Infrared Radiation"

The harmful effects of infrared radiation, produced by glassblowers' furnaces were first reported by the Dutch Physician Heister in 1739 (Vos and van Norren, 2004). These effects have become commonly known as "Glassblower's cataracts".

Other infrared damage to the eye and skin has been summarized by ICNIRP (2013).

The human body regulates its internal temperature quite precisely, maintaining a nearly constant "core temperature" of 37 °C (with a variation at most of 1 °C), and any significant increase in an individual's core temperature can lead to heat stress.

It is pointed out in the earlier ICNIRP Guideline (ICNIRP, 2006) that hot industrial environments are dominated by IR-B and IR-C exposure, which is not significantly reflected by the skin. As a result, this energy is absorbed by the human body. In situations where it is difficult for the body to "shed" this energy to the environment, either due to an increase in the ambient temperature or a reduction in the body's ability to cool through evaporation (sweat), an individual may suffer heat stress as a result of their core temperature being affected.

All these potential hazards indicate that there is a need to regularly assess infrared exposure to workers in industries and workplaces where there are high-temperature furnaces or other technologies capable of producing infrared radiation.

However, infrared measurement may be too complex for routine occupational assessments and involve the use of sophisticated equipment (radiometers) (Sliney, 1998). Furthermore, standards may be difficult for the nonspecialist to interpret, as exposure limits often require the calculation of wavelength dependent equations.

As a result, there are many exposure guidelines available that have been based on measurements of a wide variety of infrared sources found in industry. These are summarized in Section 9.8.

9.6 Personal Protective Equipment

It is common practice when minimizing the exposure to potential workplace hazards to implement a hierarchy of hazard controls, which range from eliminating the hazard to the use of personal protective equipment (PPE) (Alli, 2008).

When exposure to infrared radiation cannot be eliminated at the source and other engineering controls do not reduce exposure significantly, the use of PPE is often employed. The PPE is designed to address eye and skin safety as well as heat stress.

Eye protection can be afforded by glasses and face shields containing infrared filters. It is important that the glasses meet appropriate safety standards such as EN 171:2002 "Personal eye protection – Infrared Filters – Transmittance Requirements and Recommended use" (Comite Europeen de Normalisation, 2002).

Protection of the skin and heat stress is often considered jointly as covering the skin is a simple way to reduce infrared exposure; however, it may limit the body's ability to cool itself through evaporation. In situations where personal cooling is an issue, auxiliary body cooling may be achieved through the use of cooling vests or suits (OSHA, 1999).

9.7 Recent and Emerging Infrared Technologies, Including Lasers, Laser Diodes, LEDs, and Terahertz Devices

Infrared lasers find use in modern optic fiber communication systems, medicine, and science. Lasers are characterized by producing "coherent" radiation or radiation comprising a single frequency, which is reflected back and forth between very nearly parallel mirrors. The "front mirror" is typically only around 99% reflective and the thin beam that emerges from that mirror is highly collimated. This highly collimated property of lasers makes them unique and useful among light sources, but also means that potential hazards can exist at great distances from the source. In medicine, CO_2 lasers (10.6 µm) are commonly used in surgery, while the Nd:YAG laser (2.8–2.92 µm) is commonly used for ophthalmic treatments.

Laser diodes are solid-state lasers. While they were first reported in 1962 by several research groups in the United States, it was not until the early 1970s that a semiconductor laser was operated continuously at room temperature (Zappe, 2004). These advances mean that such devices have come to prominence more recently in consumer products such as CD and DVD players. Unlike nonsemiconductor lasers, laser diodes produce a divergent cone of radiation that needs collimating optics to reduce the divergence.

Submillimeter or terahertz radiation ranges from 0.1 mm to 100 µm and sits between microwaves and the traditional infrared wavelengths. While terahertz radiation is strongly absorbed by water, it can still be used for wireless applications for distances up to several meters.

Passive terahertz scanning may also find further use in medical diagnostic imaging and security screening due to its higher resolution than millimeter scanners and its ability to penetrate clothing.

A recent review of possible biological effects of THz radiation (Wilmink and Grundt, 2011) concluded that although biological changes have been noted across a wide range of organisms, the results are still at a somewhat preliminary stage and that "the majority of the genotoxicity studies performed to date show that THz radiation does not cause adverse effects to DNA structure or function".

9.8 Infrared Exposure Standards and Guidelines

In Australia and elsewhere, national authorities refer to "Guidelines on Limits of Exposure to Incoherent Visible and Infrared Radiation" (a "trusted international standard"; produced by the International Commission on Non-Ionizing Radiation protection (ICNIRP, 2013)).

These guidelines establish maximum levels of exposure to incoherent optical radiation produced by natural and artificial sources. They do not cover exposure to coherent radiation produced by lasers.

In addition, the guidelines do not address how to measure and calculate the potential hazards produced by incoherent sources but they do provide a detailed overview of the sources of this radiation and the biological effects.

The European Commission's "Non-binding guide to good practice for implementing Directive 2006/25/EC 'Artificial Optical radiation' " is a more "operational document" as it claims to have been designed to assist employers in small- to medium-sized businesses in assessing hazards posed by artificial sources of optical radiation. The guide focuses on common exposure situations found in the workplace.

The usefulness of the guide lies in the fact that it provides a list of sources that can be generically assessed as not being likely to exceed exposure limits. For example, an infrared radiation hazard without strong visual stimulus within 1000 seconds is in the guide's "Exempt Group", which is considered not to pose "photobiological hazards". Appendix D of the guide provides a number of useful "Worked examples" and useful simplifying assumptions for hazard assessment.

The American Conference of Governmental Industrial Hygienists (ACGIH) publishes "Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices" and various guidelines to be used by industrial hygienists when making decisions regarding safe levels of exposure to various physical agents found in the workplace. The threshold limit values (TLV) and biological exposure indices (BEI), published by the ACGIH, are commonly adopted by the US Occupational Health and Safety Administration (OHSA, 1999).

Exposure standards for lasers are covered in detail in Chapter 10.

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10

Laser and Optical Radiation Guidelines

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10.1 Introduction

There are many standards and guidelines available to aid in the regulation of lasers and ensure that lasers in use are fit for purpose and that the associated hazards are appropriately characterized and managed. Some guidelines have also been developed to place restrictions on the use of specific lasers by the public based on output power levels.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has developed several guidelines for lasers and other optical sources emitting both visible and infrared radiation. The ICNIRP guidelines focus on safe exposure limits for people exposed to a wide range of optical radiation sources, including lasers, based on the specific mechanisms of damage or biological effect from the exposure. There is also the International Organization for Standardization (ISO), which develops international laser standards for both operational and safety purposes.

The majority of developed countries implement the standards and guidelines produced by the International Electrotechnical Commission (IEC). Other countries that use lasers commercially, in industrial or medical applications and for private use, such as the United States of America, have developed their own standards under the governance of the American National Standards Institute (ANSI).

The IEC and ANSI standards apply to the classification of laser products and the requirements for operators in promoting and practicing an acceptable level of safety in their use. These standards cover the operation of lasers over a variety of applications, environments, and industries and focus on defining safety requirements for people who may be exposed to lasers.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

10.2 Guidelines and Standards for Lasers

An exhaustive overview of the available standards and guidelines that have been developed globally for the purposes of promoting and maintaining a level of safety around the use of lasers and other optical sources is beyond the scope of this chapter. However, the main guidelines will be discussed along with some of the differences between them. The IEC and ANSI standards may be considered as "mainstream" in laser protection, covering the general aspects underpinning safe laser use and also applying these concepts to specific settings. Both the IEC and ANSI series of standards are derived from a selection of ISO standards appropriate to their specific scope and objective. ICNIRP provides useful information on health effects and exposure limits.

10.3 Laser Standards

10.3.1 International Electrotechnical Commission (IEC)

The IEC standards governing laser safety, known as IEC 60825, are the most widely adopted and therefore most applicable laser safety standards in the world. The IEC is dedicated to the harmonization of global standards. The standards developed are adopted on a voluntary basis by the member countries of the IEC. In the case of laser safety, the IEC standards have been adopted by Europe, Australia, New Zealand, Canada, the United Kingdom, Japan, and many other countries. The exception is the United States of America, a member nation of the IEC that has not adopted these IEC laser-specific standards.

The IEC laser safety standards generally take on a country-specific designation when adopted. For example, IEC 60825 are listed as AS/NZ IEC 60825 in Australia and New Zealand and (European Standard) EN 60825 in Europe with each country having its own version such as (British Standard/European Standard) BS EN 60825 for the United Kingdom.

There are a number of IEC standards for laser safety that cover general and specific aspects of laser safety in various industries. Collectively, they include information on:

- The classification system and classification requirements including measurements of laser products
- Guidance and checklists for laser manufacturers
- Engineered safety guards requirements for protection against laser beams
- Requirements for laser safety protective eyewear
- Laser safety training and responsibilities of laser safety officers
- Identification and characterization of hazards associated with the use of lasers
- Engineering, administrative, and personal protective equipment guidelines for laser hazard mitigation

- Guidance for the use of lasers in the entertainment industry where lasers are used in light shows and active or static displays
- Use in optical fiber communications systems
- Guidelines for the safe use of laser medical equipment.

10.3.2 American National Standards Institute (ANSI)

The laser safety standards applied in the United States, known as the ANSI Z136 Series, cover very similar topics to the IEC standards and some other more specific applications of lasers. There are a number of differences between the requirements set out in ANSI standards versus IEC standards. For example, the laser classification system differs slightly. There are, however, measures in place in the United States to allow for industry to accept the use of the IEC system for imported laser products. The ANSI laser safety standard series contains information, and requirements covering topics common to the IEC standards. In addition, the ANSI standards cover some more specific areas including the following:

- Guidance for safe use of lasers in educational settings and educational institutions, which focuses on mitigating exposures to employees and students
- Guidance for the use of lasers in research where traditional safeguards that are present in a commercial setting may be absent from laser design or management practices
- Safe use of lasers in outdoor environments including applications in astronomy, construction and the military
- Guidance on the safety of visible lasers in commercial flight zones
- Safe use of lasers in manufacturing aimed at protecting individuals in the public and workforce from potential exposure.

10.4 Laser Guidelines

10.4.1 International Commission on Non-ionizing Protection (ICNIRP)

ICNIRP has produced two major guidelines and a supplementary revision in regard to laser protection. The guidelines are based on biological effects of exposure to laser radiation. Exposure limits to the eye are based on ocular damage thresholds through two mechanisms, photoretinitis (photochemical) and retinal burns (thermochemical). Limits on skin exposure are similarly derived through these mechanisms and focus on similar effects to sunburn (erythema – reddening of the skin) at short wavelengths and thermal injuries in the infrared region.

The primary guideline sets out limits of exposure to laser radiation covering the spectrum from the UV region, from 180 nm, through the visible and into the far infrared region up to 1000 μm. The purpose of this guideline is to establish the limits of exposure at which there are no adverse effects to the eyes and skin. The limits are dependent on wavelength, laser type (CW, pulsed, etc.), and duration of exposure. The different biological effects and mechanisms of injury are discussed in reference to the particular wavelength regions. Exposure limits are expressed as irradiance or radiant exposure over wavelength ranges for a defined exposure timeframe.

There was a revision of the guidelines on limits of exposure to laser radiation of wavelengths between 400 nm and 1.4 μm. Through the review of past criteria for establishing the ocular exposure limits, the revision resulted in splitting exposure limits for the eye into two groups based on the mechanism of damage. As a result, this guideline gives exposure limits for photochemical injuries and thermochemical injuries separately.

ICNIRP has also produced a statement and rationale for limits imposed on the use of laser pointers for the general public. This document contains a brief description on the potential retinal hazards and discusses the potential for injury based on wavelength and consequently the mechanism of biological effect.

10.4.2 Inconsistencies in Laser Classification

One of the broader challenges concerned with laser safety is the classification of laser products. This is important from the perspective of characterizing the risk in the use of specific lasers in regards to the accessible emission limit (AEL), which is based on a combination of power output and wavelengths (Schulmeister, 2013). As it is the requirement of the manufacturer of lasers to provide the laser classification and label the equipment accordingly, a nonharmonized system can be potentially burdensome. The problems arise when requirements for importation and licensing in the use of lasers are measured against these requirements.

Table 10.1 summarizes the difference in laser classifications between the IEC and ANSI standards. The main differences are in the use of terminology across laser classes with common classification criteria. There are also subclasses of lasers that are not covered consistently across both standards.

10.4.3 Other Optical Radiation Guidelines

ICNIRP provides a range of guidelines for the exposure limits and health effects associated with the use of visible and infrared radiation sources. These limits are also based on the biological mechanisms discussed for lasers, photochemical, and thermochemical injuries.

The principal guidelines give exposure limits, derived from current knowledge on damage thresholds of the eyes and skin, applied to incoherent and broadband visible and near infrared radiation. The limiting exposure is considered in terms of ocular damage in the visible and infrared wavelengths for these sources.

Table 10.1 Differences in laser classification between IEC and ANSI standards.

<table>
<tr><th>Laser class</th><th>IEC 60825</th><th>ANSI Z136</th></tr>
<tr><td>Class 1</td><td colspan="2">Lasers that are safe under reasonably foreseeable circumstances and normal operation. They can emit laser radiation in both the visible and nonvisible wavelength regions</td></tr>
<tr><td>Class 1M</td><td>Class 1 lasers that may be hazardous if viewed in conjunction with magnifying optics. These lasers usually have high divergence or large beam diameters</td><td>N/A</td></tr>
<tr><td>Class 1C</td><td>Class 1 lasers that are used in contact with a targeted area of treatment such as the skin. These types of lasers would include those intended for hair removal and various other skin treatments</td><td>N/A</td></tr>
<tr><td>Class 2</td><td colspan="2">Low-power visible wavelength lasers. Protection of the eyes is provided by the aversion blink response, which takes 0.25 s. The AEL for these lasers when they are CW is restricted to no more than 1 mW</td></tr>
<tr><td>Class 2M</td><td>Class 2 lasers that may be hazardous despite the blink aversion response if used in conjunction with magnifying optics. These lasers usually have high divergence or large beam diameters</td><td>N/A</td></tr>
<tr><td>Class 3A</td><td>N/A</td><td>Lasers that have between one and five times the AEL of a Class 1 laser in the wavelength ranges lower than 400 nm and higher than 700 nm or no more than five times the AEL of a Class 2 laser</td></tr>
<tr><td>Class 3R</td><td>Lasers that have up to five times the AEL of a Class 1 nonvisible wavelength laser or Class 2 laser. Restricted to an AEL of between 1 and 5 mW</td><td>N/A</td></tr>
<tr><td>Class 3B</td><td colspan="2">Medium-power lasers restricted to an AEL of between 5 and 500 mW. Hazards are significant from intrabeam viewing and specular reflections. The emission can be either visible or nonvisible</td></tr>
<tr><td>Class 4</td><td colspan="2">High-power lasers that have an AEL in excess of 500 mW. Intrabeam viewing is dangerous and there are significant hazards from both specular and diffuse reflections. They are also hazardous to the skin and may ignite fires. The emission can be either visible or nonvisible</td></tr>
</table>

To supplement these guidelines, ICNIRP has also developed statements on hazards, hazard assessment, biological effects and recommendations for protection, and the application of exposure limits for light-emitting diodes (LEDs), laser diodes, and far infrared radiation.

10.4.4 List of Laser and Optical Radiation Guidelines

American National Standards Institute, ANSI Z136.1 – Safe Use of Lasers.

American National Standards Institute, ANZI Z136.2 – Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources.

American National Standards Institute, ANSI Z136.3 – Safe Use of Lasers in Health Care.

American National Standards Institute, ANSI Z136.4 – Recommended practice for laser safety measurements for hazard evaluations.

American National Standards Institute, ANSI Z136.5 – Safe Use of Lasers in Educational Institutions.

American National Standards Institute, ANSI Z136.6 – Safe Use of Lasers Outdoors.

American National Standards Institute, ANSI Z136.7 – Testing and Labeling of Laser Protective Equipment.

American National Standards Institute, ANSI Z136.8 – Safe Use of Lasers in Research, Development, or Testing.

American National Standards Institute, ANSI Z136.9 – Safe Use of Lasers in Manufacturing Environments.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 180 nm and 1000 μm.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), Revision of Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 400 nm and 1.4 μm.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Statement on Laser Pointers.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Guidelines on Limits of Exposure to Incoherent Visible and Infrared Radiation.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Guidelines on Limits of Exposure to Broad-band Incoherent Optical Radiation (0.38–3 μm).

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Statement on Far Infrared Radiation Exposure.

International Commission on Non-Ionizing Radiation Protection (ICNIRP), ICNIRP Statement on Light-Emitting Diodes (LEDs) and Laser Diodes: Implications for Hazard Assessment.

International Electrotechnical Commission, IEC 60825-1 Safety of Laser Products – Part 1: Equipment classification, requirements and user guide.

International Electrotechnical Commission, IEC 60825-2 Safety of Laser Products – Part 2: Safety of optical fiber communication systems (OFCS).

International Electrotechnical Commission, IEC 60825-3 Safety of Laser Products – Part 3: Guidance for laser displays and shows.

International Electrotechnical Commission, IEC 60825-4 Safety of Laser Products – Part 4: Laser guards.

International Electrotechnical Commission, IEC 60825-5 Safety of Laser Products – Part 5: Manufacturer's checklist for IEC 60825-1.

International Electrotechnical Commission, IEC 60825-8 Safety of Laser Products – Part 8: Guidelines for the safe use of medical laser equipment.

International Electrotechnical Commission, IEC 60825-12 Safety of Laser Products – Part 12: Safety of free space optical communication systems used for transmission of information.

International Electrotechnical Commission, IEC 60825-13 Safety of Laser Products – Part 13: Measurements for classification of laser products.

International Electrotechnical Commission, IEC 60825-14 Safety of Laser Products – Part 14: A user's guide.

International Electrotechnical Commission, IEC 60825-17 Safety of laser products – Part 17: Safety aspects for use of passive optical components and optical cables in high power optical fiber communication systems.

References

Schulmeister, K. 2013. The Upcoming New Editions of IEC 60825-1 and ANSI Z136.1 – Examples on Impact for Classification and Exposure Limits. Proceeding of the International Laser Safety Conference, Laser Institute of America, 18-21 March 2013 Orlando, Florida. pp. 330–337.

11

Laser Measurements

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11.1 Introduction

The accurate measurement of laser power or energy output is important in characterizing the hazard from a protection perspective. However, measuring the parameters of a laser can present major challenges due to the large number of wavelengths and power ranges. The choice of instrument or method will depend on the specific parameters (power, energy, divergence, and beam width) being measured and the properties of the laser (wavelength and mode).

In high-powered lasers, the exposure to the eye, and sometimes even the skin, can be many orders of magnitude higher than prescribed exposure limits. The laser hazard, unlike other hazards such as chemical or noise, can still be significant at large distances. This is due to the point source nature of lasers where the energy is focused into a very small area. The beam itself can often be perceived by an observer, so protection comes as a result of avoidance of the hazard. Injury will often result as a consequence of accidental or indirect (reflection) exposure or by misuse.

Although the hazard of reflections during the setup and operation of Class 3B and Class 4 lasers should be considered, measurements prove to be both difficult and not reproducible from a quantitative perspective. For example, any environmental changes such as inconsistencies in the reflecting surfaces (e.g., flatness, shape, and position) or changes in operational mode of the laser itself may significantly alter the results. Measuring reflections from lasers that emit nonvisible wavelengths also makes these measurements difficult. Generally, the easiest and most common way to categorize the hazard from a laser is to restrict the measurements to its output.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

11.2 Measurement Parameters for Lasers

From a radiation protection perspective, the radiometric parameters that are of most importance when measuring the output from lasers are *radiant power* and *radiant energy*. The radiant power (P_0) of a laser, also referred to as the radiant flux, is measured in watts. This parameter applies where the beam power output is constant over time as in a continuous wave (CW) laser or in the case of a pulsed laser where it is the average power. The radiant energy (Q), measured in joules, of a laser refers to the output from a pulsed laser. The radiant energy is a function of the pulsed lasers' peak power output (P_p) multiplied by the pulse duration (t). This relationship is expressed as

$$Q = P_\text{p} \times t \tag{11.1}$$

The average power (P_a) of a pulsed laser is calculated by measuring the pulse energy (E_p) and multiplying it by the *pulse repetition rate or frequency (f)* in hertz. This is shown by the following equation:

$$P_\text{a} = Q \times f \tag{11.2}$$

The average power is relevant from both a safety and an operational perspective. When characterizing the hazard associated with a pulsed laser, the peak power may also need to be considered as it may be many orders of magnitude higher than the average power. In this instance, the specific hazard is highly dependent on the length of the pulse and the time of exposure. If the peak power of the laser beam is high but the pulse duration is in the order of femtoseconds, the total energy delivered is very low per pulse. However, if exposure to several pulses over a longer time period occurs, or the pulses are of longer duration (milliseconds), then the energy delivered will be much higher. More fundamental measurements conducted on lasers are associated with the beam profile. These usually include the *beam diameter* (d_u) and the *beam divergence* (ϕ) in radians. The beam diameter is one of the most important properties of a laser beam as there are many types of laser beam profiles. The beam divergence is a measure of how quickly the beam expands as it travels in air. These measurements can often be challenging to perform because the beam profile is not always single mode and can fluctuate significantly in some cases. These parameters are important in order to characterize risk at a distance from the emergent beam. For example, in Chapter 8, the nominal ocular hazard distance (NOHD) was described as a significant factor in minimizing the hazard from the laser radiation. For highly divergent beams, the radiant power and radiant energy decrease with increasing distance. From the knowledge of the parameters described, other properties of a laser can be calculated including:

- Irradiance (E) – the radiant power or flux *received* by a surface in watts/meter
- Radiant exposure (H_e) – the radiant energy *received* by a surface in joules/meter.

These quantities can also be measured directly and are important in defining the maximum permissible exposure (MPE) as described in Chapter 8.

Table 11.1 shows the important parameters for different lasers that are useful to measure or calculate in order to characterize each laser type. This information can then be used to characterize the hazard.

11.3 Measurement Methods

11.3.1 Radiant Power and Radiant Energy

There are several types of detectors available for measuring the radiant power and radiant energy of lasers. The choice of detection system will depend on the properties of the light being measured. The primary consideration will be the wavelength of interest in the measurement. The detector should have an acceptable sensitivity or response within the wavelength band to be measured. Conversely, another factor that may be considered is blindness to bands of radiation that are not of interest. This is useful in negating the effects of ambient background light interfering with measurements. For example, if one is measuring visible wavelengths, it would be useful to select a detector that shows a low response or is blind to infrared wavelengths.

Other properties that may be considered include the linearity in response, stability, and durability of the detectors. Linearity is important because it allows for easier calibration of the detector and greater certainty in the measurements. Stability is taken into account because the response of some detectors changes with environmental factors such as temperature. As a result, some detectors must be cooled or modulated to remain stable. Durability is considered due to the delicate nature of some detectors. Some may be damaged from excessive light or may have detection surfaces or optical components that are easily damaged by surface contact.

Finally, the measurement of the emission from different types of lasers requires the use of specific types of detectors. The main types of detectors that will be discussed include the following:

- Pyroelectric sensors that can only be used to measure the output from pulsed lasers
- Thermopile sensors that can be used to measure both CW and pulsed lasers
- Semiconductor photodiodes/optical sensors that are mostly used for low-power CW lasers but may be used for low energy pulsed lasers under certain circumstances.

11.3.2 Pyroelectric Sensors

This type of sensor is very useful for measuring the energy output of pulsed lasers. These sensors work by absorbing light onto the surface of the detector

Table 11.1 Key parameters for characterizing different types of lasers.

Laser type	**Key measurement parameters**						
	Beam diameter (d_u) (m)	**Beam divergence (ϕ) (rad)**	**Average radiant power (P_a) (W)**	**Peak radiant power (P) (W)**	**Radiant energy (Q) (J/m^2)**	**Pulse duration (t) (s)**	**Pulse repetition rate or frequency (f) (Hz)**
Continuous wave (CW) laser	Yes	Yes	Yes				
Repetitively pulsed laser	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Single pulse laser	Yes	Yes		Yes	Yes	Yes	

that consists of a metal doped crystal. The crystals polarize when the incident light heats them, creating an equal and opposite charge on the other side of the detector surface. This charge, which is proportional to the pulse energy, is collected by a capacitor and translated into a signal that can be read by an appropriate meter. Due to the fact that the metal is doped within the crystal, the capacitor responds consistently regardless of position on the surface the incident light hits.

The crystal depolarizes very quickly and the capacitor is electronically discharged which gives this type of detector a very fast response rate. This makes them useful for measuring peak energy in lasers with pulse repetition rates of in the order of thousands per second. Their sensitivity also means that low-energy pulses can be measured. However, they are affected by high-energy pulses because of the low durability of the sensor surface. Attenuating or diffusing optical components (filters or diffusing mirrors) are often needed in order to decrease the intensity of high-energy pulses before they reach the detector surface.

11.3.3 Thermopile Sensors

These sensors are used to measure the radiant power of CW lasers with power outputs from tens of milliwatts to the kilowatt range and the average radiant power of pulsed lasers with repetition rates in the order of kilohertz or less.

These sensors work by measuring the quantity of heat flowing through the detector surface. The thermal energy interacts with thermocouples that are arranged in an array near the edge of the sensor's surface. This array normally takes the form of a disk as shown in Figure 11.1. The incident light hits the central disk area and the heat generated radiates toward the periphery that serves as a heat sink. This area of the disk is cooled to ambient temperature by means such as convection cooling or water cooling.

The heat flowing through the detector surface is independent of the beam position and size. As long as the light hits within the central area, the readings will be consistent, allowing for the measurement of lasers with a range of beam profiles.

Further, changes in ambient temperature do not affect the reading because the absolute temperature of the sensor is not what is being measured. Rather, it is the change in temperature across the thermopile, which is measured as thermal power and is converted into a signal for the meter. As long as the initial ambient temperature in the central disk area and the periphery is the same, the temperature change caused by the laser radiation is generally relative.

Thermopiles have the largest optical wavelength range, in terms of sensitivity and responsivity, of all sensors. They are therefore particularly useful for measuring infrared wavelengths, especially beyond 1800 nm. Due to their wavelength independence, durability, and reliability, thermopiles are one of the most popular measurement sensors for lasers. They are, however, limited by their slower

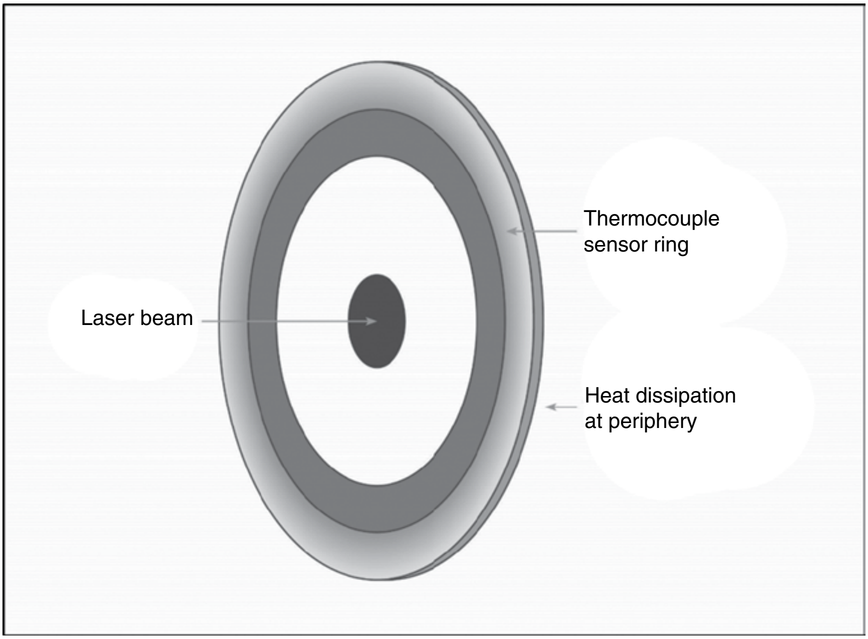

Figure 11.1 Thermopile sensor arrangement for measuring laser power.

response time and lower energy sensitivity. This means that they are not able to measure repetitive pulses or very low radiant power or energies.

11.3.4 Semiconductor Photodiodes/Optical Sensors

Photodiode detectors and optical sensors work by converting the incident light hitting the photodiode into a current. The most common photodiodes are semiconductor P–N junctions. The current is created when light of sufficient energy gives an electron within the depletion region of the semiconductor diode enough energy to go from the valence state to the conduction state, releasing it from the atomic structure. This creates an electron–hole pair where the electron is negatively charged and the hole is positively charged. This electron–hole pair is collected in an associated circuit producing a photocurrent.

The efficiency of these detectors is highly wavelength dependent. Shorter wavelengths with high energy release the same number of electrons as longer wavelengths with less energy. This means that the energy conversion efficiency increases with wavelength until the wavelength is so long that the photons hitting the sensor have insufficient energy to release the electrons in the semiconductor diode. At this point, the efficiency rapidly drops off.

Photodiode sensors are very sensitive and are useful for measuring the output from CW lasers of very low power in the nanowatts to low milliwatt range.

Under these circumstances, their response is very linear, but at higher powers, they are prone to photocurrent saturation that affects their linear response. Higher powers in the order of watts can be measured provided that attenuating optics are incorporated into the measurement setup. In addition, due to the response being wavelength dependent, calibration over a complete range of wavelengths is necessary.

11.3.5 Meters

The choice of meter will depend on the radiometric measurements and has to be compatible with the specific sensor. For example, if a sensor was used to measure radiant power, then a meter also capable of measuring radiant power is required.

Whatever the application, there are some characteristics that affect the performance of a meter. For the measurement of radiant power, the background levels of the signal noise of the meter should be considered. This is especially important when performing measurements of lasers with low-power output. For meters that measure the radiant energy, the maximum repetition rate and resolution time is an important feature. Higher performance meters for energy measurements are required for measuring lasers with fast pulses.

It is important that any meter and sensors used to measure laser output are calibrated to traceable standards both initially and on a regular basis to assure correct response. Calibration is necessary not only for radiant power and energy response but also for response across wavelength bands.

11.4 Beam Diameter and Beam Divergence

The measurement of beam diameter is fundamentally important for characterizing the hazard from the laser and comes with its own set of challenges. The difficulty primarily arises from the fact that it is problematic for an instrument to calculate or define where the beam boundary is spatially because the energy profile does not have a sharp edge. This problem is often referred to as the laser energy extending into the “wings” of the beam much like the wings in a Gaussian distribution. The beam diameter is also important in determining the divergence of the beam. The divergence will determine the diameter of the beam at points along its pathway of propagation.

There are several methods available for measuring the beam diameter and divergence of emergent laser radiation. In this chapter, the more recent and common measurement techniques will be discussed. Laser beams come in different shapes and modes, however, for simplicity in describing the methods of measurement only beams that have Gaussian (the maximum energy or power is at in the center of the beam and drops off toward the edge of the emission cross-sectional area) energy profiles will be considered.

11.4.1 Full-Width at Half Maximum (FWHM) Measurement

In this method, a beam profiler is used to measure the width between two opposite points in the beam where the peak energy is half of its maximum value. These two points then define the edges of the beam. Due to the fact that the energies measured are relative to each other, this method was commonly employed because the calculation is not effected by the signal-to-noise ratio of the measurement instrument or the energy in the wings of the beam. This makes measurements relatively consistent.

11.4.2 $1/e^2$ Measurement

This method of beam diameter profiling measures a specific percentage of the beam intensity. This is often referred to as measuring the Gaussian diameter. In this case, the diameter of the beam at which its intensity equals $1/e^2$ (e is a constant where $e \approx 2.7183$) times the maximum intensity of the laser beam. Therefore, the edges of the beam profile are defined at the point where the energy intensity drops to 13.5% ($1/e^2$) of the intensity of the beam axis or center (Jacobs, 2006).

This measurement can be accomplished by placing an adjustable circular aperture within the beam center. The diameter of the aperture is then adjusted until 86% of the laser energy propagates through the hole and reaches a detector ($100\text{–}13.5\% \approx 86\%$). The diameter of this hole is then accepted as the $1/e^2$ diameter of the laser beam. Another way of accomplishing this is to use a camera system or a charged couple device (CCD) and simply count the number of pixels and their intensity in the image created by the beam profile. To characterize the beam diameter, this is done until 86% of the energy is counted.

This method is limited as the results of both of the techniques used can be somewhat subjective and therefore uncertainty in measurement may be higher than desired. It is also only applicable to round beams and will not give any information on the nature of elliptical beam profiles and may create underestimates in diameters of beams with holes in the center.

11.4.3 Knife-Edge Measurement

Until recently, this method was one of the most commonly used techniques for achieving accurate measurements of beam diameter. This made it a very widely used method and as a result is still currently in use. In the past, this technique of beam profiling was more commonly accomplished by using mechanical scanning beam diameter measurements. This involved literally placing a knife-edge obstruction at specific energy points along the beam profile. More recently, camera-based electronic beam profilers are used for this task; however, the principle is essentially the same.

Whether the edge is mechanical or determined by software, it is defined as a position where a percentage of the laser energy is "clipped". The most common diameter definition is the 10/90 knife edge where the boundaries are defined and the energy is at 10% and 90% of the maximum energy of the beam, respectively (Photonics, 2016). This means that the beam diameter encompasses 80% of the total energy of the beam.

This method is useful for defining the diameters of beams that are elliptical because the measurement can be performed on both the *x*- and *y*-axis of the beam cross section.

11.4.4 Second Moment or D4σ Measurement

This method is captured within the ISO 11146-1(2005) standard for measurement of laser beam diameters and is widely considered to be the truest method of estimating the beam diameter. The second moment, or variance, of the Gaussian beam takes into account the energy in the wings of the beam profile and is independent of the structure of the profile in the wings. Energy versus distance from the beam axis is integrated which allows for the measurement of a weighted beam diameter. This technique is also called the D4σ method because the resultant calculation of the beam diameter is four times the standard deviation of the energy distribution in the profile.

The problems that are associated with this method include the measurement of beams with high diffraction and noise in the profiling CCD camera. If there is enough diffraction in the incident beam, this creates a situation where there is energy in the wings of the beam that is not part of the actual beam coming from the laser. Until recently, the noise from the CCD camera added a signal far out into the wings. This was integrated as part of the energy in this region resulting in a heavier weighting in this area and thus effecting the diameter measurement. For this reason, it is important to use CCDs with low signal noise.

11.5 Divergence Measurements

11.5.1 Beam Diameter at Distance

The simplest way of measuring the divergence of a laser beam is to measure the beam diameter at different distances along its propagation path. Although this technique seems to be theoretically sound and intuitive, the methods used for beam diameter estimation must be appropriate for the type of beam being measured in order to minimize uncertainties in the result. The propagation of uncertainties in measurements along the pathway may make the divergence measurement problematic. In addition, the distances may not be long enough to measure small angles of divergence so this technique is restricted to highly divergent lasers.

11.5.2 Divergence at Focal Length Measurement

The divergence at focal length method utilizes optics such as reflectors or, more commonly, refracting lenses to focus the incident laser beam toward a CCD camera or other detector. This detector is used to take a measurement at the focal length (f) of the focusing optic. The divergence can then be calculated by measuring the size of the resultant spot that is focused onto the detector surface. The spot size is related to the divergence by taking into account the focal length of the imaging optic at the specific wavelength of the laser.

The principles behind this measurement technique are shown in Figure 11.2. For a collimated beam with no divergence, the focus of the spot will occur at the surface of the detector. For a beam that diverges, the focus will occur behind the surface of the detector. Hence, the larger the spot, the greater is the divergence of the laser beam.

Using this method, the beam divergence can be measured at any point along the propagation path of the beam. The optical setup has to be performed with meticulous care. The lens must be large enough in diameter in relation to the beam to negate the effects of diffraction and has to be of extremely high quality in order to minimize internal effects based on imperfections in the material.

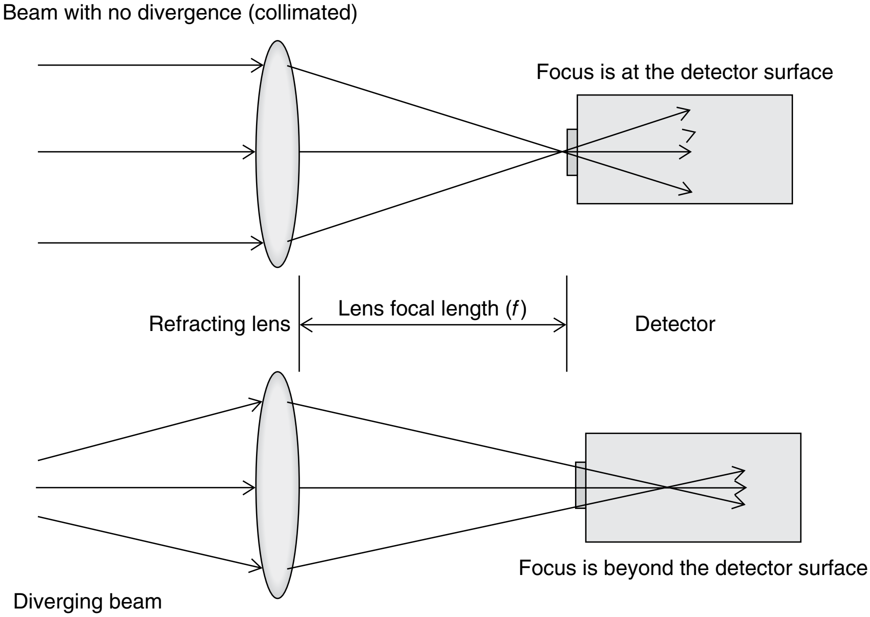

Figure 11.2 Setup for measuring divergence with lens and a CCD camera. The lens is placed at the focal length of the lens at the wavelength being measured.

Tutorial Problems

1. Name four important parameters that are measured to characterize lasers from a safety standpoint. For each of the parameters, decide if it is applicable to CW or pulsed lasers. (Note that some parameters may be applicable to both.)

2. Describe the most applicable sensor for measuring:
   a. low average radiant power output from a CW laser
   b. pulse energy from a pulsed laser
   c. infrared wavelength lasers or infrared sources

3. Describe two methods for measuring the beam diameter of a laser.

4. Describe how divergence is measured using the divergence at focal length measurement method. Why is the divergence of a laser important from a safety perspective?

References

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Part IV

Radiofrequency (RF) and Microwave Radiation

12

Thermal Effects of Microwave and Radiofrequency Radiation

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12.1 Introduction

Whatever disagreement might exist about “nonthermal” biological effects of radiofrequency (RF) and microwave energy, there is no doubt that the dominant mechanism by which RF and microwave energy produces biological effects is through the deposition of power and the consequent temperature increase in the biological system.

This chapter considers *thermal effects* of RF and microwave energy. “Thermal” is used in this chapter in a mechanistic sense (referring to effects caused by a local increase in temperature), not with reference to whether an effect is reported at low exposure levels. This terminology is not consistently used in the literature; however, some authors use the term “nonthermal” or “athermal” with reference – even in the same paper – to an effect that was reported at exposure levels that the investigator considers to be “low” (even though the mechanism for the effect may be completely unknown and may indeed be thermal). Expert groups that review the literature acknowledge the difficulty of distinguishing “thermal” from “nonthermal” effects (in the mechanistic sense) (NCRP, 1986, p. 5) and focus their attention on a search for evidence for adverse effects that can be used as a basis to design exposure guidelines, without regard to whether they are "thermal" or not.

This chapter focuses on thermal effects of RF energy in three sections: (i) thermal effects that are potentially related to hazards, (ii) mechanisms for thermal effects in biological systems, and (iii) models for heating of tissue by RF energy. Introductory technical comments about the physics of RF energy

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are in Chapter 1. An enormous literature exists on related topics, for example, RF-induced hyperthermia for treatment of cancer and (RF) catheter ablation for treatment of cardiac arrhythmias. These will not be discussed in this chapter.

As electromagnetic energy is absorbed by tissue, it is converted into heat. In the absence of heat transfer, this will result in a rate of increase in temperature T with time t

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{1}{C_p}\mathrm{SAR} \tag{12.1}$$

where C_p is the specific heat of the material and SAR the specific absorption rate. The SAR is related to the RMS electric field strength E by

$$\mathrm{SAR} = \frac{\sigma E^2}{\rho} \tag{12.2}$$

where σ is the electrical conductivity of the tissue (S/m) and ρ its mass density (kg/m^3). In the absence of heat transfer, a SAR of 1 W/kg will result in a rate of temperature increase in about 0.018 °C/min in typical soft tissue. The rate of heating is associated with the root-mean-squared field strength and does not directly depend on the frequency of the field.

Due to the complex nature of the coupling between RF energy and the body, a number of different exposure scenarios exist that result in different problems related to heating of the body. These include the following:

- *Contact currents, which are passed into a subject from touching a conductive object that is located in an RF field or is otherwise charged with RF energy*: This can lead to serious injuries to personnel even if the external fields are far below safety limits, due to the ability of conductive objects to act as antennas and couple significant RF energy into the body. Examples include touching a construction crane that is located in the vicinity of an AM transmitting tower or touching the open end of a transmission line that is connected to an RF generator.
- *Partial body exposure from sources of RF energy that are located near an individual*: This is a typical scenario for occupational exposures in which workers are present near equipment that generate RF energy at high power levels. In such cases, the exposure may be localized to part of the body, but at a level that can produce significant tissue damage. Exposure in such cases typically occurs in the near-field of transmitters and may be technically challenging to evaluate.
- *Whole-body exposures, typically when a person is located in the far-field of a transmitting antenna*: In such cases, the total heat load to the body may be physiologically significant (in terms of thermoregulatory mechanisms), even though localized heating of the body may not be damaging thermally.

- *Exposure of the skin to high-frequency microwaves, which results in near-surface heating*: This situation has taken on greater importance with the advent of high-powered sources that operate at millimeter wave frequencies. An example is the "Active Denial" system, developed as a nonlethal weapon for crowd control by the US military that uses intense pulses of millimeter waves (at about 95 GHz) to produce thermal pain in the intended targets. The risk management issues for such high-frequency energy are similar to those associated with high-intensity infrared radiation.

At sufficiently high frequencies (called the quasi-optical range), the pattern of energy deposition in the body becomes similar to that for a plane wave incident on a plane slab of tissue. In that case, the SAR as a function of depth x into the tissue is given by

$$\mathrm{SAR} = \frac{I_o T_{\mathrm{tr}}}{\rho\delta} e^{-x/L} \tag{12.3}$$

where T_{tr} is the energy transmission coefficient from air into tissue and L the energy penetration depth. In terms of the relative permittivity and conductivity of the tissue ($\boldsymbol{\varepsilon}_\mathrm{t}$, $\boldsymbol{\sigma}_\mathrm{t}$) and air ($\boldsymbol{\varepsilon}_\mathrm{o}$), these quantities are

$$\begin{aligned} T_{\mathrm{tr}} &= 1 - \left| \frac{\sqrt{\varepsilon_\mathrm{t}^*} - 1}{\sqrt{\varepsilon_\mathrm{t}^*} + 1} \right|^2 \\ L &= \frac{-c}{4\pi f \,\mathrm{Im}\left(\sqrt{\varepsilon_\mathrm{t}^* \varepsilon_\mathrm{o}}\right)} \end{aligned} \tag{12.4}$$

where $\varepsilon_\mathrm{t}^* = \varepsilon_\mathrm{t} - \frac{j\sigma_\mathrm{t}}{2\pi f \varepsilon_\mathrm{o}}$, c is the velocity of light, f the frequency, and ε_o the permittivity of space (a constant). Tables of the dielectric properties of tissues versus frequency are given by Gabriel, Lau, and Gabriel (1996). Figure 12.1 shows the energy penetration depth and transmission coefficient into a planar surface of tissue whose dielectric properties are typical of soft tissue such as muscle. At frequencies above about 6 GHz, the heating is, for all practical purposes, confined to the surface of the tissue.

12.2 Thermal Effects Relevant to Health and Safety

The well-known hazards of low-frequency (powerline) currents include shock and pain and (at higher current levels) involuntary contraction of skeletal muscle and cardiac fibrillation. These effects are associated with the excitation of cellular membranes by the electric current. As the frequency is increased

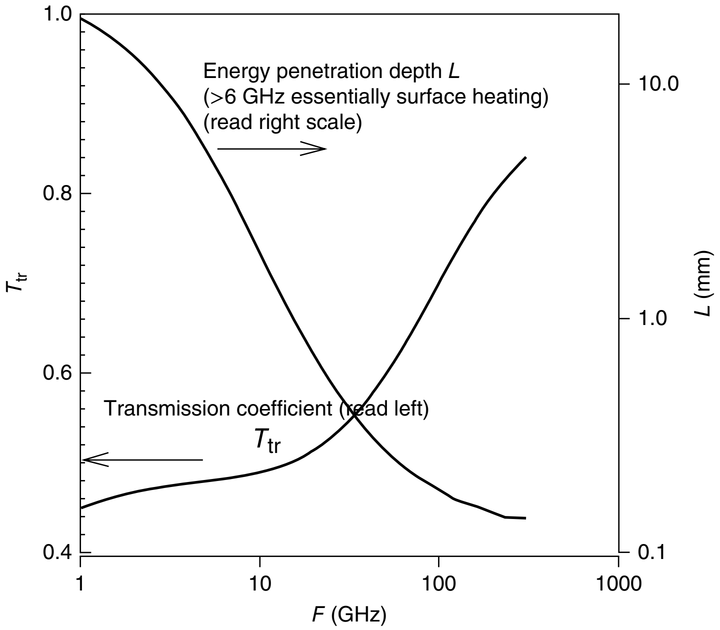

Figure 12.1 Energy penetration depth L and transmission coefficient T_{tr} for plane wave energy incident on a plane tissue surface with dielectric properties similar to soft tissue. Reprinted from Foster et al. (2016) with permission.

into the kilohertz range, the current thresholds to produce such effects increase (due to the inability of cell membranes to respond to rapidly changing fields) and thermal effects, rather than membrane excitation effects, gradually become the dominant hazard mechanism.

12.2.1 Perception and Pain

In 1986, Chatterjee and colleagues reported an extensive study of human perception of RF currents, using a total of 367 subjects. In these experiments, the subject briefly grasped a metal cylinder of 1.5 cm diameter or placed a finger against a metal plate; a metal band around the arm served as the reference electrode. Below about 100 kHz, the subjects reported prickling sensations at the threshold for perception; at higher frequencies, "almost all subjects described a heating sensation or a sensation of warmth in the hand or wrist region when perception was reported" (Chatterjee, Wu, and Gandhi, 1986). The thresholds for perception and pain increased roughly linearly with frequency from 10 to 100 kHz and then leveled off to the highest frequency of the measurements, 3 MHz.

Blick et al. (1997) measured the thresholds for perception of microwave energy for brief (10 second) exposures to microwave energy over an area of 0.024 m^2 on the backs of human volunteers at several frequencies. Regardless of frequency, the estimated increase in temperature at the skin surface at the threshold for perception was about 0.07 °C, which is in line with similar estimates for thresholds for perception of infrared energy (Riu et al., 1997). However, in terms of incident power density, the threshold for perception decreased with increasing frequency because of the shorter penetration depth into tissue and corresponding higher energy deposition near the skin surface. The same group later reported thresholds for thermal pain under similar exposure conditions, which were approximately 100 times higher than thresholds for perception and corresponded to peak skin temperatures of 43.7 °C (Walters et al., 2000).

One can expect that the threshold for perception of RF energy will depend on the part of the body that is exposed, exposure duration, the individual exposed, and other variables, and few data exist over a wide range of exposure conditions in a range of individuals, which would be desirable to set exposure limits for the population to protect against painful heating. However, it is clear that the perception of RF energy, and painful sensations from exposure, is purely a thermal phenomenon.

12.2.2 Burns

There is a considerable literature (Geddes, 2002), and many lawsuits, connected with RF-induced burns to patients from a variety of medical procedures. Examples include burns to patients undergoing MRI imaging from RF currents that are induced in electrode leads and other metal objects in contact with the patient's bodies.

There is also a scattering of reports of RF burns to workers in the proximity to high-powered RF sources. Many of these involve contact currents that are passed into the body before the worker has a chance to withdraw. For example, a well-recognized occupational hazard occurs when construction cranes are operated in the vicinity of AM radio broadcasting towers. The cranes become charged from RF fields and can pass strong RF currents into the body of a grounded worker who touches one. AM transmission towers are typically charged with high RF voltages (the entire tower is part of the antenna) and can present serious burn hazards to workers who touch them. More rarely, workers climbing towers on which antennas from high-powered broadcast transmitters are mounted can suffer burns if they come too closely to the transmitting surfaces of the antennas. Needless to say, work rules and exposure limits are in place to prevent such workplace accidents. RF burns can be very nasty, with deep tissue damage and long-term consequences to the victim. On the other hand, many reported incidents of overexposure of workers to RF fields may have involved exposures only marginally above recommended limits, where no significant thermal injury occurred because of the high level of conservatism built into the limits. In such cases, the major task of the treating physician is simply to reassure the patient (Ziskin, 2002) and see Chapter 28.

Given the ubiquity of RF technology in modern environments, remarkably few burn injuries from overexposure to RF energy are reported. Most reported injuries involve accident scenarios with very high exposures that injure the worker before he/she can withdraw, for example, from touching a conductor that is charged to high RF potential or somehow being trapped in front of a high-powered transmitter. (Hocking (Chapter 28, this volume) has documented several such injuries.) RF (and other) burns are very painful, and normal pain avoidance mechanisms would ordinarily force the victim to withdraw from exposure before damage occurs. In the same way, one can reach into the broiler in one's oven to turn over a steak. Even though the levels of infrared exposure are thermally very hazardous, it is simply too painful to keep one's hand under the broiler long enough to be burned. Kitchen stoves are potentially very hazardous, but catastrophic injuries in the kitchen chiefly involve accidents involving extreme exposure levels incurred in short times such that the victim cannot escape in time to avoid injury, for example, tipping a pot of boiling water over the body.

12.2.3 Cataracts

The possibility that RF exposure can produce cataract or other ocular damage has been controversial for many years. In the early 1970s, an ophthalmologist (Milton Zaret) reported finding subtle indications of a particular form of cataract in patients due to exposure to low-level microwave energy, for example, by use of a microwave oven (Zaret, 1974). A number of follow-up animal studies (e.g., Cleary, 1980) failed to find consistent evidence for damage at levels below recommended exposure limits. It is now well established that cataracts can be produced in animals at high exposure levels, with SAR levels above 150 W/kg, that raise the temperature of the lens to 41 °C or more over extended times (>30 minutes) (Elder, 2003). Such cataracts are clearly a result of thermal damage, and the exposure levels are similar to those needed to produce frank thermal injury in other tissues as well. In retrospect, Zaret may have simply observed minor abnormalities in the lens and attributed them to cataracts.

More recently, as part of a larger controversy about possible hazards of mobile phones, the issue has resurfaced. For example, Dovrat et al. (2005) reported damage to cultured bovine eye lenses after exposure to low-level microwave energy, which the authors considered to arise from some unknown mechanism other than thermal damage. Hässig et al. (2009) reported a "potential association" of cataracts in newborn calves with nearby presence of mobile phone antennas. While these reports would undoubtedly be insufficient to cause health agencies to revise their opinions about the lack of demonstrable eye damage from exposure to low-level microwave radiation, they will help to keep the issue alive and should lead to more research into the issue.

12.2.4 Adverse Reproductive Effects

Heat is well known to induce birth defects and cause other adverse reproductive effects as well. This has long been a source of concern to investigators and government agencies in connection with ultrasound and MRI imaging of the fetus, which can involve deposition of considerable power in the body. Birth defects and other adverse reproductive effects have been convincingly demonstrated in animals exposed to RF energy, albeit at levels that are sufficient to produce significant increases in body temperature (and which would be close to lethal levels to the exposed animals). In his extensive review, Juutilainen (2005) concluded that "there is no consistent evidence of [teratogenic] RF field effects at nonthermal exposure levels". A major review of RF-induced teratology (which was developed as part of the process of developing IEEE exposure limits (IEEE, 2005)) concluded that a temperature threshold of 41.5 °C exists for thermally induced birth defects in animals (Heynick and Merritt, 2003).

However, given the exponential dose–response relation for thermal injury (see the following discussion), the possibility of teratogenic effects at lower exposure levels cannot be ruled out and some authorities consider them to be possible. Moreover, animal teratology experiments involving RF energy have used small numbers of animals and consequently had low statistical power and inability to discern infrequent effects. "There is a range of opinions about threshold temperatures that will induce birth defects", Miller, Miller, and Church (2005) concluded, and "during pregnancy, any temperature increment above physiological levels for any duration has some potential for inducing a birth effect". By extrapolating the Arrhenius equation (see Eq. (12.6)) from high-dose studies to lower temperature increases, Church and Miller (2007) predicted that a 1 °C increase in fetal temperature maintained for 5 minutes during a sensitive period of gestation will increase the risk of a birth defect in a human by 0.004–0.05% (depending on the assumed value of the activation energy in the Arrhenius relation). Given the 4% prevalence of major birth defects in the human population in developed countries, this would translate to an increase in risk of birth defect from a nominal 4% to a nominal 4.004–4.05%, which is far too small to be observable by any conceivable epidemiology study. Moreover, this extrapolation assumes the exact validity of the Arrhenius (exponential) dose–response relation far beyond the range where it can be experimentally tested and ignores the effects of repair mechanisms that are likely to be present. If Miller et al. are correct, however, ultrasound and MRI exams that resulted in any heating of the fetus during critical times of gestation would result in some additional cases of birth defects in a large population of exposed women (even though the numbers of such additional cases might be immeasurably small given the unfortunately high background rate of birth defects in the human population).

Deliberate exposure of the testes to microwave energy at clearly thermal levels was explored in China during the early 1990s as a means of contraception, with some men receiving more than 100 treatments that raised the surface temperature of the scrotum to 40–42 °C. In a follow-up study, the authors reported that, 0.5 years after cessation of treatment, "no individuals were found to be sterile, though spermatogenesis had been severely inhibited during the period of exposure. Vestiges of damage remained, however" (Liu et al., 1991). In 2012, a California group reported that ultrasound applied to the testes of rhesus monkeys can work as a reversible contraceptive (evidently due to heating effects) and suggested that this approach is feasible for human use (VandeVoort and Tollner, 2012). So far, there appears to have been no rush to commercialize the method, which would undoubtedly raise risk-perception issues with the public and occasion many jokes by late-night television comedians.

12.2.5 Behavioral Disruption

When exposed to RF energy at thermally significant levels, animals show a range of behavioral responses ranging from obvious perception of the energy, avoidance, and disruption of performance of assigned tasks, to complete work stoppage.

The limits for whole-body exposure to RF energy that are in effect in most of the countries around the world were designed to avoid, with a large safety margin, a behavioral effect observed in animals called behavioral disruption. The phenomenon has been noted in several species of animals, at several different frequencies but at whole-body SAR levels of about 4–6 W/kg irrespective of frequency or whether the energy was pulsed or continuous-wave (d'Andrea, Adair, and De Lorge, 2003). In this effect, the animals cease to carry out an assigned task during exposure to RF energy. For example, rats trained to press a lever to obtain food pellets will, at some level of exposure, stop performing the assigned task and change to a different behavior, typically one associated with thermoregulation (in rats, spreading saliva on their tails). At some point, the motivation for food becomes weaker than the motivation to dissipate heat.

Behavioral disruption is clearly a behavioral response of the animals to an excessive thermal load imposed by the RF energy. While behavioral disruption is not directly an adverse effect, the imposed thermal loads are undoubtedly stressful to the animals. An analogous response would be a human in an overheated room who interrupts doing an assigned task and walks to the air conditioner to turn it on. Basing exposure limits for humans on thresholds for behavioral disruption observed in animals is highly conservative, in view of the far more efficient thermoregulatory systems of humans.

12.2.6 Thermal Death

Over the years, a number of studies have been undertaken to document physiological effects of RF exposure at super-lethal levels. Undoubtedly, the best documented of such studies were done in the mid-1990s by Frei and colleagues in San Antonio, Texas, in collaboration with a group in the Air Force (e.g., Jauchem and Ryan, 2000). At high exposure levels (whole-body SAR of 12 W/kg), rats exhibit a range of cardiovascular effects: increased heart rate, initial increase in arterial blood pressure followed by a decrease and ultimately circulatory failure and death.

12.3 Mechanisms for Thermal Effects of RF Energy

Several thermal mechanisms have been identified by which RF fields can produce biological effects (Foster and Glaser, 2007). These can be divided into mechanisms that depend on the temperature increase and the rate of temperature increase.

12.3.1 Mechanisms Related to Temperature Increase

The temperature of the human body has a diurnal variation diurnal of about 1 °C, and core body temperature increases by 2–3 °C during sustained exercise; skin temperature varies by several degrees Celsius depending on environmental conditions and the presence of clothing or other insulation. Given such variations, changes in tissue temperature less than a degree or so are within the range of normal variation and presumably innocuous. (However, it would require rather high RF exposure levels, well above present limits, to raise the core body temperature of a human by 1 °C by direct heating given the effectiveness of the human thermoregulatory system.)

A frequent topic of discussion is whether a reported effect (i.e., changes noted by an investigator after exposure of a preparation to RF energy) is "nonthermal" or a mundane "thermal" effect of heating. Even in the best bioeffects studies, it is often difficult to control (or even measure) temperature increases in the exposed preparation with a precision less than about 0.1 °C, and evidently many studies do much worse than that. Consequently, separating "thermal" from "nonthermal" effects is difficult given the existence of mechanisms that could result in measurable changes in a biological system after relatively small changes in temperature. In reviewing the scientific literature for purposes of designing exposure limits, the more important question is whether health hazards are present at exposure within allowable limits, and standards setting organizations are loath to speculate whether reported effects from low-level exposure are "thermal" or "nonthermal" in mechanism.

12.3.2 Temperature Dependence of Biochemical Reactions

The rates of all biological processes vary exponentially with temperature, following the Arrhenius law. It is customary to express the temperature dependence of a biochemical reaction in terms of a temperature coefficient $Q_{10,}$ which is defined as the factor by which the reaction rate increases for every 10° rise in the temperature. Thus

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\left(\frac{10}{T_2 - T_1}\right)} \tag{12.5}$$

where R_1 and R_2 are the reaction rates at T_1 and T_2, respectively. The theoretical basis of this is the Arrhenius equation:

$$k = Ae^{-E_a/RT} \tag{12.6}$$

where E_a is an activation energy, R the gas constant, T the temperature in K, and A a constant of dimension $1/s$ and k is a measure of the reaction rate.

Typical biochemical reactions double their rate with a 10° increase above ambient, corresponding to a Q_{10} of 2. This corresponds to a 7% increase with each degree increase in temperature. With a sensitive enough assay, even small (<1 °C) temperature increases will produce measurable changes in a biological material, particularly if the exposure were continued for some time.

Some biological processes are remarkably sensitive to temperature. In mammals, TRPV3 and TRPV4 are membrane channels that respond to temperature changes in the physiological range, used by the organism to help adapt to changing temperature (Benham, Gunthorpe, and Davis, 2003). These channels can show remarkably high sensitivity to temperature changes. For example, between 24 and 36 °C, the membrane conductance of TRPV4 channels exhibits a Q_{10} of 19.1, compared with about 2 for most biochemical reactions due to the Arrhenius factor (Watanabe et al., 2002).

The difficulty of separating thermal (temperature produced) from nonthermal effects is seen in the studies by de Pomerai et al. (2000), who reported induction of heat-shock proteins (which are also involved in adaptation of an organism to changing temperature) in the nematode *Caenorhabditis elegans* after extended (2–24 hour) exposures to microwave energy, which they considered to be a nonthermal effect. The investigators later discovered that these exposures led to a small (0.2 °C) temperature increases in the irradiated samples that were sufficient to account for the observed effects, and they retracted their paper in 2006 (de Pomerai et al. 2006). This is not to say that all reported biological effects of exposure to low-level RF fields are thermally induced, but that is an interpretation that needs to be considered in particular cases.

12.3.3 Thermal Damage to Tissue

The kinetics of thermal injury to tissue has been studied extensively, both with reference to thermal damage from a variety of sources, and in developing therapeutic applications such as hyperthermia treatment for cancer. For a recent review of thermal dosimetry, see Yarmolenko et al. (2011).

The kinetics of thermal injury to tissue is characterized by an exponential relation between the rate of damage to tissue and temperature (Eq. (12.6)), whose activation energy is that for protein denaturation. The rate of tissue damage $\mathrm{d}\Omega/\mathrm{d}t$ can be expressed as

$$\frac{\mathrm{d}\Omega}{\mathrm{d}t} = Ae^{\frac{-E_\mathrm{a}}{RT}} \tag{12.7}$$

The total thermal injury to tissue is the time integral of this expression:

$$\Omega = A\int_{t_\mathrm{o}} e^{\frac{-E_\mathrm{a}}{RT(t)}}\,\mathrm{d}t \tag{12.8}$$

where the integral is over the duration of the thermal treatment (t_o). For human tissues, the Arrhenius plot for thermal damage shows a breakpoint at about 43.5 °C, which has been interpreted as reflecting the buildup of thermal tolerance during long heating times below this temperature.

Based on these considerations, in a landmark 1984 paper, Sapareto and Dewey proposed that thermal dose be measured in terms of the cumulative equivalent minutes, CEM43, which is defined as

$$\begin{aligned}\mathrm{CEM43} &= \frac{t}{60}R^{43-T}\\ &= \frac{1}{60}\int R^{43-T(t)}\,\mathrm{d}t\end{aligned} \tag{12.9}$$

where t is the time in seconds and R is defined below. (This paper has been cited nearly 1100 times as of early 2016, according to Web of Science.) The second expression above would be used if the temperature varies with time. In the above expression,

$$R = \left|\begin{array}{l} 0, \quad \text{for } T < 39^\circ\mathrm{C} \\ 0.25, \quad \text{for } 39 < T < 43^\circ\mathrm{C} \\ 0.5, \quad \text{for } T > 43^\circ\mathrm{C} \end{array}\right. \tag{12.10}$$

CEM43 is the time for which a tissue would have to be held at 43 °C to experience the same thermal damage as is produced during the actual duration of exposure at the respective temperature. For a table of CEM43 values, see Yarmolenko et al. (2011). While the thermal damage thresholds vary with species and tissue, values of CEM43 of the order of 10 (minutes) for noticeable damage have been reported for numerous animal tissues. Human tissues are somewhat more resistant to thermal damage than corresponding animal tissues (Dewhirst et al., 2003).

These considerations have several implications for thermal damage from RF energy. First, human tissues can typically tolerate temperatures up to about 43 °C for prolonged periods without damage, but even brief exposures at higher temperatures can quickly lead to injury. However, such exposures would ordinarily be extremely painful and force the exposed person to withdraw before damage occurs; thermal pain is an important defense mechanism in the body.

Conversely, tissues can be heated for brief times to surprisingly high levels without sustaining much damage. For example, human corneas can tolerate brief (second or less) exposures to high-powered millimeter wave energy sufficient to raise their temperature to 50 °C or more without evident damage (Foster et al., 2003). The "Active Denial" system, developed as a nonlethal weapon by the US military, exploits this effect, using brief, high-intensity millimeter waves to raise the skin temperature far above the threshold for pain. Because of the very shallow penetration depth of this energy in skin (a millimeter or less), after the pulse ends, heat diffuses away from the skin surface before significant thermal damage occurs. However, the pain response occurs very quickly.

Strictly speaking, the exponential temperature-damage function does not show a threshold response, and mathematically (if not realistically), an arbitrarily small temperature increase continued for very long times will, in theory, lead to thermal damage. The Arrhenius relation, however, does not include effects of repair of thermal damage in the body, and using it to predict thermal damage from small temperature increases sustained for very long times is an extrapolation of the theory far beyond areas for which there is experimental support.

That said, the impression is very strong that a "threshold" temperature exists for thermal damage. For example, heating ear skin to 43.5 °C for 60 minutes will lead to complete necrosis; no injury is observed if the exposure time is 30% shorter (Dewhirst et al. 2003). For practical purposes, it is often sufficient to suggest that 43–44 °C is a "threshold" for producing thermal damage, although a more careful analysis would have to consider the thermal dose CEM43 instead.

12.3.4 Thermophysiological Effects of Exposure to RF

A considerable literature exists on the thermophysiology of RF energy exposure, most prominently by Eleanor Adair (1926–2013) during her long career at the John B. Pierce Foundation in New Haven, followed by several years as a senior scientist at Brooks Air Force Base, San Antonio. She and her colleagues explored thermoregulatory responses of animals and, more recently humans, to extended exposures to RF energy, sometimes at levels above US safety limits.

Particularly noteworthy is a series of experiments that she and her colleagues conducted on seven fit and generally young subjects exposed at whole-body SAR of 1 W/kg at 20, 28, 31 °C and at frequencies of 100, 450, and 2450 MHz (for reviews, see Adair and Black, 2003; D'Andrea, Ziriax, and Adair, 2007). All of the subjects tolerated the RF exposure well, although they sweated profusely when exposed at the highest ambient temperature. In the warmest ambient temperature (31 °C), the average core body temperature in the subjects increased by 0.15 °C. In one of these subjects, however, core body temperature had increased by 0.5 °C and was still increasing at the end of the 45-minutes exposure. These exposures were about twice those allowed for occupational exposures by major international limits such as ICNIRP (1998) and IEEE C95.1-2005 and evidently approach the maximum that fit people can tolerate under uncomfortably warm ambient temperatures. This is one of the few available studies on the response of humans to whole-body RF exposures, and the completeness and quality of the work make it particularly valuable. Given the difficulty and expense of the studies, and the difficulty that Adair and colleagues had in receiving ethics-board approval for the studies, it seems unlikely that the work will be significantly extended any time in the future.

12.3.5 Modulation Dependent Thermal Effects

The thermal effects of RF energy described earlier are independent of frequency, modulation, or other characteristics of the electromagnetic wave (except, indirectly, as the frequency determines the pattern of heat deposition in the body); the biologically relevant quantity is the temperature increase in the exposed tissues. By contrast, a few effects of RF energy, under very specialized exposure conditions, are associated with the time rate of change in temperature.

One example is the microwave auditory effect in which a subject perceives "clicks" or other auditory sensations when the head is exposed to pulsed microwaves of high-peak but low-average power (such as produced by radar transmitters). The "clicks" are elicited by acoustic transients generated within the head due to expansion of tissue water resulting from the abrupt (but very tiny) temperature increases as the microwave pulses are absorbed. The microwave auditory effect is associated with exposure to radar-like pulses, typically with a carrier frequency of about 1 GHz, microsecond pulse lengths, and peak field intensities above 10,000 W/m^2. The corresponding temperature increases produced in the head are of the order of a few microdegrees – which is sufficient to produce peak acoustic transients in the head exceeding 100 dB peak sound pressure (Foster and Finch, 1974). These transients are heard by the subject through a normal hearing mechanism. This is clearly a thermal effect in the mechanistic sense, albeit a physiologically trivial one, even though the actual changes in temperature in the head are far too low to measure directly.

Under extreme exposure conditions, it is possible to elicit other, more physiologically significant, effects related to the time rate of change in tissue temperature. For example, mice exposed in the head to intense microwave pulses, sufficient to heat their brain temperatures by a few tenths of a degree within 1 second, exhibit a variety of involuntary body movements and other stun phenomenon (Wachtel, Brown, and Bassen, 1990). A preliminary theoretical analysis suggests that the effect is related to depolarization of cellular membranes by the rapidly changing temperature of tissue (Barnes, 1984). The exposure levels needed to produce these effects are far above those encountered in virtually any occupational or residential environment; indeed, in the experiments, the animals had been placed inside waveguides that were connected to high-powered military transmitters.

12.4 Modeling Thermal Response of Humans to RF Energy Exposure

12.4.1 Thermal Models for Bioheat Transfer

An enormous literature exists on heat transfer in tissue, focusing both on fundamental mechanisms of heat transfer and on practical applications for hyperthermia and other medical purposes. While the fundamental principles of heat transfer are well understood, the anatomical complexity of tissue requires the use of simplified models for any practical application, which raises the issues of model accuracy and validity.

However, there is a simple quantitative description of heat transfer in tissue and its applications that is sufficient for many purposes. This is the so-called bioheat equation (BHTE), which was first proposed by Pennes (1948) in a paper that has been cited more than 2200 times (as of early 2016) since its original publication.

Pennes' bioheat equation can be written as

$$k_t \nabla^2 T - \rho_b \rho_t m_b C_b \left(T - T_b\right) + \dot{q}_m + \dot{q}_{env} + \rho_t \mathrm{SAR} = \rho_t C_t \frac{\partial T}{\partial t} \tag{12.11}$$

where

T = the temperature of the tissue (°C) above mean arterial temperature T_b

k_t = the thermal conductivity of tissue (W/m °C)

SAR = the rate of electromagnetic power deposition rate (W/kg)

C_t (C_b) = the heat capacity of blood or soft tissue (assumed in the following discussion to be the same) (W/second/kg °C)

ρ_t, ρ_b = the density of tissue and blood (kg/m^3)
$\dot{q}_m$ and $\dot{q}_{env}$ = energy inputs from metabolic processes and the environment (W/m^3)
m_b = the blood perfusion rate (m^3/kg/second).

In the physiology literature, blood perfusion is commonly cited as a volumetric flow (e.g., liters of blood per kilogram of tissue per minute). The terms ($\dot{q}_m$,$\dot{q}_{env}$) represent rates of heat input from metabolic processes and the environment.

For practical modeling applications, Eq. (12.11) can be simplified considerably. The material properties (density and heat capacity) of all soft high water content tissues are similar (being determined chiefly by water content) and can be expressed as C and ρ using approximate values of heat capacity and density of muscle. In addition, when calculating the increase in temperature above baseline due to RFR exposure, the heat input from metabolic or environmental sources can often be ignored; a full thermoregulatory model would have to include such effects.

With these simplifications, Eq. (12.1) becomes

$$k\nabla^2 T - \rho^2 C m_b \left(T - T_b\right) + \rho \mathrm{SAR} = C\rho \frac{\partial T}{\partial t} \tag{12.12}$$

Equation (12.12) is the usual expression for heat conduction (Fourier's law) modified with an additional term that quantifies the removal of heat by blood perfusion due to convection. In this simple continuum model, blood itself does not appear explicitly but acts as an invisible sink for energy. In some applications (typically for hyperthermia treatment planning), investigators have developed hybrid models in which the bioheat equation is used to determine heat transfer in tissues away from major blood vessels, with the vessels themselves considered as separate geometric entities.

However, several important issues arise that bear on the validity of the BHTE. On face value, the equation violates the first law of thermodynamics – energy disappears into the heat sink term – and thus, it cannot be a complete description of transfer of heat in a tissue. Moreover, Fourier's law of heat conduction itself is unphysical, since the heat conduction equation (Eq. (12.12) minus the term with the blood perfusion) implies that the response to heating occurs instantly at all distances. A theoretically more correct approach is to formulate a wave equation for heat transfer. However, at the modest heating levels that characterize RF exposures to humans, thermal wave effects are negligible, although some authors have argued that such effects are important for some applications using RF hyperthermia in conjunction with injection of magnetic nanoparticles into tissue to enhance heating (Liu and Lin, 2010).

These objections aside, the BHTE is typically presented with narrative that states that the heat sink is provided by blood in the capillary bed, and the strength of the sink is proportional to the difference between local tissue temperature and mean arterial or core body temperature. Both of these assumptions are clearly wrong. In tissues, capillaries are thermally equilibrated with their surrounding tissue and cannot be a source of heat exchange. Rather, significant heat transfer between tissue and blood occurs at the level of "thermally significant" vessels that are about 100 μm or more in diameter (e.g., Weinbaum et al., 1997). The ability of these vessels to remove heat from a region of tissue depends on their size, flowrate, and the nature of the thermal interaction among vessels. For example, vessels arranged in countercurrent pairs have reduced ability (compared to single isolated vessels) to carry heat away from a region of tissue due to countercurrent heat flow. When a region of tissue is subject to heating from external sources, such as RFR, blood entering the region of interest will not be at core body temperature but will have been heated before arriving at the point of interest. Such effects would require a more detailed model than the simple Pennes' BHTE to model.

These problems with the bioheat equation above have been extensively discussed, and indeed, an entire research literature exists on the subject. Numerous attempts have been made to develop conceptually valid alternatives to the bioheat equation. One approach has been to use a modified heat conduction model, using an effective thermal conductivity to represent the effects of blood flow. Another approach has been to retain the bioheat equation, but adjusting the blood perfusion parameter m_b by an "efficacy function" in the range of 0.5–1.0 to take into account countercurrent heat exchange (Brinck and Werner, 1995). After many years of debate, consensus seems to have emerged that the BHTE is a reasonable model for heat transport in tissue provided that m_b is interpreted as an empirical parameter and not literally as a capillary perfusion rate (Baish, 2014; Wissler, 1998).

Pennes' bioheat equation has been used to model the thermal response of tissue many times over the years (where, it seems, engineers sometimes treat it as a kind of Maxwell's fifth equation). Several widely sold finite different time domain (FDTD) computer programs for electromagnetic modeling in tissue now include modules that solve the BHTE to calculate the increases in tissue temperature; one widely used program provides an extensive table of thermal properties of tissue on its web site (Hasgall et al., 2015). This numerical approach has reached a high level of sophistication in hyperthermia treatment planning (including RF hyperthermia), where the need is to maintain the temperature of a treated region of tissue within narrowly fixed limits using external sources of power at SARs up to the range of hundreds of watts per kilogram.

One problem, however, has been a chronic dearth of tests of the predictive ability of these models. The vast majority of thermal modeling studies on RF-exposed tissue have been in one direction only (fitting the model to data); by comparison, there have been few attempts to assess the adequacy of a model by testing its predications against new sets of data. The few studies that have compared predictions against measurements, in the context of hyperthermia treatment planning, show astonishingly large errors unless blood flow is treated as an adjustable parameter. For example, Verhaart et al. (2014) used the BHTE to predict temperature increases in brains of patients undergoing RF hyperthermia treatment for brain cancer, using parameter values from a commercial FDTD package (Hasgall et al. 2015). The model, using a fixed value of m_b, predicted temperature increases in the patients' brains as much as 30 °C above observed values, presumably because it did not take into account the increase in brain blood flow with temperature. For more moderate heating levels, the BHTE using "stock" parameter values may be more satisfactory – but nobody knows for sure. The BHTE does, however, work well in some limited cases, for example early transient heating or exposure to small areas of the body (Foster et al. 2016)

12.4.2 Models for Thermophysiological Responses of Humans to RF Energy Absorption

There have been a number of attempts to model the thermal response of the body to RF heating, coupling the heat input from exposure with a model of the thermoregulatory response of the body taking into account environmental variables such as ambient temperature (e.g., Bernardi et al., 2003; Foster and Adair, 2004).

These have been remarkably successful. For example, Foster and Adair (2004) modeled the thermoregulatory responses of human volunteers to whole-body RF exposures, as measured in the experiments by Adair et al., by adapting an older lumped parameter thermal model developed by Stolwijk and Hardy (1977) with no adjustable parameters. The predictions of the model agreed with experimental data (sweat rate, skin temperature, and core body temperature) very well. Such models can be valuable in establishing the ranges of RF exposure/environmental conditions/work intensity that are thermally tolerable by humans.

12.5 Conclusion

Whatever one may think about "athermal" effects of RF energy, there is no doubt that the major effects of RF energy on biological systems are associated with heating of tissue. Moreover, given the high sensitivity of biological systems to temperature changes, and the difficulty of controlling temperature adequately in RF bioeffects studies, it can be difficult in practice to be sure that supposedly "athermal" effects are not thermally produced after all.

A reasonable question is why RF exposure limits are not explicitly based on limiting temperature increases in the exposed subject. In part, there is not much need for this kind of analysis, given the extremely conservative nature of present limits (at least for the general public). The whole-body exposure limit for the general public in major international limits (0.08 W/kg averaged over 6 or 30 minutes) corresponds to the thermal load from very slight exercise and is very unlikely to represent any thermal hazard.

Second, given biological variability, calculating the temperature increase in RF-exposed tissues raises a number of vexing issues. IEEE C95.1-2005 (p. 89) recognizes this problem:

> interpretation of the temperature data from modeling studies of the brain and eye must include consideration of the following limitations of the models: (i) the adequacy of physiological blood flow in many of the numerical model studies has not been verified; (ii) none of the results for brain and eye have been validated in live animals and humans; and (iii) the results from independent laboratories varied over a wide range. Until these limitations can be resolved, thermal models are useful but in and of themselves are not sufficient for safety standard development.

Third, the experimental data for thresholds for thermal damage to tissue (expressed in terms of CEM43 or other measure) are very scattered and approximate. Moreover, the amount of experimental data on thermal responses of humans to RF energy is very limited and for many exposures virtually nonexistent.

That said, it is important to understand the mechanisms by which heat affects biological systems for a variety of basic scientific and practical reasons. Thermal models have significant applications to analyzing the health and safety issues with RF energy, ranging from predicting the maximum temperature at which coffee should be served to reduce the likelihood of injury if it is spilled on the consumer (Brown and Diller, 2008) to modeling the thermal response of workers exposed to RF energy (e.g., Foster and Adair, 2004). Compared to scientifically more exotic studies of "athermal" effects of RF energy, the topic is both well developed scientifically and clearly relevant to the health and safety of people exposed to RF energy. However, major gaps in knowledge also exist that need to be addressed by future research.

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13

RF Guidelines and Standards

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13.1 Introduction

Radiofrequency (RF) guidelines are designed to cover a large range of frequencies, from a few kilohertz to several hundred gigahertz. Since the wavelength changes by a 14 orders of magnitude, there is an enormous variety in the types of devices that emit RF across this range. Although many of these devices are connected with telecommunications, many are not. It is important that the philosophy of standard setting is not governed exclusively by the former. There are at least two sets of RF standards currently in use for the purposes of demonstrating that particular exposure situations are within compliance. The major international bodies setting these standards are the International Commission for Non-Ionizing Radiation Protection (or ICNIRP) and the Institution of Electrical and Electronic Engineers (or IEEE). To be more accurate, the RF standard issued by the latter body has been developed by a specialist group within IEEE, the International Committee on Electromagnetic Safety (or ICES). Since the secretariat for ICNIRP is in Germany and IEEE is a US-based organization, there is some variation, based on region, of which standard tends to be used for official purposes. However, for the ranges of frequencies used for telecommunications, the differences between the standards are relatively minor. For some frequency ranges, this is not so, and the implications of this will be highlighted later. In relation to the range of frequencies covered by an RF standard, there is some overlap with extremely low-frequency (ELF) standards (to be discussed in Chapter 18), but 3 kHz is regarded by both standards as the frequency above which the electric and magnetic fields can be considered to be *propagating* (and therefore useful in radio communications) rather than being associated with a specific item of equipment. At 3 kHz, the wavelength is

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still a relatively long 100 km; 3 kHz marks the beginning of the range designated RF (e.g., 3–30 kHz is very low frequency, VLF). Similarly, the choice of 300 GHz as the highest frequency considered as RF is also somewhat arbitrary, being the frequency where the ultra high frequency (UHF) range ends and the transition to the infrared begins (see Chapter 9). Some of the terahertz (THz) in this transitional range between UHF and infrared is now being considered for communications purposes. At 300 GHz, the wavelength in air is 1 mm, and for this reason, the UHF range is often referred to as the "millimeter band".

13.2 How Do the Standards-Setting Bodies Operate?

Both ICNIRP and IEEE operate in a similar way in that the committees attempt to assess the strength of evidence by establishing a literature database and then conducting extensive reviews of the amassed material (for ICNIRP, see http://www.icnirp.org/en/home/home-read-more.html; for IEEE, see http://www.ices-emfsafety.org/). IEEE actually has a more open review process in that they conduct regular subcommittee meetings (see http://www.ices-emfsafety.org/meetings_archive_sc3.php) that are open for all interested parties to attend (although voting on drafts is only open to members of the relevant committee).

ICNIRP and IEEE also take into account major reviews on health effects literature from around the world (and conduct reviews of their own). Recent reviews include several from the former National Radiation Protection Board/Health Protection Agency of the United Kingdom (now part of Public Health England) – (particularly 2012 AGNIR review). These are summarized in Table 13.1: most of these are available by download from the respective organizations. The World Health Organisation, via the Environmental Health Criteria (EHC) series continues to monitor and review world literature. The RF research literature was reviewed in EHC monographs numbers 16 (1981) and 137 (1993) and another is expected in 2016.

These bodies tend to be made up of respected scientists drawn from many disciplines. ICNIRP, in particular, has representatives from every region of the globe. A common criticism leveled at these bodies is that they have not considered epidemiological evidence in assessing long term effects of electromagnetic fields (EMF). However, an examination of the backgrounds those involved in relevant expert panels of the bodies just mentioned will reveal that epidemiological expertise is included. Results from epidemiological studies and long-term animal studies have formed a significant component of these reviews and have been taken into consideration when setting guidelines.

Both IEEE and ICNIRP committees meet on regular occasions to consider whether any changes need to be made to the advice contained in the standards, in the light of additional scientific evidence as it becomes available. It is

Table 13.1 Recent reviews of research literature (where there are multiple reports the latest one is shown).

Year	Organization, country	Title
2012	Advisory Group on Non-ionising Radiation, UK	Health Effects from Radiofrequency Electromagnetic Fields (RCE-20)
2015	Scientific Committee on Emerging and Newly Identified Health Risks, EU	Opinion On: Potential Health Effects of Exposure to Electromagnetic Fields (EMF)
2009	ICNIRP, International	Exposure to High Frequency Electromagnetic Fields, Biological Effects and Health Consequences (100 kHz to 300 GHz), ICNIRP 16/2009
2012	Bioinitiative, International	A Rationale for Biologically Based Public Exposure Standards for Electromagnetic Fields (ELF and RF)
2004	NRPB (now Public Health, England), UK	Review of the Scientific Evidence for Limiting Exposure to Electromagnetic Fields (0–300 GHz)
2014	Health, Canada	Royal Society of Canada Expert Panel: A Review of Safety Code 6 (2013): Health Canada's Safety Limits for Exposure to Radiofrequency Fields
2014	Australian Radiation Protection and Nuclear Safety Agency, Australia	Review of Radiofrequency Health Effects Research – Scientific Literature 2000–2012
2015	Swedish Radiation Safety Authority, Sweden	Tenth Report from SSM's Scientific Council on Electromagnetic Fields 2015:19

important to be aware that revision of both standards is expected in 2017, so for up-to-date information, it is best to refer to the web sites given above.

In view of the sometimes controversial nature of health effects evidence, particularly in relation to everyday levels of exposure, there have been calls for the standards to incorporate some degree of precaution. This may take the form of a statement encouraging reduction of exposure where this would not significantly affect service delivery or in a less-satisfactory form may advocate extra safety margins than those discussed in the following section. The whole area of precautionary (or "prudent avoidance" strategies) is discussed in Chapters 25–27.

13.3 Standard or Guidance Levels

In some areas of nonionizing radiation (NIR) protection, limits are quite precise and the consequence of exceeding them is easy to predict. As explained in Chapter 12, over-exposure to RF radiation produces heating of tissue beyond the range of internal compensation, which leads to irreversible denaturation of proteins. It is therefore necessary to prevent deliberate overexposure and to minimize the risk of accidental overexposure by the various control mechanisms discussed in Chapters 28 and 29. Although the IEEE document is described as a "standard" and that of ICNIRP as "guidelines", there is little significance in the difference in terminology, since both bodies see their role as providing advice to relevant legislative or regulatory bodies to adopt all or part of this advice. In the United States, the regulatory body for RF if used in communications is the Federal Communications Commission (FCC), but for other contexts, other bodies may take on a regulatory role. In Europe, the EU Commission has mandated the ICNIRP guidelines regarding physical exposures in the workplace for both RF and ELF occupational exposures. NATO has recently adopted an updated version of the IEEE standard for use among military personnel.

13.4 Basic Restrictions

As we saw in Chapter 12, RF energy interacts with biological material to cause (i) electrostimulation and (ii) rise in temperature. There is a third interaction at frequencies greater than around 200 MHz due to thermoelastic or mechanical responses to particular regions of the brain, giving rise to perceptions of the sounds of buzzing or clicking. However, protection against excessive rise in temperature will be sufficient to protect also against this "microwave hearing" phenomenon. Electrostimulation of nerves or muscles becomes less important as frequency rises, so basic restrictions (BRs) based on these phenomena are not provided above 5–10 MHz. In order to avoid duplication, discussion of these phenomena will be discussed in Chapter 18, rather than here, in the context of ELF guidelines, but a note will be added in this chapter to go there for further information. For the bulk of this chapter, we will note that the chief concern of RF exposure is that local temperatures may rise sufficiently to cause irreversible damage to proteins. To a certain extent, the body's thermoregulatory system is able to compensate for added heat input from RF exposure by stimulating mechanisms such as sweating or panting. However, these mechanisms may be impaired, so a conservative strategy is important. The protection strategy can be summarized as follows:

> Temperature rise should not exceed 1°C in 30 minutes

We saw in Chapter 12 that temperature rise ($\Delta T/\mathrm{d}t$, in °C/s) can be estimated from specific absorption rate (SAR; in W/kg) from the following expression

$$\Delta T / \mathrm{d}t = \mathrm{SAR} / K \tag{13.1}$$

Here K is the (specific) heat capacity of tissue (which has a value of around 4000 W/kg/°C (see http://www.itis.ethz.ch/itis-for-health/tissue-properties/database/heat-capacity/) for values). Thus, for a linear rise of 1 °C temperature over a 30-minute period (1800 seconds), a SAR value of 2.3 W/kg would be necessary. However, this would only be the case if there was no ability of the body to lose heat to the environment, which normally there would be (although in extreme environments with ambient temperatures above 37 °C, this would be limited to sweating and panting). It is normally considered that a higher SAR value than 2.3 W/kg would be needed to produce this temperature rise reflecting the fact that the rise would not be a straight line but a convex curve. After considering a wide range of evidence, standards bodies have determined 4 W/kg to be the SAR value above which tissue temperature could rise by more than 1 °C in 30 minutes and therefore hazardous to health.

It is normal to set a safety margin between the levels at which the biological effect becomes a concern and the level which is set as the exposure limit. This is to allow for uncertainties in estimation of SAR and for biological variation. The margin varies, to a certain extent, for different circumstances. However, for most of the circumstances of RF exposure, a margin for 10 is used to set the occupational limit on SAR, then a further margin of 5 for general public exposure. Thus, for an exposure to the whole of the body, a SAR value of $4/10 = 0.4$ W/kg is the limit for occupational exposure and $4/(5 \times 10) = 0.08$ W/kg for the general public.

The rationale for the factor of 5 between occupational and general public exposure takes into consideration the fact that some members of the public are more vulnerable to the effects on body temperature than others. Since "general public" is intended to include all sectors, such as the very young, the very old and those suffering from illness an extra margin is thought appropriate. There is also the notion that "occupational" in this context does not mean exposure during any type of work, it means those work settings where the worker would be expected to be aware of the nature of RF radiation and would know how to minimize the chance of over-exposure. The precise definition of "occupational exposure" will be expanded on below.

Since it is possible, in cases of nonuniform exposure, to have regions more highly exposed than others, and since there is rapid heat diffusion from one region to another, there is also provision for allowing a higher SAR for a small region of tissue. There has been some debate over whether the averaging should be over 10 g, 1 g, or even smaller, since SAR can vary significantly over quite short distances (e.g., going from one tissue type to another). On the other hand, the characteristic "heat diffusion length" in tissue is of the order of a few centimeters, which would make a 10-g cube quite adequate (assuming a density of 1000 kg/m^3 for tissue, a 10 g cube of tissue would have sides of 2.15 cm). Heat diffusion length is determined by $2\sqrt{(\alpha t)}$, where α is the diffusivity of heat in tissue, which has the value of approximately 2×10^{-3} cm^2/second in many tissues (Duck, 1990) and t is the elapsed time in seconds. Thus, in half an hour, heat will have diffused 4 cm, approximately. On the other hand, local maxima can be much higher for 1 g compared to 10 g averaging (Wang et al., 2007). There is a slight difference between IEEE and ICNIRP in that the former interprets the 10 g as tissue in the form of a cube but the latter as "contiguous tissue". In small structures (such as the cornea or the lens of the eye, which are both quite sensitive to RF heating), it is not possible to form 10 g of a single tissue type using either criterion.

Estimation of whole body specific absorption rate (wbSAR) and 1 or 10 g average SAR ($\text{maxSAR}_{1\text{g}}$ or $\text{maxSAR}_{10\text{g}}$) is not trivial, because as we saw in Chapter 12, it is a function of local RF current, which in turn depends on the way electrical conductivity and permittivity varies from place to place within the body. For example, near to bones and air spaces, the current may be constrained into narrow tracts of tissue where the current density J (and thus SAR) could be high. Chapter 14 will discuss in greater detail how the computations are carried out to demonstrate whether in a particular circumstance (e.g., a specific mobile phone handset) these limits could be exceeded. Because SAR estimations are, in general, quite involved, there is an alternative path to demonstrating compliance, that is, to evaluate compliance with electric or magnetic field measurements in the near vicinity of the person. These maximum permitted exposures (MPEs; in IEEE) or reference levels (RLs; in ICNIRP) refer to electric (E) or magnetic (H) field measurements (which can be carried out using survey meters) or power density (PD), which can be calculated from E and H (and is often just the product $E \times H$ and is usually denoted by the symbol S). In order for the MPE or RL measurement to be conservative in relation to compliance, it is important to establish the precise relationship between these quantities and the regional SAR that results from these. This can be done using (i) computational models, (ii) fluid representations of tissue, or (iii) internal direct measurement in frozen animal cadavers. In general, a worst-case scenario should be assumed when estimating, for example, what value of SAR (in W/kg) could eventuate in a particular location within the body for a specific value of PD (in W/m^2) in the immediate external environment of a person's body.

13.5 Temporal Averaging

Since the RF waveform could be quite complex, with pulsing and other forms of modulation, some standardization in the method for time averaging needs to be specified. In fact, even continuous unmodulated waves are averaged. This is illustrated in Figure 13.1a to show that a simple average of the value of the signal (E field or H field) would be zero (because the values are equally likely to be positive as negative), but if the values at each instant are squared (so now both positive and negative values give a positive square), then the square root taken for the average of the squares, the value obtained, is nonzero and is the "root mean square" or RMS value. This is shown in Figure 13.1b. For a pure sine wave, the RMS value is $1/\sqrt{2}$ (=0.707) of the peak value (or "amplitude"). Figure 13.1c shows an example of an amplitude-modulated wave (which is typical of AM radio transmissions) and Figure 13.1d shows essentially random

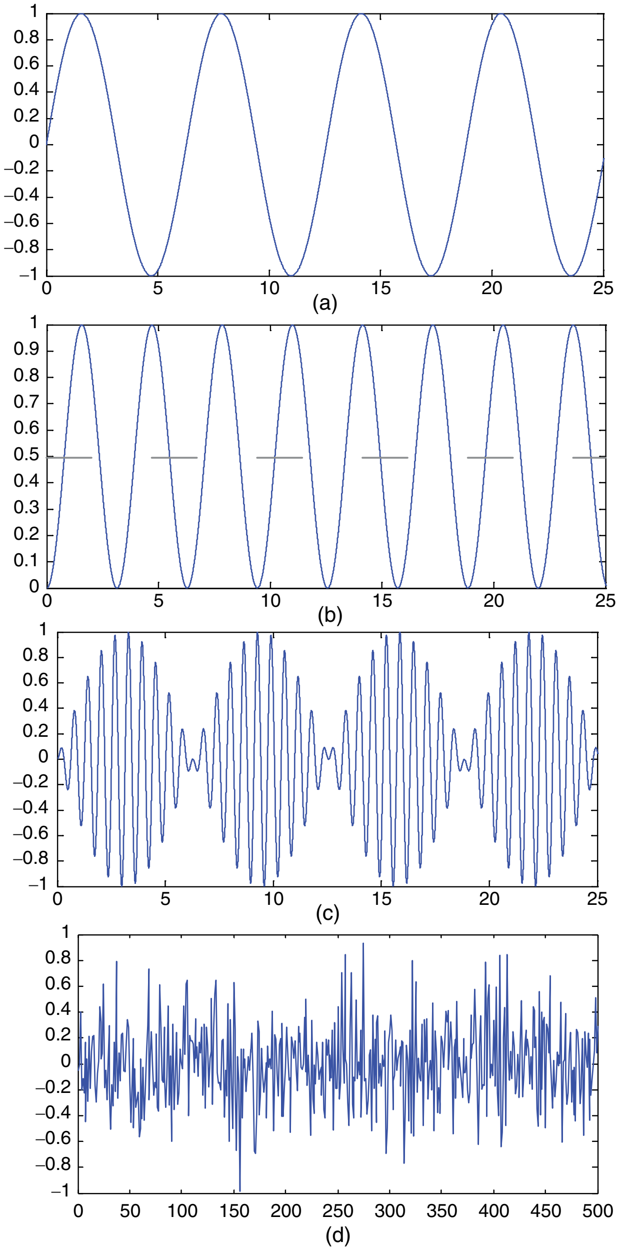


Figure 13.1 Waveforms of representative radiofrequency electric (*E*) or magnetic (*H*) fields. (a) simple sine wave, showing an average value of 0; (b) the square of the values shown in (a), with an average value of 0.5 and a root mean square value (RMS) of $\sqrt{0.5}$, or 0.707; (c) an amplitude-modulated wave, with an RMS value of 0.5; and (d) a normally distributed random sequence, with an RMS value of 0.3.

variations or "noise". The latest generation of mobile phone transmissions is essentially "pseudo-random" in nature. When the RMS value itself is changing (e.g., if the RF is being pulsed on and off or the level of transmission is altering) then further averaging needs to be specified. For example, tables in both IEEE and ICNIRP standard/guidelines give details of the appropriate averaging times over a range for frequencies from 0.1 MHz to 300 GHz. However, for many telecommunications ranges, the appropriate time for general public exposure is over a 30-minute period, and with a shorter period (6 minutes) for "controlled environments", that is, those where activities and personnel within the environment are subject to RF safety programs. For ICNIRP, both SAR values and RLs are to be averaged over a 6-minute period, although for frequencies above 10 GHz, where BRs are based on PD rather than SAR, the averaging times are shorter.

13.6 Contact Current Restrictions

Part of the hazard of working in high RF field areas is the possibility of suffering a burn, shock, or at least discomfort, when touching a metallic conductor. It is important to distinguish between situations where the RF current flowing in the body is due to contacting a "live" conductor and situations where this current arises because the external field is directly inducing charge in the body, which then flows to ground when a passive earthed conductor is touched. Another situation is where a metallic structure acquires a charge (due to the influence of RF fields) and then a person without footwear touches or brushes against this structure. ICNIRP provides limits on what contact currents are acceptable in the range from essentially dc up to 110 MHz, with a relaxation of just over twofold for currents purely in limbs (10–110 MHz). Again, there is an approximately twofold margin between occupational and general public exposure. IEEE go further by considering various types of contact situations (e.g., feet versus touch or grasp contact) and specifying electric field values below which no further evaluation of contact current is necessary. Both standards differentiate between nerve stimulation hazards (below 100 kHz, and where the limit value rises with frequency) and tissue heating hazards, which are independent of frequency and are more of a concern above 100 kHz. The averaging times differ, being 6 minutes for SAR values (in ICNIRP) above 100 kHz and much shorter averaging times below 100 kHz (in fact, the 2010 ELF standard recommends that no averaging should be carried out below 100 kHz (ICNIRP, 2010)). In IEEE, the averaging times above 100 kHz range from 6 to 30 minutes (in a frequency-dependent and field type-specific manner) up to 5 GHz, then falling again in the range 5–300 GHz IEEE (2005). In both sets of standards, the averaging time falls to around 10 seconds at 300 GHz.

13.7 Reference Levels as a Function of Frequency

The ratio of tissue SAR to incident PD varies throughout the range 3 kHz–300 GHz because external *E* and *H* fields couple with the body, or specific regions of the body, more efficiently at some frequencies than others. In general, if the wavelength of the RF radiation in air is a simple multiple of the dimension of the body (e.g., the height or the girth or the size of the head), the ratio will be high and at other frequencies significantly lower. For example, the wavelength at 90 MHz (in air) is given approximately by

$$\lambda = c/\left(f\sqrt{\varepsilon}\right) = 3\times10^{8}/\left(90\times10^{6}\times\sqrt{1}\right) = 3.3\,\text{m} \quad (13.2)$$

(where λ is the wavelength in meters, c the velocity of propagation in meter per second, f the frequency in Hertz, and ε the dimensionless dielectric constant). So half wavelength corresponds to 1.65 m approximately, which is the height of an average human.

Figure 13.2 indicates the variation of the SAR values required to produce unit PD (1 W/m^2) in the range 0.01 MHz–100 GHz, showing three different orientations of the incident fields with respect to the long axis of the body. The peaks correspond to resonant absorption. With the *E* field parallel to the long axis of the body, the peak is lower than for the other orientations. This is because the *E*-field is the main determinant of SAR, so when the *E* field is directed front and back or side to side

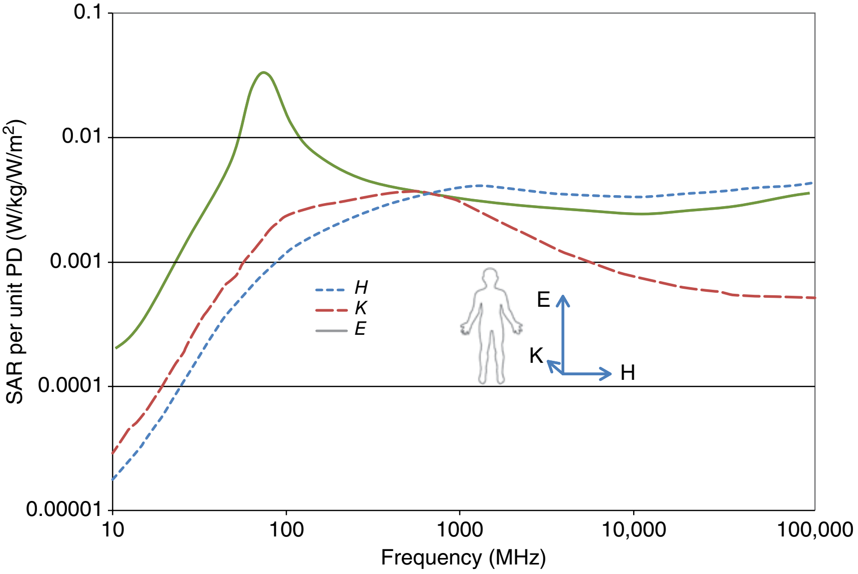


Figure 13.2 Variation of SAR per unit plane wave power density in three orientations in relation to long axis of body: *H* is magnetic field vector parallel, *K* is direction of propagation parallel, and *E* electric field parallel to long axis.

the characteristic distance is shorter and therefore the resonant frequency higher. For small animals, the peak in SAR/PD is much higher (e.g., the resonant peak for a rat occurs at around 660 MHz, compared to 90 MHz for a human).

The RLs in general assume a uniform exposure over the cross-section presented to the incident fields (in fact, the same is assumed in deriving the SAR/PD ratios shown above). Where this ratio is higher implies that the PD needs to be lower to stay below the SAR limit (which is a constant 0.08 W/kg for general public throughout this range). This means that the RLs for PD are expected to follow the inverse of the curves shown in Figure 13.2. These are shown in Figure 13.3a for occupational exposures: to obtain values for general public exposure, the values are divided by 5. Note that ICNIRP and IEEE have identical values only in the range 100–300 MHz and the range of frequencies for which PD is defined extends to much lower frequencies in the case of IEEE, who in fact provide separate sets of values for PD, depending whether the exposure is from *E* fields or *H* fields. This is recognizing the increasing importance of nerve stimulation at frequencies below 10 MHz (again, *E*-fields have a greater capacity for stimulating nerves compared to *H*-fields, so the limits are more conservative in the former).

Deriving the most appropriate form of curve for Figure 13.3 is not a trivial exercise, since in the same way that predicting localized SAR requires sophisticated models of the human body, with data on individual organs within the body, the same type of modeling is required to predict what SAR would eventuate from a particular PD. To a certain extent, both the IEEE and ICNIRP rely on the relatively unsophisticated models available at the time of publication. Modeling has now progressed beyond simple homogeneous oblate spheroid representations of the human body to models based on up to 40 different tissue types with a resolution down to millimeter cubes. Some data has emerged from this improved modeling which challenges the claim that the RLs are formulated conservatively (the notion that if compliance with the RLs can be demonstrated, then there as a guarantee that the BR is complied with). At the time of writing, this has not been reflected in modifications to the RL values, but this may happen in the next year or so.

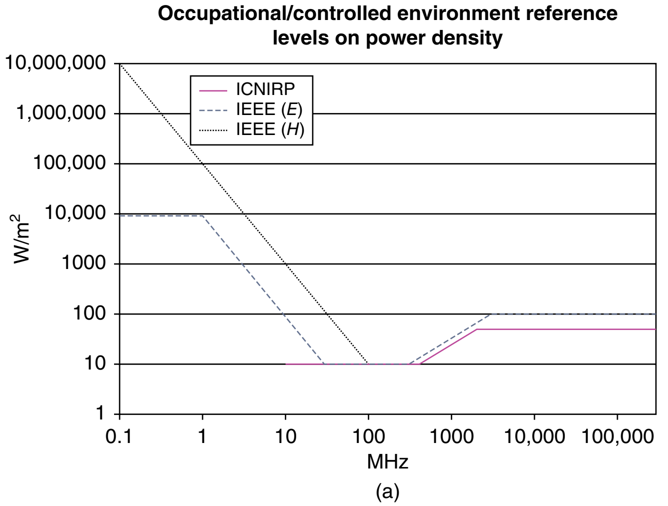
13.8 Near-Field versus Far-Field

When an alternating current is fed to a transmitting aerial or antenna, both an *E* field and an *H* field are associated with this flow of current. Immediately surrounding the antenna, the fields can be thought of as being localized to the antenna, but further away the flow of energy into the antenna is converted into a radiating pattern, with the crests of the waves moving away from the antenna at approximately the speed of light (3×10^8 m/second in air or vacuum). The latter region in termed the "far field" and the region close to the antenna the "near field". The transition from the latter to the former occurs at a few wavelengths (the precise distance depending on several factors, which need not concern us here). In the far field, the *E* and *H* fields are related by the following:

$$E / H = 377\Omega \tag{13.3}$$

And since PD $(S) = EH$ (if E and H are perpendicular to each other, which they normally would be in the far field), we can derive E and H from the PD as follows:

$$E = \sqrt{(S \times 377)}(\mathrm{V/m}) \tag{13.4}$$



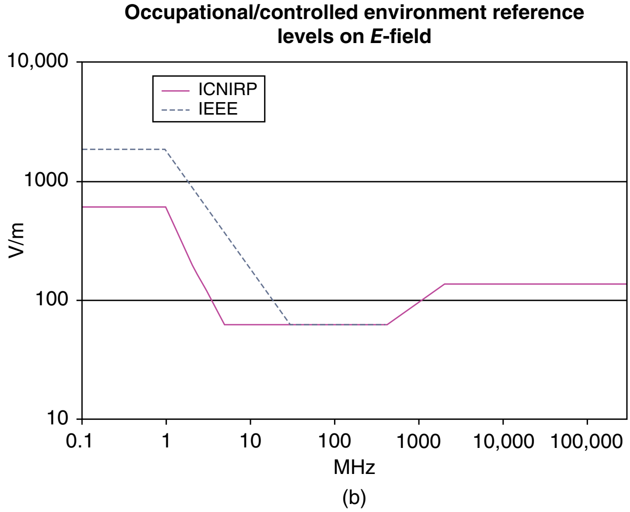


Figure 13.3 The variation in reference levels for occupational exposures (controlled environments) comparing IEEE with ICNIRP. (a) The values are strictly the "equivalent plane-wave" power densities S_{eq}, which refers to any electromagnetic wave that is equal in magnitude to the power density of a plane wave having the same electric (*E*) or magnetic (*H*) field strength. (b,c) The values of *E* and *H* fields, respectively, refer to unperturbed values of RMS fields (unperturbed by the act of measurement).

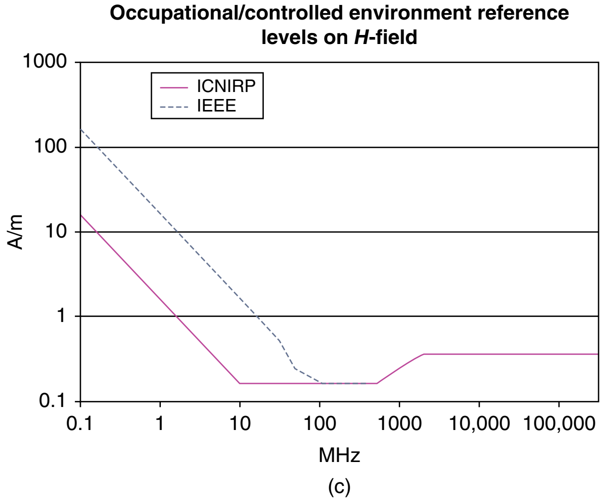


Figure 13.3 Continued

$$H = \surd\left(S / 377\right)\left(\mathrm{A} / \mathrm{m}\right) \tag{13.5}$$

Consideration of Figure 13.3b,c will show that this is indeed the case for ICNIRP in the range 10 MHz–300 GHz and for IEEE in the range 0.1–300 MHz (using the appropriate set of PD values for *E*- or *H*-field exposure). Demonstration of compliance in near-field exposure situations (such as a mobile phone handset held to the face) presents more of a challenge, since the sensors of field meters will significantly distort the field patterns if held too close to the antenna. The standard method of showing compliance is to directly estimate SAR in these cases, and the method of doing this will be described in Chapter 14.

13.9 Dealing with Multiple Frequencies

The fields associated with many RF-emitting devices (such as welding apparatus, broadcast antennas, radars, and Wi-Fi routers) consist of complex waveforms, with modulations and multiple frequencies (broadband) represented. Since the RLs (and to a lesser extent the BRs) are specific to a single frequency or range of frequencies, there is a challenge in how to sum the contributions of all of these components. The essential part of this exercise is to compare each component against the RL at that particular frequency. So, for example, if there are two frequencies represented, 100 kHz and 100 MHz, with the amplitude of each frequency 10 V/m, then the 100 kHz component is 10/87 or 0.115 of the (general public) limit and the 100 MHz component is 10/28 or 0.357 of the limit at that frequency (87 and 28 being the appropriate limit in V/m at those particular frequencies). Thus, the sum of the two is 0.115 + 0.357 = 0.472 or 47% of the MPE. Of course, with more complex mixes of frequencies, this computation is more involved. In Chapter 14, there will some discussion on how modern survey meters are able to take this into account.

13.10 Spatial Averaging

RLs were derived from the BRs using simple models of humans exposed to uniform fields under conditions of maximum coupling. In a nonuniform field, a simple measurement of the spatial peak field may give an unnecessarily conservative indication of exposure. A more realistic indication can be obtained by determining the spatial average of the incident plane wave equivalent PD (or squares of electric and magnetic field strengths, which are proportional to PD) over the projected area of the body. However, an important proviso is that the BRs on localized exposure are not exceeded. To meet this proviso, an upper limit is placed on the spatial peak field strength in terms of a multiple of the RL. For example, IEEE (2005) states that "the spatial peak value of the PD or mean squared field strength shall not exceed 20 times the square of the allowed spatially averaged values .. at frequencies below 300 MHz". Types of spatial averaging schemes can be found in measurement standards documents. The schemes include averaging over a vertical line from 0.2 to 2 m above ground in 0.1 m increments, or over a vertical plane or volume, or over a predefined set of points.

13.11 Specific Issues Regarding Risk Management

Neither ICNIRP nor IEEE provide specific advice on how to manage risk in occupational settings, other than the need for workers to receive training on what these risks might be. Many standards or advice documents in particular jurisdictions give further directions: for example, the Australian standard sets out the principles of risk identification, assessment, control measure choice, implementation, and on-going monitoring as well as having a provision that on declaration of pregnancy, workers should be subject to general public rather than occupational limits.

In some countries with a significant agricultural industry, the protection of nonhuman species becomes an issue. In general, it is assumed that the thermally based BRs should apply to other species, but it should be recognized that the thermoregulatory systems will differ, so caution should be applied.

Advice to those with metallic implants such as pacemakers and joint replacements is also something not covered by standards and careful modeling needs to be undertaken to ensure that thermal effects are negligible.

Demonstration of compliance of particular RF-emitting devices or infrastructure is also outside of the scope of the standards described in this chapter, although separate jurisdictions have their own standards documents that deal with these practical issues. The manufacturers of mobile phone handsets subject new models to an internationally recognized type-testing regime to determine SAR values (at a distance of 1 cm) using a tissue phantom that has been validated against more realistic models of the body, including the head and ear. The change in use patterns of handsets from against the head to within the palm has also been recognized by some authorities.

A recent trend toward low-power transmission of data and voice communication (such as Wi-Fi access points, routers, cordless phones, and microcell base-stations) has led to the blanket exemptions of transmitters below a certain power from compliance testing. This has considerably simplified compliance demonstration processes, but some sections of the community are concerned that the additive effect of multiple RF-emitters may lead to inadvertent exceeding of general public limits. Modern survey meters do allow for the integration of exposures across multiple frequency bands, so this possibility is recognized and monitored.

13.12 Scientific Input

There is a wealth of literature regarding the levels of RF fields or SAR values above which detrimental effects to humans or other organisms are identified. Many of the earlier studies focused on thermal distress or cataract formation in laboratory animals. The specific biological effects of concern are (i) the compromising of thermoregulatory control and (ii) the denaturation of proteins (or the irreversible change in molecular shape due to rise in temperature). Many of the changes in reproductive ability or birth outcomes have been attributed to rise in temperature and would be also produced by temperature rise by conventional heating.

Another area of research intensity, as has been indicated, has been to estimate (by computer modeling) the regional SAR resulting from incident RF fields and also the accurate prediction of the field patterns surrounding RF emitters (such as welding equipment, base station antennae, surgical diathermy units, and the like). There has been an on-going concern that low-level exposures, where significant rises in temperature are not expected to occur, could give rise to detrimental effects through nonthermal means. Chapter 16 will review this possibility.

13.13 The Place of Epidemiological and Low-Level Effects Research in Standard Setting

Chief among the “low-level” effects is a suggestion that epidemiological evidence, mainly from mobile handset use, points to an increased risk of brain and other cancers. This, in many ways, is the “elephant in the room”, and Chapter 15 will review some of this evidence.

In 2011, the International Agency for Research on Cancer (IARC) concluded deliberations on whether or not RF could cause cancer ("the carcinogenic potential"). There are a number of categories, and RF was placed into Group 2B, that is, "possibly carcinogenic to humans". The definitions of the five groups are given in (http://monographs.iarc.fr/ENG/Classification/). This is the same group as ELF–EMF (see Chapter 20). For other forms of NIR, UV radiation is in Group 1 (carcinogenic to humans) and optical and infra-red radiations have not yet been categorized. All forms of ionizing radiation are naturally enough in Group 1.

The Group 2B categorization of RF was driven almost entirely by meta-analyzes of epidemiological studies, with a summary of the rationale published in The Lancet (Baan et al., 2011). The full rationale has been published in the form of a monograph (IARC, 2013), which describes the evaluation process and also the significance of this particular categorization. However, (i) this categorization based on epidemiological evidence does not establish causality, (ii) the monograph is silent on whether or not regulators should adopt particular levels used as cut points in epidemiological analysis as a basis for exposure limits, and (iii) there are many other agents similarly categorized for which exposure limits (if there are any) are determined primarily by epidemiological data.

Similarly, there are studies performed in the laboratory which provide *prima facie* evidence for RF biological effects at low levels, some of which could be interpreted as being indicative of an increased carcinogenic potential. However, the IARC summary (Baan et al., 2011) states that there is no consistent evidence from these types of study:

> although there was evidence of an effect of RF–EMF on some of these endpoints, the Working Group reached the overall conclusion that these results provided only weak mechanistic evidence relevant to RF–EMF-induced cancer in humans.

On the other hand, the Bioinitiative Report (BioInitiative Working Group, 2012) reached a different conclusion:

> … RFR 'effect levels' for bioeffects and adverse health effects justify new and lower precautionary target levels for RFR exposure (Section 1, p 17).

In fact, a PD level around a million times less than those shown in Figure 13.3a are advocated, by taking published literature at face value, rather than looking for consistent replication. Both IEEE and ICNIRP emphasize the need to base limit values on well-established bioeffects that have clearly identified adverse health consequences. Thus, the so-called nonthermal effects, which most authorities would regard as not having been linked to adverse health consequences, or indeed having been established as occurring at all, do not have a part in setting exposure limits. Some of the specific end points in this literature are discussed in Chapter 16.

Table 13.2 Basic restrictions on specific absorption rate in W/kg for IEEE (IE) and ICNIRP (IC).

Exposure type	**Designation**	**Persons in controlled environment (IE) Occupational (IC)**	**Action level (IE) General public (IC)**
Whole body	Whole-body average	0.4	0.08
Localized	Peak spatial average (IE) Head and trunk (IC)	10[a]	2[a]
Localized Limb	Extremities and pinnae (IE) Limbs (IC)	20	4

Frequency range: 0.1 MHz–3 GHz (IE); 0.1–10 MHz (IC).

[a] The FCC and Health Canada recommend 8 and 1.6 W/kg, respectively.

Nevertheless, there have been calls to lower the limit values from those discussed in Table 13.2 and Figure 13.3, perhaps as a form of precaution, the rationale being that since there is some evidence of harm from long-term cellphone handset use and for possible nonthermal effects, reduction of the limits to below, say, the upper few percentile levels *normally encountered* would attenuate the putative risk. However, this logic is flawed for several reasons: (i) it introduces the notion of low-level RF damage being cumulative (for which there is no evidence); (ii) it assumes that the biases in the epidemiological studies cannot adequately account for the positive findings; and (iii) it weighs the existence of *some* positive laboratory findings as having a greater significance than an overall weight of evidence evaluation. Having said this, there is no denying that there is scientific uncertainty, but this is probably best handled by an appropriate precautionary strategy rather than introducing "as low as we can go while still delivering service" standards, not based on science. Appropriate strategies will be discussed in Chapters 25–27, but in regard to standards and guidelines, the Australian and NZ RF standards have the clause, in relation to public exposure:

> Minimising, as appropriate, RF exposure which is unnecessary or incidental to achievement of service objectives or process requirements, provided that this can be readily achieved at modest expense.

This means that, for example, telecommunications network operators, in addition to complying with the numerical limits, also consider ways of reducing exposures to the general public and can demonstrate how they have done this. This has tended to work well (since 1999 in the case of New Zealand) to provide a basis of discussion for the resolution of disputes regarding the siting of telecommunications infrastructure away from community-sensitive locations.

Table 13.3 Comparison between basic terminology from the IEEE Standard and the ICNIRP Guidelines: where no formal definition is given, parts of relevant text paraphrased in brackets.

IEEE	ICNIRP
General public	*Public exposure*
All individuals who may experience exposure, except those in controlled environments	All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures
Controlled environment	*Occupational exposure*
An area that is accessible to those who are aware for the potential of exposure as a concomitant of employment, to individuals cognizant of exposure and potential adverse effects, or where exposure is an incidental result of passage through areas posted with warnings, or where the environment is not accessible to the general public and those individuals having access are aware of the potential for adverse effects	All exposure to EMF experienced by individuals in the course of performing their work
Maximum permitted exposure (MPE) levels	*Reference levels*
The RMS and peak electric and magnetic fields or equivalent power densities to which a person may be exposed without an adverse effect and with acceptable safety factors	Obtained from basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies
Safety factor	*Safety factor*
A multiplier (≤ 1) used to derive MPE levels, which provides for the protection of exceptionally sensitive individuals, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in reaction thresholds, and uncertainties in induction models	Above 10 MHz: a restriction factor of 10 below threshold for 1 °C rise for occupational and a further factor of 5 to derive the general public basic restriction

Thus, although the limits for the IEEE standard and the ICNIRP guideline are very similar, especially for telecommunications frequencies, there are some differences, as shown in Figure 13.3. There are also differences in terminology and in other details, as shown in Table 13.3. Although ICNIRP guidelines are being increasingly adopted in countries outside the EU (where it is recognized in an official directive), IEEE tends to be accorded an “official” status in North America (Stam, 2011). However, the US FCC recognizes the 1992 IEEE SAR limits (which are not the ones given in Table 13.2), and the PD and *E*- and *H*-field limits are also different. In Canada, the limits in Safety Code 6 are similar to FCC (see Table 13.2).

Tutorial Problems

1 A survey report of in-building RF exposures has tabulated values in mW/cm^2. The maximum reading in the report is 1.1 of these units at 900 MHz. With reference to Figure 13.3, what class of personnel would comply with the ICNIRP guidelines?

2 Some survey meters give values in dBm, which is a logarithmic scale related to 1 mW. Given the conversion formula PD (in dBm/m^2) = 10. $\log_{10}$(PD (in mW/m^2)), what would be the IEEE occupational limit at 10 GHz expressed in dBm/m^2?

3 You receive a letter from a person you do not know claiming a magnetic field value of 0.1 A/m at a distance of 3 cm from a mobile phone handset. If you had to respond to this person, how would you go about explaining how phone handsets are tested for compliance?

4 At 200 m from a TV transmission tower a survey meter returns a value of 8.9 mV/m. What is the expected PD (in W/m^2) and magnetic field (in A/m) given this reading? If the transmission is mainly at 300 MHz, what is the percentage of the public exposure limit of this transmission?

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14

Assessing RF Exposure: Fields, Currents, and SAR

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14.1 Introduction

In Chapter 12, we saw that specific absorption rate (SAR) estimation was the most direct way to demonstrate compliance, but that in many settings, this is inconvenient to do, in which case compliance with *E* field, *H* field, or power flux density (*S*) limits will be sufficient (since reference levels have been formulated conservatively). This chapter discusses how these measurements are made, together with the limitations and levels of uncertainty accompanying such measurements and computations. Because field measurements are easier to do, they will be discussed first, followed by SAR estimations.

14.2 RF Sources and the Environment

The use of radiofrequency (RF) electromagnetic energy has increased significantly over the past 100 years notably since Guglielmo Marconi (1874–1937) demonstrated its usefulness for wireless communication over long distances. RF electromagnetic fields are now used for radionavigation, in radar systems, terrestrial microwave links, analog and digital radio and television broadcasting, amateur radio, mobile services including cellular networks, satellite systems, wireless local area networks (WLANs), induction cooking, dielectric heating (glue drying and plastic welding), magnetic resonance imaging (MRI) scanners, medical diathermy, millimeter wavelength whole body scanners, and RF identification devices (RFID), to name a few applications.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

A source of RF fields can be categorized as either a deliberate radiator, such as an antenna (dipoles, dishes) that is designed to radiate or receive electromagnetic energy efficiently, or an unintended radiator that produces fields as a result of imperfect seals or unavoidable gaps and openings in its construction. Unintended radiators are often equipment designed to process materials with RF energy such as dielectric and induction heaters, microwave ovens, electrosurgical devices, and arc welders. The fields from unintentional radiators, sometimes referred to as leakage fields, can be very difficult to evaluate by calculation and are generally assessed by measurement.

Quantifying RF field strengths can be performed either by measurement or computation and is a specialized activity that involves certain knowledge, technical and mathematical skills, and experience. Assessment of human exposure to RF fields may be required in many and varied places such as in homes, schools, hospitals, commercial premises, on building rooftops, basements, and the like. There may be a single dominant RF source or multiple sources and frequencies. Reflections and scattering by objects such as buildings, trees, and the like will contribute to spatial variations of the field. Other factors affecting an assessment are the modulation of the signal, the time-varying nature of the signal (due to network traffic in a mobile network or changing load conditions during RF welding), the radiation pattern and propagation direction, the polarization of the field, and whether measurements are to be performed in the near- or far-field regions.

In addition to assessing fields, an assessment may also require measurement of body currents that may occur as a result of either induction or direct contact with the source. Situations in which body current measurements may be required include assessing exposure of individuals operating RF-dielectric and induction heaters, electrosurgical devices, and arc welders. The measurement of RF body current is, in many cases, required to assure compliance with exposure standards and guidelines that specify current limits such as ICNIRP (1998) and IEEE C95.1-2005. These are described in Chapter 13.

14.3 Planning an Exposure Assessment

An important part of an exposure assessment is to first understand its purpose and then to prepare an assessment protocol. The purpose may be to satisfy a mandatory compliance requirement or for informative purposes only; provide a “snap shot” of the field strength at a particular time and place or to assess the maximum or peak field strength that could occur at that place; find the locations around an RF source where the field strength reaches the occupational or public exposure limit; and assess the cumulative, total field strength (contributions from all sources), or the level from an individual RF source.

If measurements are to be performed, the purpose will determine the instrumentation that will be required and whether additional processing of measurement results will be necessary. For example, in an environment that contains multiple RF sources and frequencies, a frequency-selective instrument such as a spectrum analyzer or receiver is required if the field strength at a specific frequency is to be measured. If the cumulative, total field strength is being assessed, then the individual field strength components measured with a frequency-selective instrument must be combined mathematically. Alternatively, the total field strength can be measured with an appropriate broadband instrument.

In most situations, the field strength will be varying with time and be composed of multiple waves due to scattering from stationary and moving objects in the environment. This leads to a complex spatial distribution of the field resulting in localized maxima and minima. To ensure accurate measurements, antennas must be physically small compared to the distances between maxima and minima. The effect on measurement accuracy caused by scattering from the measuring instrument itself and from the assessor should be quantified and minimized where possible. The measurement protocol should also incorporate both spatial and time (temporal) averaging of the field (Chapter 13). Furthermore, both the electric and magnetic field components will need to be measured if the assessment is being performed in the near field of the source.

Assessing RF field strengths by computation may be the only option if the purpose is to estimate exposure to sources that are yet to be built or installed such as radio towers and mobile base station antennas. Typically, an assessment by computation will require knowledge of the source and the radiating structure to be modeled and analytic or numerical tools for the calculation of radiated fields or power absorbed in a human body.

Computational techniques are also efficient and accurate for assessment at short distances from an RF source that is well defined in terms of its physical and electrical properties and away from the influence of environmental scatterers. Computational assessments of RF exposures in complex scattering environments may however be more problematic than measurements.

The following steps may be helpful in the planning and execution of an assessment:

- Define the purpose of the assessment;
- Gather information about the characteristics of the RF source(s) (e.g., power, frequency, and modulation) and the environment in which the assessment is to be performed;
- Determine the applicable exposure limits;
- Perform a preliminary desktop assessment to estimate RF field strengths and consider options for either measurement or computation. Assessment by measurement must consider the safety of the assessor and other persons;
- Choose either measurement or computation and define the assessment protocol;
- Perform assessment, process results, and prepare report.

14.4 Quantities and Units

The physical quantities most frequently encountered in exposure assessments are the electric (E) and magnetic (H) field strengths, the power flux density (S), contact and limb currents, and SAR. The E is the root-mean-square (RMS) electric field strength in volt per meter (V/m) and H is the RMS magnetic field strength in ampere per meter (A/m), S is the power density in watt per meter squared (W/m^2), current in ampere (A), and SAR in watt per kilogram (W/kg). Determining S at a point in space is inherently difficult as it requires knowledge of both the E and H field strengths, the direction along which they act, and the phase difference between them.

In Figure 1.2, a simple plane electromagnetic wave propagating in free (unobstructed) space is shown with the E and H fields at right angles to each other and to the direction of propagation. For this condition, S can be determined precisely from either the E or H field strength given that the ratio E/H is equal to 377 Ω:

$$S = E \times H = E^2 / 377 = H^2 \times 377 \tag{14.1}$$

This propagation condition is rarely encountered in practice. Typically, the ratio E/H varies significantly at different points in space and will not generally be equal to 377 Ω. Such conditions would apply in the near field of an RF source or in scattering environments (e.g., containing buildings, walls, and ground) that create complex field structures requiring assessment of both the E and H field components. Therefore, only an estimate of the precise value of S can be obtained from a measurement of E or H and this estimate, denoted here by S_{equ}, is often referred to as the "equivalent plane wave power flux density". It is a commonly used term associated with any electromagnetic wave, equal in magnitude to the power flux density of a plane wave having the same E or H field strength. Field strength instruments that display results in units of power density usually measure E and/or H and convert to S_{equ} using (14.1).

Field strength values in exposure assessments can range over a 1,000,000 times or more – from fields due to radiation from distant TV transmitters to localized, intense fields near industrial RF welders. It is therefore usually more convenient to express measured quantities in logarithmic units such as *decibels* (*dB*). Power quantities (W or W/m^2) can be expressed in decibels by evaluating 10 times the base-10 logarithm of the ratio of the measured value P_1 to the reference value P_0 or $10 \times \log_{10}(P_1/P_0)$ (or simply $10\log_{10}(P_1/P_0)$). As an example, for a measured power density $P_1 = 1000\,\mathrm{mW/m^2}$ and a reference power level $P_0 = 1\,\mathrm{mW/m^2}$, the measured level in decibels is 30 dB referenced to 1 mW/m^2, or written as 30 dBmW/m^2. E and H fields can also be expressed in dB notation. Since power is proportional to the square of the field, then the ratio in dB is $10\log_{10}(E_1/E_0)^2 = 20\log_{10}(E_1/E_0)$. Similarly, for a ratio of H fields, we get $20\log_{10}(H_1/H_0)$. Often, a voltage measurement will be referenced to 1 µV ($E_0 = \mu\mathrm{V}$ (often written uV)). This is referred to a dBuV. The equivalent for current is dBuA, referenced to 1 uA. Similarly, E and H field measurements can be expressed in dBuV/m and dBuA/m when referenced to 1 uV/m and 1 uA/m, respectively.

14.5 Broadband Field Strength Measurements

Instruments for measuring RF field strength are usually categorized as either broadband or frequency selective. A broadband instrument combines all signals that are present within the bandwidth of the measuring probe at the measurement location.

The essential components of a broadband field strength measuring instrument are the broadband probe, the connecting leads, and the meter. A user may select from different probes depending on the frequencies being measured or different intensity ranges and for measuring the E or H field. Typically, E field probes are designed to cover frequencies from around 100 kHz up to 6 or 18 GHz or higher. H field probes are typically designed to measure over the range from 100 kHz to 1 GHz. The meter contains electronics used for measuring the output from the probe, processing and storing the measured data, and displaying the result.

The basis of many broadband E field probes is the electrically small dipole antenna. For H field measurements, the broadband probe relies on electrically small loop antennas. The term "small" means that the largest physical dimension of the antenna is much less than the wavelength ($<\lambda/10$) of the signal being measured. A small dipole (tip-to-tip length L) and small loop antenna (circumferential length $2\pi a$) are shown in Figure 14.1. The output signal across the

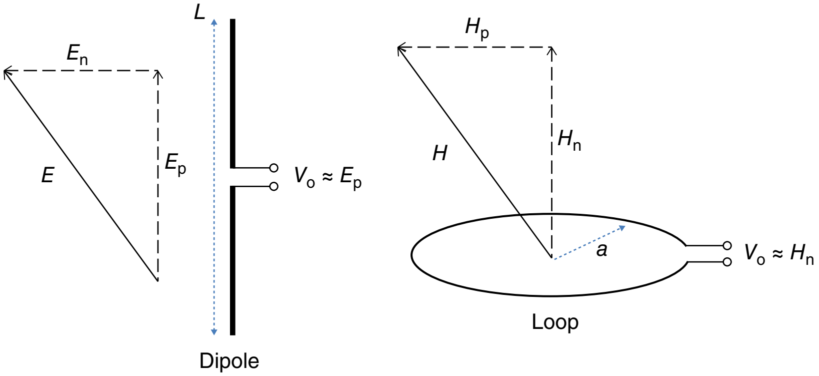


Figure 14.1 Response of electrically small dipole ($L < \lambda/10$) and loop ($2\pi a < \lambda/10$) antennas to an incident electromagnetic field. The voltage V_o across the terminals of the dipole is directly proportional to the parallel component of the incident field, E_p. For the loop antenna, V_o is directly proportional to the H field component normal to the plane of the loop, H_n.

terminals of the small dipole is directly proportional to the parallel component of the incident E field, while the output signal across the terminals of the small loop is directly proportional to the normal component of the incident H field and frequency. It follows that a small antenna has a lower sensitivity compared to the larger, half wavelength ($\lambda/2$) resonant (tuned) antenna, but it offers the important advantages that it is compact, its response can be tailored to be constant or shaped over a large range of frequencies (i.e., broadband), and it minimizes the disturbance of the field being measured and reduces the adverse effects of electrical coupling of the antenna to objects in close proximity – at distances comparable to its physical size.

In most real life measurement situations, it is not possible to know the orientation of the electromagnetic field. Furthermore, it could be constantly changing due to the propagation conditions existing at the measurement location (e.g., reflections from moving objects). In these situations, it is advantageous for the response of the antenna to be isotropic, that is, uniform in all orientations. An isotropic E or H field probe can be constructed by using three dipole or loop antennas arranged orthogonally to each other. Each antenna would respond to the component of the field acting along one of the orthogonal axis (e.g., E_x, E_y, or E_z). Furthermore, if a “square law” detector is placed at the terminals of each small antenna, then the constant level (the direct current or DC level) component of the output voltage will be proportional to the square of the field. For an isotropic E field probe, the total or sum of the DC voltages will be proportional to the square of the total E field.

$$E^2 = E_x^2 + E_y^2 + E_z^2 \tag{14.2}$$

The isotropic H field probe output will be proportional to the square of the total H field.

$$H^2 = \mathrm{H}_x^2 + \mathrm{H}_y^2 + \mathrm{H}_z^2 \tag{14.3}$$

The meter processes the total DC voltage and displays a measurement result in terms of E or H field strength or an equivalent plane wave power flux density S_{equ}. The value of S_{equ} can be calculated from (14.1) in combination with (14.2) or (14.3):

$$S_{\text{equ}} = E^2 / 377 = \left(E_x^2 + E_y^2 + E_z^2\right) / 377 \tag{14.4}$$

$$S_{\text{equ}} = H^2 \times 377 = \left(H_x^2 + H_y^2 + H_z^2\right) \times 377 \tag{14.5}$$

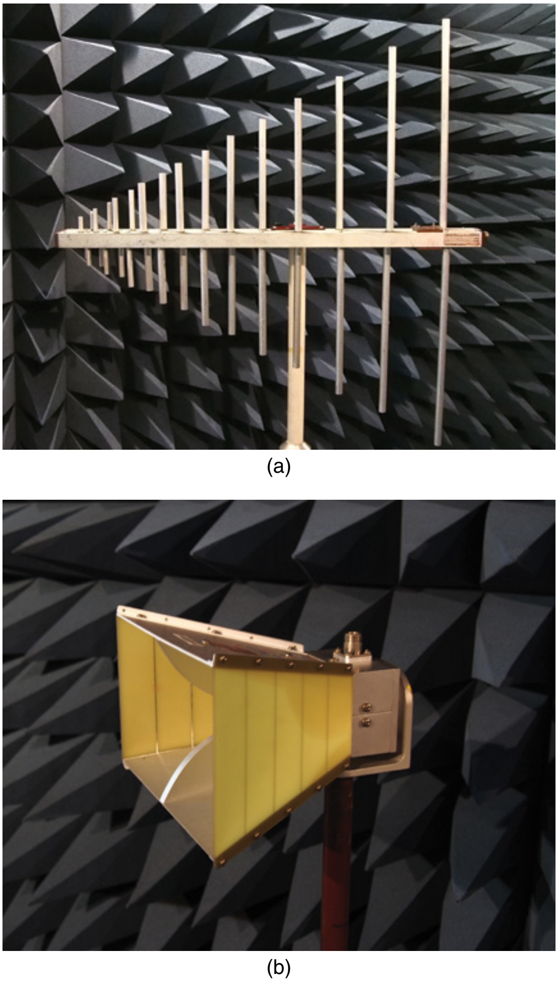
Examples of square law detectors are the diode, thermocouple, and thermistor. The thermocouple and thermistor measure the heating capacity of a signal that equates to the power in the signal. While these types of detectors provide extremely good adherence to square law operation, their major limitation is burnout. A diode is not a heat-based sensor but rectifies the signal instead (converts an alternating RF signal to a DC signal). At low signal levels, the DC voltage is proportional to power flux density or the square of E (or H). At higher signal levels, the DC voltage becomes directly proportional to E (or H). This change in characteristic means that the range of operation of the diode must be restricted to low levels to provide a true indication of total power flux density. This is an important consideration when measuring signals with high instantaneous peak amplitude but low time averaged level such as radar signals. The transition from square law to linear performance is gradual and manufacturers of broadband probes will typically specify a peak field strength beyond which square law performance cannot be assumed.

It is important to note that measurements using square law detectors will not provide frequency information and therefore cannot discriminate between individual frequencies. In a survey of a multifrequency RF environment, such as where AM radio, TV, and mobile base station signals are present at the same location, the meter will display the sum total field strength from all sources hence the term "broadband meter".

14.6 Frequency-Selective Field Strength Measurements

A frequency-selective measuring instrument consists of a spectrum analyzer and an antenna directly mounted on the analyzer or connected with a coaxial cable. The antenna is typically mounted on a stand (e.g., tripod) to minimize the effect of an assessor's body on measurement accuracy. Spectrum analyzers for field strength measurements are typically battery powered, compact, and handheld in design with a range of preset instrument settings that provide for a wide range of measurement scenarios. While this type of instrument can provide for a simpler, more practical approach to frequency-selective measurement, it does require the operator to fully understand its limitations. For example, it is important that the input level to the spectrum analyzer be kept within the maximum rating of the instrument. High input levels can cause overloading, which results in compression of the signal level and production of unintended, spurious harmonics leading to measurement error.

The antenna may be an isotropic probe similar in concept to that used by a broadband instrument but without square law detectors. The antenna may however incorporate active electronics allowing the frequency response to be modified as well as providing signal amplification. Alternatively, the spectrum analyzer may be connected to an antenna that has not been designed for isotropic response or is intrinsically nonisotropic. This includes the resonant, half wavelength single dipole or loop, and antennas designed for operating over a wide frequency range such as the log-periodic (e.g., 300–1000 MHz) and the broadband horn



(a)

(b)

Figure 14.2 Log-periodic antenna (a) and broadband horn (b).

(e.g., 1–10 GHz), shown in Figure 14.2. An important consideration when using nonisotropic or single axis antennas is that they must be rotated through each of the orthogonal directions in order to determine the maximum field strength.

14.7 Induced and Contact Current Measurements

As noted in ICNIRP (1998) and IEEE C95.1-2005, contact current limits are defined for frequencies up to 110 MHz and are intended to provide protection against RF shocks or burns when making point contact (e.g., via a fingertip) with an RF-energized conductor. The limb current limits are also defined for frequencies up to 110 MHz and are intended to prevent excessive RF heating in the wrists and ankles caused by grasping contact with an RF-energized conductor. They also protect against excessive RF heating in the ankles for whole body exposure of a freestanding person. Two types of commonly used equipment for measuring induced currents are the clamp-on "loop"-type current transformers for measuring current through the ankle or calf and the parallel plate "stand-on meters" for measuring currents that flow to ground through the feet, see Figure 14.3.

Commercially available lightweight clamp-on current transformer instruments have been developed that can be worn by a person to measure current through the leg or arm. A meter, either mounted directly on the transformer or connected through an optical link for remote reading, provides a display of the current flowing through the arm or limb. Current detection in these units may

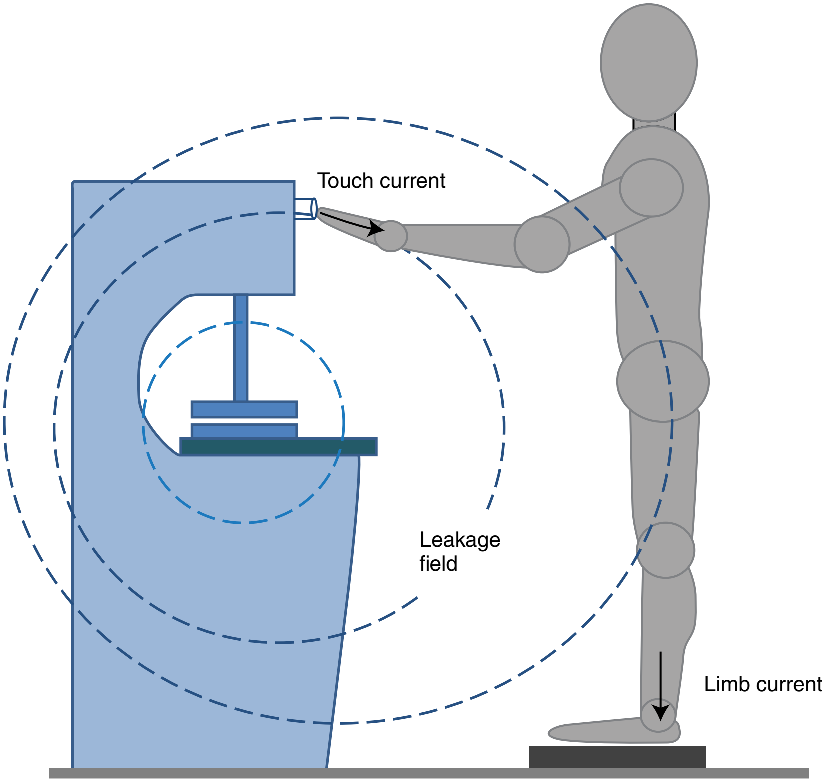


Figure 14.3 Touch and limb currents in a worker operating an RF welding machine. Touch currents are caused by direct contact with the machine, while stray leakage fields couple to the body causing current to flow to ground.

be accomplished using either frequency-selective techniques using spectrum analyzers/tuned receivers or broadband techniques employing diode detection/thermal conversion. As noted, diode detection must be used with care to ensure that the diodes are operated in their square law response region to achieve a true RMS current indication.

14.8 SAR Measurements

Accurate determination of human exposure from devices that are normally used close to or worn on the body will require a SAR assessment. Two approaches to the measurement of SAR can be taken both involve using a thin fiberglass shell filled with human tissue-equivalent liquid. The shell is a phantom, or anthropomorphic model of the human body (or perhaps just the head) and the liquid simulates the electrical properties of tissue at the operating frequency of the device. In the first approach, the device is placed close to the phantom, mimicking normal or usual position of use, and a fiber optic temperature measurement sensor is positioned in the liquid near the device/liquid boundary to measure temperature rise. When determining SAR through temperature rise, it is only appropriate to use the initial rise after the RF exposure is applied. SAR is then given by the formula:

$$\mathrm{SAR} = C_p \Delta T / \Delta t \tag{14.6}$$

where C_p is the specific heat of the material (e.g., a value of 3250 J/(kg °C) for skin) and $\Delta T/\Delta t$ the ratio of the change in temperature T (°C) to the change in time t (seconds) determined at the instant that the RF source (e.g., wireless device or mobile phone) is turned on. In practical terms, such a calculation is performed using measurements at discrete, short time increments. It is important that such a calculation uses data for no more than the first few seconds of exposure, for typical exposure levels such as from a mobile phone (of the order of 1 W/kg) in a localized volume of human tissue. After this time frame, the formula will no longer be valid due to heat transfer away from the point of measurement. A further difficulty with this approach is that the low RF power emitted by many consumer devices will cause only a very small and gradual temperature rise, of the order of a fraction of 1 °C or less, so that the sensitivity of the fiber optic probe and the temperature stability of the test laboratory conditions are crucial.

An alternative measurement method is to replace the fiber optic probe with a SAR measurement probe. This is the approach adopted in the SAR measurement standards IEC 62209-1:2005, IEC 62209-2:2010, and IEEE 1528-2013. These standards also describe the phantoms to be used for SAR measurements. The localized SAR, an average value over 1 g or 10 g of tissue, is measured using a miniature, millimeter-sized isotropic broadband electric field probe. The probe uses square law detectors and measures the total E field strength. The SAR is computed from the measured E field strength:

$$\mathrm{SAR} = \sigma E^2 / \rho \tag{14.7}$$

where σ is the conductivity of the liquid in Siemens per meter (S/m) and ρ the mass density in kilogram per meter cubed (kg/m^3).

This SAR probe is moved within the fluid of the phantom (with the device under test placed in its normal position), next to the "ear" of the phantom to find the maximum SAR value. This search is usually done by a computer-controlled robot. Other, less anatomically correct phantoms are also used (the "flat" phantom) to further simplify this measurement. There has been much research into whether a phantom needs to be a multilayered fluid (heterogeneous tissue phantom) or just a single fluid (homogeneous tissue). The consensus is that if a device is compliant in a homogeneous phantom it will also be in a heterogeneous one and the former is much easier to implement. Some countries require manufacturers to include SAR information with handsets and other RF-emitting devices they sell.

14.9 Computation of Fields, Currents, and SARs

There are a range of analytic and numerical methods for computing the exposure produced by antennas and RF-emitting devices generally. Computation can assist during preliminary phases of an assessment and during full assessments where detailed and comprehensive analysis of human exposure is required. Computational tools can range from ray-tracing techniques using analytic formulas to estimate the field produced by antennas or other radiating or reradiating structures, through to computer-based computational electromagnetics (CEM) packages that can provide a more complete and detailed numerical analysis of the fields or SAR in complex environments. At the heart of a CEM package is the computational code that decomposes the "real-world" problem using numerical forms of Maxwell's equations to compute the electric and magnetic fields and SAR. The finite difference time domain (FDTD) modeling, finite element method (FEM), and the method of moment (MoM) techniques are some of the more popular numerical methods that form the basis of today's CEM packages (Govan et al., 2004).

Analytic formulas can be relatively easy to implement in software and may provide sufficient information regarding the RF exposure environment under consideration. For example, the value of S in the far field at a distance (R) from an antenna can be calculated from knowledge of the power (P) supplied to the antenna and its antenna gain (g):

$$S = Pg / 4\pi R^2 \tag{14.8}$$

The gain g is a dimensionless quantity that is a measure of the ability of an antenna to transmit (or receive) a signal in a given direction relative to a perfectly isotropic antenna. It is a measure defined under far-field conditions.

The distance from an antenna (or radiating structure generally) to the far field is usually given as

$$R_{\min} = 2D^2 / \lambda \tag{14.9}$$

The minimum distance to the far field is $R_{\min}$, the largest dimension of the antenna is D, and λ is the wavelength. For example, from (14.9), the far-field distance for a half wavelength dipole ($D = \lambda/2$) is $R_{\min} = \lambda/2$. The far-field distance for a 2-m tall mobile base station antenna operating at 900 MHz ($\lambda = 0.333$ m) is $R_{\min} = 24$ m.

The product of power P and gain g, Pg, is commonly called the equivalent isotropic radiated power (EIRP). It can be thought of as the amount of power an isotropic antenna would need to radiate to achieve the same S value as that of the actual antenna. By definition, a perfectly isotropic antenna transmitting uniformly in all directions has a gain of 1. The gain can be computed (or measured) for other types of antennas. A dipole antenna has a maximum gain of 1.64 while complex multielement antennas such as those employed in mobile telecommunications networks can have gains of around 30 or more. The gain is often expressed in decibels so that the gain of a dipole (relative to an isotropic antenna) is 2.15 dBi ($=10\log_{10}(1.64)$). It is important to note that gain will vary with position around the antenna so that, for example, the maximum gain (e.g., $g = 30$) for a mobile base station antenna will occur directly in front while the gain to the rear can be very much smaller (g of 1 or less).

For some scenarios, more accurate and advanced full wave computational techniques can be employed to analyze human exposure in more detail; for example, field evaluation in the near-field of an antenna or SAR evaluations to the side of a base station antenna. Sophisticated, three-dimensional voxel (element of volume)-based models of the human body (or of the head) are available to compute localized SAR (and whole body SAR, if appropriate). The resolution of these models has improved to the point where voxels less than a cubic millimeter in volume are commonly used to model the complex structure of a body. From MRI or other imaging data, each voxel is assigned to a particular tissue type, with relevant electrical properties for the frequencies studied. This is a useful method, but there is always uncertainty in model validity (although there is constant improvement in model complexity). The other aspect is to correctly model the handset, which in the case of smart phones is becoming increasingly difficult, because a simple current dipole representation is no longer suitable.

A critical aspect to the use of computational tools is the process of validating their algorithms. An uncertainty budget should be developed for each computation tool used for assessment of fields, currents, or SARs.

14.10 Calibration of Instruments

Calibration involves ascertaining and documenting deviation of the measured value from a traceable, accurate test standard. The measured value obtained from a measuring instrument is thus compared with the known value of the test standard under specified reference conditions using reproducible measuring procedures. A statement of uncertainty will accompany a calibration report.

Consider the calibration of a broadband field strength probe. It is placed in an accurately known and well-defined electromagnetic field and its meter reading is compared to the value of the known field. The difference between the meter reading and the known field is recorded and can be used as a correction factor. Other components of a system, such as coaxial cables, can also be calibrated against a known standard. In this way, calibration helps to minimize any measurement uncertainty by ensuring the accuracy of measuring instruments and their components. Calibration quantifies and controls errors or uncertainties within measurement processes to an acceptable level. To be confident in the results being measured, there is an ongoing need to service and maintain the calibration of measuring instruments throughout their lifetime for reliable, accurate, and repeatable measurements. The calibration interval depends on the individual instrument and is commonly recommended by the instrument manufacturer.

The calibration of measurement instruments requires specialized knowledge and facilities and would not normally be a task undertaken by an assessor. Instruments should be calibrated by competent independent laboratories that have been accredited by a recognized national accreditation body. A comprehensive list is maintained by International Laboratory Accreditation Cooperation (ILAC) (http://ilac.org/ilac-membership/).

14.11 Validation of Computational Tools and Simulations

Despite all computational tools having their basis in Maxwell's equations of one form or another, their accuracy and convergence rate depends on how the physics equations are cast, what numerical techniques are used, inherent modeling limitations, approximations, and so forth. Validation of computational tools is therefore a key issue and it is a requirement of the user to understand the validity of the simulation in order to provide an estimate of the uncertainty in the result. Validation therefore encompasses the process of verifying that the computational tool produces results that are consistent with its design through to establishing how well the results conform to the physical reality of intended applications (Miller, 2006).

There are two measures that can be used to quantify the uncertainty in a computation. The measures involve either a global quantity such as total (integrated) radiated or absorbed power or a local quantity such as point values on an antenna pattern, peak spatial SAR, or field strength. The choice between global or local measure will be dependent on the problem to be solved (e.g., solving for the whole body average SAR or wanting to know the field strength at a specific point in space). Having chosen the appropriate measure, a series of internal and external checks can be performed. Based on the results of checks, an inherent uncertainty (appropriate to the range of intended applications) can be attributed to the computational tool.

An internal check provides confidence in the self-consistency of results with respect to Maxwell's equations. The checks include tests for convergence to establish that a model has been sampled finely enough, to determine continuity of tangential fields at boundaries, and using geometry-based changes in an original model to predict specific changes in the solution (e.g., changes in resonant frequency as antenna size changes).

External checks include comparisons with results obtained using analytic solutions to Maxwell's equations and with data obtained from measurement and other computational tools.

14.12 Uncertainty in Measurements and Computations

Every measurement or computation is prone to errors and a result is said to be complete only when accompanied by a quantitative statement of its uncertainty. Uncertainty is simply a statement of our incomplete knowledge of the value of the measured or computed quantity and of the factors influencing it. Importantly, it is also a statement about the quality of the measurement or computation. Minimizing the sources of errors and their effects will lead to greater certainty in the result.

Errors can result from random and systematic effects. A systematic effect is one that biases the result consistently and repeatedly in one direction. Calibration of equipment with respect to a "standard", for example, will reveal any systematic errors. Random errors are caused by unknown and unpredictable changes and must be treated on a probabilistic basis. When a measurement or computation is performed, it is generally assumed that some exact or true value exists based on a definition of what is being measured or computed. In practice, the exact or true value will be unknowable but can be approximated by the value of the quantity measured or computed. Results are usually reported by specifying a range over which the true value is expected to fall within. The most common way to show the range is

$$\text{Result} = \text{best estimate} \pm \text{expanded uncertainty}$$

The best estimate is the measured or computed value after correction for all systematic effects. The expanded uncertainty is the combination of uncertainties from all the major sources of random error. For example, the result of an assessor's E field strength measurement may be reported as 17.6 V/m ± 28%. The best estimate of the measured field strength is 17.6 V/m but random errors associated with the measurement mean that the true value could lay up to 28% above or below the best estimate.

The range of values that one can expect this "true value" to fall within is often well approximated by a bell-shaped probability distribution curve commonly known as a normal or Gaussian distribution. The distribution is defined by the mean value (μ) and the standard deviation (σ). Figure 14.4 shows the bell-shaped nature of the distribution. The expanded uncertainty (U) is the combination of uncertainties from all the major sources of random error and is related to σ. The value of U is often chosen to be equal to two times the standard deviation (i.e., $U = 2\sigma$) so that the probability that the true value lies in the interval between the lower bound value of $\mu - \mathrm{U}$ and the upper bound value of $\mu + U$, commonly referred to as the confidence interval (CI), is 95%. This implies that there is a 2.5% chance that the true value may lay below $\mu - U$ or above $\mu + U$. When $U = \sigma$, the CI is 68%.

Measurement uncertainties can come from the measuring system, the measurement procedure, the skill of the operator, the environment, and other effects. This includes uncertainties related to the following:

- calibration of meter or spectrum analyzer
- isotropic response and gain of the antenna/probe

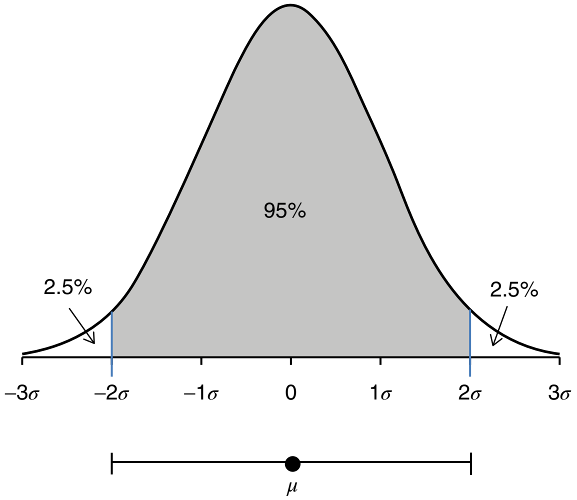


Figure 14.4 Two-sided confidence range. The best estimate lies at the center of the normal or Gaussian probability distribution probability distribution. The true value is unknown but will lie in the symmetric range between the interval between the lower bound value $\mu - 2\sigma$ and the upper bound value $\mu + 2\sigma$ with 95% confidence.

- calibration of coaxial cable losses
- power variations in the RF source, and
- unintended scattering of the field by the assessor, instruments, and other stationary or moving objects.

Computational solutions for complex real-world problems can be obtained by simulating the propagation and interaction of electromagnetic fields with objects in the environment including a human body. The numerical treatment of the “real-world” problem leads to results that can only be an approximation of the true value. Sources of uncertainty in computations include the following:

- inherent uncertainties and limitations associated with the approximate numerical model used to represent the antenna
- cable and connector losses
- variation in transmitter power, and
- scattering from objects and the ground.

Guidance on individual uncertainties and how they are combined to determine the overall uncertainty can be found in assessment standards such as the IEC 62209 series, IEC 62232:2011, IEEE C95.3-2002, and AS/NZS 2772.2:2011.

14.13 Compliance with Limits

An important consideration is how uncertainty information should be used when assessing compliance or noncompliance with exposure limits (Chadwick, 2008). While this is desirable to define, clear statements of the compliance conditions (i.e., a *decision rule*) may not always be stated. Where a standard or regulation (or client specification) makes no reference to taking into account the uncertainty, then it may be acceptable to make the judgment of compliance or noncompliance based on whether the result of a measurement or computation (the best estimate) meets or exceeds the exposure limits with no account taken of the uncertainty. Two important issues arise: when the result is equal to the limit, there is a 50% chance that the true value exceeds the limit and importantly; there is no statement concerning the maximum permitted value of the uncertainty. This leaves open the possibility that the true value may lay below or above the limit by a considerable margin due to large, unconstrained uncertainties.

The SAR measurement standards for wireless devices held near the head stipulate that for the purpose of demonstrating compliance with exposure standards, the measured SAR values must be used for comparison with SAR limits provided that U is less than or equal to 30% (CI = 95%). The value of U should be recorded by the laboratory undertaking the measurement but should not be included in the comparison with the limit. A statement in Clause 7.3.2 of IEC 62209-1:2005 (and a similar statement in IEEE 1528-2013) leaves open the possibility that a correction or adjustment can be applied to the result of measurement if U is greater than 30%:

> If the uncertainty is greater than 30%, reported data may need to take into account the percentage difference between the actual uncertainty and the 30% target value.

The IEC 62232:2011 and AS/NZS 2772.2:2011 standards provide details on how a correction or adjustment can be applied if U exceeds an allowed amount. The method is as follows. If the assessor's expanded uncertainty, U is greater than a prescribed allowed amount U_0, the best estimate must be increased by an amount equal to the difference $U - U_0$ and then compared with the compliance limit. If U is less than or equal to U_0, the best estimate is simply compared to the limit. For example, an allowed amount $U_0 = 3$ dB is defined in AS/NZS 2772.2:2011 and $U_0 = 4$ dB in IEC 62232:2011 when assessing compliance to field strength reference levels in exposure standards. If an assessor states the result as a measured field strength (best estimate) with an expanded uncertainty $U = 5$ dB (CI = 95%), then the measured level must be increased by 2 dB (AS/NZS 2772.2:2011) or 1 dB (IEC 62232:2011) before comparing with the compliance limit. If the assessor's expanded uncertainty does not exceed U_0, then compliance is demonstrated if the measured field strength does not exceed the limit.

CIs are often expressed as a two-sided range; however, if the goal is to show that the result of measurement or computation is not worse than the limit, then a more conventional approach is to employ a one-sided 95% CI, shown in Figure 14.5. In this case, only an upper bound $\mu + U$ is specified, where $U = 1.64\sigma$. If we take the SAR example and assume a two-sided distribution such that the

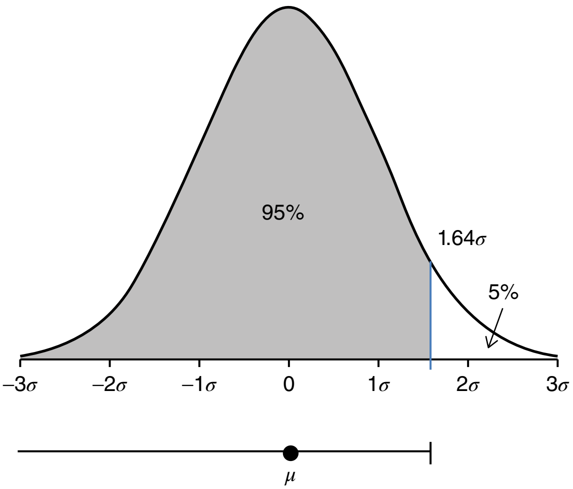


Figure 14.5 One-sided confidence range. The best estimate lies at the center of the normal or Gaussian probability distribution. The true value is unknown but will be less than the upper bound value $\mu + 1.64\sigma$ with 95% confidence.

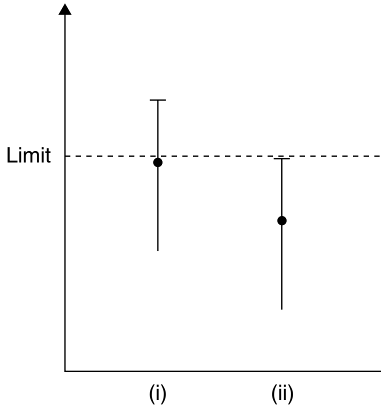


Figure 14.6 Compliance with a limit. In both the cases, the assessor's expanded uncertainty is within a prescribed allowance. In the first case, the upper bound extends above the limit so that there is close to a 50% chance that the true value exceeds the limit and around a 45% chance that it is between the limit and the upper bound. In the second case, the upper bound is just below the limit and there remains a much lower chance that the true value exceeds the limit.

expanded uncertainty U be no more than 30% ($U = 2\sigma$), then converting to a one-sided 95% CI will mean that the upper bound is equal to the measured SAR increased by 24.6%. Examples showing compliance with a limit are given in Figure 14.6.

Tutorial Problems

1 In a workplace survey, the maximum measured field strengths were found to be 23.5 V/m and 0.104 A/m over a frequency range 100 kHz to 10 MHz. Express these levels in units of decibels relative to 1 uV/m and 1 mA/m, respectively?

2 What is the distance to the far field of a 2-m tall mobile base station antenna operating at 700 MHz?

3 In Figure 14.6, what is the chance (probability) that the true value exceeds the limit for the case where the upper bound is just below the limit?

Glossary

Assessment A measurement or computation performed for the purpose of quantifying exposure to radiofrequency electromagnetic fields.

Assessor Person(s) undertaking an assessment.

Basic restriction Restrictions on the effects of exposure are based on established health effects and are termed basic restrictions. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure are current density, SAR, and power density.

Exposure Exposure of a person to electric, magnetic, or electromagnetic fields or induced and contact currents originating from man-made RF sources.

Exposure standard or guideline A document that specifies limits of human exposure to electromagnetic fields to prevent adverse effects. Examples include ICNIRP (1998) and IEEE C95.1-2005.

Reference level Levels provided for comparison with values of physical quantities. Compliance with all reference levels is intended to ensure compliance with basic restrictions. If values are higher than reference levels, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the basic restrictions.

Modulation The process of varying one or more properties of a carrier signal with a modulating signal that contains information to be transmitted.

Radio frequency A term (abbreviated RF) that refers to a part of the electromagnetic spectrum from 3 kHz to 300 GHz.

Specific heat capacity The amount of heat necessary to raise the temperature of a unit mass of a substance 1 °C. The unit of specific heat capacity is often expressed as joule per kilogram degree Celsius (J/kg °C).

Touch current A contact of small area (e.g., 1 cm^2) made between the human body and an energized conductor.

True value The value of the quantity being assessed that would be obtained by a perfect assessment (no errors). The true value is usually not known.

Uncertainty A parameter associated with the result of an assessment that characterizes the spread of the values that could reasonably be attributed to the quantity being assessed (e.g., field strength).

Voxel A three-dimensional volume element in a computer-based model or graphic simulation. An array of voxels is used to represent a three-dimensional object.

Symbols

A	ampere
°C	degree Celsius
c	speed of light, 3×10^8 m/s
kg	kilogram
kHz	kilohertz (10^3 Hz)
mHz	millihertz (10^{-3} Hz)

MHz	megahertz (10^6 Hz)
GHz	gigahertz (10^9 Hz)
uV	microvolt (10^{-6} V)
m	meter
λ	wavelength (m); in free space, equal to the frequency divided by the speed of light (*c*)
V	volt
W	watt

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15

Epidemiological Studies of Low-Intensity Radiofrequency Fields and Diseases in Humans

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15.1 Introduction

In recent years, most attention on exposure to radiofrequency (RF) fields has been on the effects of the personal use of mobile phones, especially on brain cancers, and on exposures to mobile phone base stations. Even before that, issues were raised about exposures to radio, television, and radar transmissions and occupational exposures to these and other sources of RF. A central biological issue is whether there are *athermal* effects, that is, effects from fields too low to cause tissue heating. Accepted exposure standards are based on the reproducible tissue heating effects, with lower intensity exposures being considered but not regarded as well-enough established to affect the standards. The best information on potential health effects of RF exposure comes from authoritative interdisciplinary groups that have documented and reproducible procedures to access and review all published peer-reviewed studies in their time frame. Useful recent reviews are those of the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) of the European Commission 2015 (SCENIHR, 2015); the Swedish Radiation Safety Authority (SSM), 2015 (Swedish Radiation Safety Authority (SSM) and SSM's Scientific Council on Electromagnetic Fields, 2015); ARPANSA (Australia), 2014 (Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), 2014); and the UK Health Protection Agency, 2012 (Health Protection Agency (HPA) and Advisory Group on Non-Ionizing Radiation (AGNIR), 2012). The monograph from the International Agency for Research on Cancer (IARC), 2011, is very important, as it classified RF in class 2B "possibly carcinogenic to humans" (International Agency for Research on Cancer, 2011); it will be

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discussed later. A World Health Organization report in the Environmental Health Criteria series is in progress.

The conclusions from the SCENIHR 2015 report (SCENIHR, 2015) on epidemiological studies are (page 5): "Overall, the epidemiological studies on mobile phone RF EMF (electric and magnetic field) exposure do not show an increased risk of brain tumors. Furthermore, they do not indicate an increased risk for other cancers of the head and neck region. Some studies raised questions regarding an increased risk of glioma and acoustic neuroma in heavy users of mobile phones. The results of cohort and incidence time trend studies do not support an increased risk for glioma, while the possibility of an association with acoustic neuroma remains open. Epidemiological studies do not indicate increased risk for other malignant diseases including childhood cancer".

A key methodological problem is that of exposure measurement. As there is no clearly defined biological hypothesis to be tested, most research estimates RF exposure from average exposure intensity, cumulative exposure (time-weighted intensity), or other metrics such as peak exposure levels. Meters capable of measuring personal exposures have been developed, but most long-term exposure assessments depend on interview-based assessments of prior exposure, for example, to mobile phone use; geographical positioning, for example, place of residence in terms of proximity to television or radar transmitters; or likely occupational exposure, based on job titles and job exposure matrices using assessments or measurements of RF exposure for typical job titles, industries, and time periods. All of these are compromises; the relationship of the assessed exposure in a study to the actual biologically relevant exposure is always unknown. The most studied outcomes have been cancers of various types, but there are also studies of cardiovascular disease, neurological diseases, reproductive outcomes, psychological effects, and sleep, among others.

15.2 Mobile Phone Use and Brain Cancer

This is a complex and controversial subject with considerable discrepancies between the results of different studies. Studies of mobile phone use and brain cancer are complex because there are several different types of brain cancer, such as glioma, meningioma, and acoustic neuroma, being, respectively, tumors of the brain cells, the tissues enclosing the brain, and the auditory nerve going to the ear. Tumors can be classified as benign or malignant. There are several different phone systems; exposure intensities relate to the design and power of the phone, the position of the aerial in the phone, whether hands-free devices are used, the location of the phone in relationship to base stations, and other factors.

The location of the tumor is important. On simple logic, if RF emissions from mobile phone use do cause brain tumors, the tumors caused will be close to the ear or the area over which the phone is held (the temporal and parietal lobes, including the acoustic nerve), and if the phone is held regularly on one side of the head, the excess tumors caused will be on that side. There should be no change in the risk of tumors at more distant sites. However, locating the anatomical position of a brain tumor is not simple; the center of the abnormal tissue when the tumor is diagnosed may not be its point of origin, and the information available on the side of the head that the mobile phone has been used on is of dubious validity, both because of recall problems and because early symptoms prior to the diagnosis of brain tumor may affect hearing and so change phone use behavior.

15.3 Case–Control Studies

Two main sets of case–control studies have given rather different results. The World Health Organization sponsored a series of international case–control studies based on a common protocol, the Interphone studies. The results for the commonest brain tumors (glioma and meningioma) were reported in 2010 (Interphone Study Group, 2010). This was a huge study, costing about US $25 million, and involved personal interviews with 2708 patients with glioma and 2409 with meningioma, and a similar number of matched controls, carried out in 13 countries. The results, however, were not all that clear. Comparing simply those who had ever used a mobile phone with never users, users had a significantly *reduced* risk: the odds ratio for glioma was 0.81, with a 95% confidence interval (CI) of 0.70–0.94, and for meningioma was 0.79, with limits of 0.68–0.91. The investigators' interpretation is that this is "possibly reflecting participation bias or other methodological limitations". But combining all users includes people with very little use or very recent use. The most detailed measures of use were lifetime number of phone calls and cumulative call time; these were analyzed by comparing each decile of users to the nonuser group. No increased risks were seen in any of the first nine deciles, but in the maximum category of cumulative call time (over 1640 hours), the ORs were 1.40 (95% CI 1.03–1.89) for glioma and 1.15 (95% CI 0.81–1.62) for meningioma; so there was a significantly increased risk of glioma. The investigators state that "there are implausible values of reported use in this group". These key results are shown in Figure 15.1. This shows that the risks in several categories were significantly lower than the nonuser group, and there is no regular trend. However, many media reports on this study mentioned only the increased risk in the highest decile of exposure. The study showed that risks for glioma tended to be greater in the temporal lobe than in other lobes of the brain and tended to be greater in subjects who reported usual phone use on the same side of the head; both these fit with a causal effect but were nonsignificant and the data on side of use is questionable. Generally similar results were found for acoustic neuroma, where the risk in the top decile was increased, but not significantly so, OR 1.32, 95% limits 0.88–1.97.

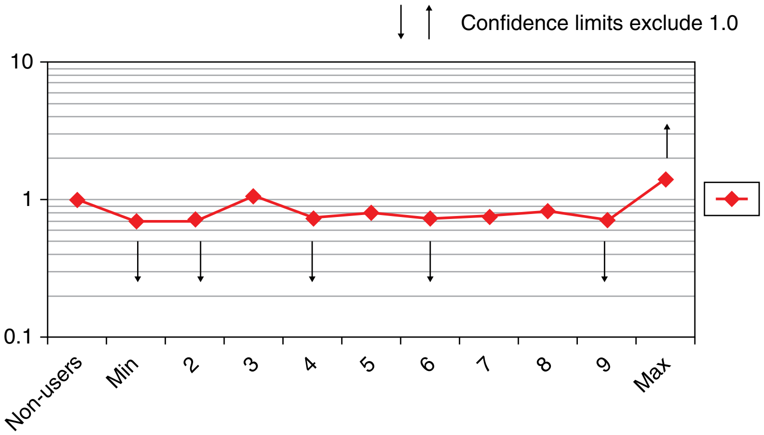

Figure 15.1 Results of the Interphone Study: relative risks (odds ratios) for glioma in deciles of cumulative call time, compared to nonusers (logarithmic scale). Arrows show statistically significant odds ratios.

The Interphone authors' conclusion was (Interphone Study Group, 2010) "Overall, no increase in risk of glioma or meningioma was observed with use of mobile phones. There were suggestions of an increased risk of glioma at the highest exposure levels, but biases and error prevent a causal interpretation. The possible effects of long-term heavy use of mobile phones require further investigation". Thus, the largest study of this question did not give a clear answer. The group also note that "the absence of associations reported thus far is less conclusive because the current observation period is still too short" and also points out that there are no useful data on possible exposures in childhood or adolescence.

These results contrast with the results of several studies from a group of investigators in Sweden led by Dr Hardell, which have shown increased risks, with some studies showing increases even after a short time of use (Hardell, Carlberg, and Hansson, 2013). Such a discrepancy is more characteristic of laboratory than epidemiological research and logically should be traceable to some difference in methods used in the studies; however, no clear reason for the differences has been determined although subtle methodological differences have been reported, which could be relevant (Lagorio and Röösli, 2014). The Interphone group have published several papers documenting quality control measures used, while the Hardell studies have not; the Interphone Study also included a Swedish component.

15.4 Cohort Studies

There have been some cohort studies, in particular a study in Denmark that identified all personal subscribers to mobile phone services in the whole country and linked that data to cancer registries (Frei et al., 2011). No interviews were needed, which limits the information available but avoids selection biases. The study included 358,403 subscription holders, who accrued 3.8 million person-years in the follow-up period 1990–2007. There were 10,729 cases of tumors of the central nervous system. For individuals with the longest mobile phone use, greater than or equal to 13 years of subscription, the incidence rate ratio was 1.03 (95% CI 0.83–1.27) in men and 0.91 (0.41–2.04) in women, similar for glioma and meningioma. The investigators concluded that there was no dose–response relationship by years since first subscription, and no higher rates in regions of the brain closest to where the handset is usually held to the head. This study has been criticized as, by using data from individual mobile phone subscriptions, it cannot include the use of a business-owned phone, which may exclude the heaviest users.

Other cohort studies include the "Million Women Study" in the United Kingdom (Benson et al., 2013), involving 791,710 middle-aged women in a UK prospective cohort, who reported mobile phone use in 1999–2005 and again in 2009. Risks among ever versus never users of mobile phones were not increased for all intracranial CNS tumors (RR = 1.01, 95% CI = 0.90–1.14), for specified CNS tumor types nor for cancer at 18 other specified sites. For long-term users compared with never users, there was no appreciable association for glioma or meningioma; however, for acoustic neuroma, there was an increase in risk with long-term use versus never use (10+ years: RR = 2.46, 95% CI = 1.07–5.64), the risk increasing with duration of use. The authors' conclusions were that mobile phone use was not associated with an increased incidence of glioma, meningioma, or non-CNS cancers. They play down the increased risk of acoustic neuroma, pointing out that this is not seen in the Danish study, there were few cases (96), and that acoustic neuroma often causes hearing loss, so long-term mobile phone users may have been selectively investigated for symptoms of hearing loss.

Some ambitious prospective studies are in progress, such as the "Cosmos" study that aims to recruit 250,000 men and women aged 18+ years in five European countries who will be followed up for 25+ years, to assess major disease risks and general symptoms such as headache, sleep quality, and general well being (Schuz et al., 2011).

15.5 Time Trends in Brain Tumors

If mobile phone use caused a substantial increased risk in brain tumors within a few years, this should have by now produced an increase in incidence rates, so several studies in many countries have looked at this, generally finding no increase (Kim, Ioannides, and Elwood, 2015; Little et al., 2012). Some studies using hospital data rather than population-based registries have shown an increase, but such studies can be affected by changing referral patterns to the hospitals. The trend studies relate to up to 10–15 years after mobile phone use became common; obviously, a longer-term effect cannot yet be assessed.

15.6 The IARC Report

This dispute is shown in the report of the IARC, and its classification of RF as 2B, "possibly carcinogenic" (International Agency for Research on Cancer, 2011). The IARC has a system for the evaluation of carcinogenic risks to humans, which is very well regarded internationally. The IARC process classifies each agent that is assessed into one of the five groups, which are defined as follows:

- Group 1: the agent is carcinogenic to humans
- Group 2A: the agent is probably carcinogenic to humans
- Group 2B: the agent is possibly carcinogenic to humans
- Group 3: the agent is not classifiable as to its carcinogenicity to humans
- Group 4: the agent is probably not carcinogenic to humans.

There are defined criteria for the assessment of the available studies, which take into account both the epidemiological and experimental scientific results to reach the final classification. UV is in Group 1, and extremely low frequency (ELF), like RF, is in Group 2B.

The review group was split in its assessment. The evaluation states (page 419) (with notes in square brackets added): "The bulk of evidence came from reports of the Interphone Study, a very large international, multicenter case–control study and a separate large case–control study from Sweden on gliomas and meningiomas of the brain and acoustic neuromas [the Hardell reports]. While affected by selection bias and information bias to varying degrees, these studies showed an association between glioma and acoustic neuroma and mobile phone use [this contrasts with the opinion of the Interphone investigators, given above]; specifically in people with highest cumulative use of mobile phones, in people who had used mobile phones on the same side of the head as that on which their tumor developed, and in people whose tumor was in the temporal lobe of the brain (the area of the brain that is most exposed to RF radiation when a wireless phone is used at the ear). The Swedish study found similar results for cordless phones. The comparative weakness of the associations in the Interphone Study and inconsistencies between its results and those of the Swedish study led to the evaluation of limited evidence for glioma and acoustic neuroma, as decided by the majority of the members of the Working Group. A small, recently published Japanese case–control study, which also observed an association of acoustic neuroma with mobile phone use, contributed to the evaluation of limited evidence for acoustic neuroma. There was, however, a minority opinion that current evidence in humans was inadequate, therefore permitting no conclusion about a causal association. This minority saw inconsistency between the two case–control studies and a lack of exposure–response relationship in the Interphone Study. The minority also pointed to the fact that no increase in rates of glioma or acoustic neuroma was seen in a nationwide Danish cohort study [discussed above] and that up to now, reported time trends in incidence rates of glioma have not shown a trend parallel to time trends in mobile phone use [also discussed above]."

15.7 Mobile Phone Base Stations

Although the exposure intensities related to base stations are extremely small, they have caused much public concern, in part because this is seen as an imposed hazard, rather than being under individual control like the use of a mobile phone. Major review groups have all concluded that there is little or no evidence of risk (Table 15.1). The health issues raised are usually general, such as sleep disturbance, anxiety, and fatigue. Many studies have been of very poor quality and open to severe biases, such as simple surveys of general health based only on subjective reporting. In a rigorous study of childhood cancer in Great Britain (Elliott et al., 2010), the addresses at birth of 1397 children with cancer at ages 0–4 and 5588 controls were assessed, looking at the distance to a macrocell base station, and the total power output and modeled power

Table 15.1 Conclusions of recent major reports on possible health effects of mobile phone base stations.

Year	Authors	Conclusions
2013	IARC	"No increased risk of brain tumors, leukemia/lymphoma, or other cancers"
2012	Health Protection Agency, UK	"There is no convincing evidence that radiofrequency field exposure below guideline levels causes health effects in adults or children"
2012	Norwegian Institute of Health	"The large total number of studies provides no evidence that exposure to weak RF fields causes adverse health effects"
2012	European Health Risk Assessment Network	Similar to IARC
2011	Health Canada	"As long as exposures respect the limits set in Health Canada's guidelines, there is no scientific reason to consider cell phone towers dangerous to the public"
2010	Latin American Experts Committee	(Studies)… "have not demonstrated any clear effects of RF exposure on morbidity, mortality, effects on well being, and health status of population groups living near the RF sources"
2010	Swedish Radiation Safety Authority	"Available data do not indicate any risks related to exposure to RF from base stations or radio or TV antennas"

density of nearby base stations. The investigators found no association between the risk of early childhood cancers and estimates of the mother's exposure to mobile phone base stations during pregnancy.

There is evidence of a "nocebo" effect: if we suspect something is harmful, we may attribute symptoms to it. In the Netherlands, a study of "nonspecific physical symptoms" used data from a survey of 3611 adult respondents, calculating the distance between the respondents' household addresses and the nearest base stations and power lines from geo-coding (Baliatsas et al., 2011). Reporting more physical symptoms was related significantly to higher levels of self-reported environmental sensitivity and to the perceived proximity to base stations and power lines, but there was no significant association with the actual distance to base stations or power lines. The same group (Baliatsas et al., 2012) did a systematic review and meta-analysis of 22 studies of symptoms and actual or perceived exposure to electromagnetic fields in the general population, concluding that there was no evidence for a direct association but that an association with perceived exposure seems to exist.

A systematic review of studies relating RF exposure to health-related quality of life found nine randomized trials and two observational studies (Roosli and Hug, 2011). The authors concluded that health-related quality of life was not affected by RF-EMF exposure, and none of the studies showed that individuals with self-reported electromagnetic hypersensitivity (EHS) were more susceptible to RF-EMF than others.

15.8 Radio and Other Transmitters

Cancer risks related to living near radio, television or microwave communication facilities, or close to military radar installations have been assessed. Some of these studies were done in response to a "cluster", the observation of an apparently abnormally high number of cases of disease in a small geographical area and time period. Thus, a cluster of leukemias and lymphomas was noted near a large radio and television transmitter in the United Kingdom. However, such an observation is very difficult to interpret, as clusters will occur by chance – it creates a hypothesis that needs independent testing. So, an investigation was made of the 20 other high-powered TV and radio transmitters in the United Kingdom; this showed no consistent excess of these or other cancers (Dolk et al., 1997). Similar studies have been carried out in several other countries, but overall, they were hampered by many methodological limitations such as diverse exposure sources, poorly estimated population exposures, and selective investigation in response to cluster concerns.

In some other situations, only parts of the work have been reported in peer-reviewed literature. These include studies related to the Swiss international service radio transmitter at Schwartzenburg, to a military radar installation at Skunda in Latvia, and to the US embassy in Moscow, which was exposed to targeted microwave transmissions in the 1950s (Altpeter et al., 2006; Brumelis, Balodis, and Balode, 1996; Elwood, 2012). These studies have looked at many end points, including physical and biochemical measurements, sleep behavior, and psychological parameters, with intense study of the relevant populations, although these have been too small to look at major diseases such as cancer or heart disease. Some innovative study designs have been used; for example, the study of the Moscow embassy staff appropriately involved comparisons with the staff of other US embassies in Eastern Europe who had gone through similar prescreening and selection processes; the study of the Swiss transmitter included some studies in which the transmitter was turned off or redirected so that the effects on parameters such as sleep behavior could be measured. However, some of these studies have been open to the biases of subjective reporting as the involved population has been aware of the issues being addressed.

15.9 Occupational Studies

Occupational studies have been done where relatively high levels of exposure to various RF sources have been documented or assumed from job descriptions. A study with over 40 years of mortality follow-up of 40,581 US Navy veterans of the Korean War with potential exposure to high-intensity radar showed no evidence of overall mortality or increased brain cancer (Groves et al., 2002). A study of Norwegian female ship-board radio and telegraph operators showed a small increase in breast cancer (Kliukiene, Tynes, and Andersen, 2003); but breast cancer is also related to shift work and changing patterns of night and day time work, which would also apply to these women doing this unusual job. A study of 196,000 employees of the Motorola company involved in the manufacture and testing of mobile phones and other equipment used job titles to group workers into high, moderate, low, and background RF exposure groups. No increases in brain cancers, lymphomas, or leukemias were seen (Morgan et al., 2000).

Some of these studies have had considerable methodological weaknesses, for example, a study of the Polish military, and they are complex because of the other associated exposures in these occupations. So again, there are many individual results but little overall consistency. Case–control studies investigating occupational RF exposure and glioma and non-Hodgkin lymphoma have improved on exposure assessment by using sophisticated job exposure matrices, finding in Australia a small increase in non-Hodgkin lymphoma and no increase in brain cancers (Karipidis et al., 2007a; Karipidis et al., 2007b).

15.10 Other Diseases

As well as cancer, several studies have looked at cardiovascular disease and related physiological measurements, in general showing no consistent associations. Some studies have assessed eye cataract in RF exposed workers. Several studies have assessed adverse reproductive outcomes, particularly in female physiotherapists who use therapeutic short-wave diathermy, usually at 27.1 MHz. Again, these studies have produced varied results and often, a result shown in one study is not replicated in a later study. Other studies have looked at sperm density and related parameters in men with microwave and radar exposure, again with little consistency in the results. Overall, the literature provides little evidence of an association with other (noncancer) health effects.

15.11 Conclusions

A central problem in this issue, as with many controversial issues of potential environmental hazards, is that it is logically impossible to prove that an association does *not* exist (Elwood, 2014). According to the predominant Popperian view of science, science can only advance by falsifying hypotheses, producing data that makes them increasing less likely, but a putative association can never be totally dismissed (Popper, 1980). Allied to that are the practical difficulties of epidemiological studies, which make it impossible to be assured that a particular study or set of studies is free of the problems of observation bias, confounding by the influence of related factors, and chance variation (see Chapter 3). Thus, if in truth there is no effect of mobile phone use on brain cancer, a perfectly designed and executed epidemiological study will show a relative risk of 1.0. However, a real-world study, dependent on voluntary participation, participants' responses to questionnaires or examinations, and a finite number of subjects, will only go as far as producing a relative risk that is close to 1 and which will have reasonably narrow confidence limits. If a large number of studies are done, by investigators varying in their expertise, sophistication, and in the resources they have available, it is to be expected that these studies will produce quite a range of results, even if there is no true association.

Many authoritative and independent groups have reviewed these studies, as mentioned earlier. These groups in general conclude that the results to date do not show a causal relationship between RF exposure and any major adverse health effects, either in a general population or in an occupational group. However, other scientists disagree. The available studies have inherent limitations that make it impossible to rule out such an association. In general, as more literature has been produced and more sophisticated and better funded studies have been published, the balance of results showing apparent increased risks of disease has not increased and has probably decreased. However, if RF exposures produce increases in diseases such as cancer only after a long latency period of perhaps 20 years or more, such an effect would not be detectable by most studies. The major unanswered questions are on long-term effects, brain tumors, or other diseases such as neurodegenerative diseases such as Alzheimer's disease; and whether the effects of exposures in children would be different.

Tutorial Problems

1 What three types of brain tumors have been considered in regard to mobile phones, and what tissues do they arise in?

2 What large case–control study (or studies) of brain cancer was coordinated by the WHO?

3 In that study, in the maximum group of cumulative call time, the odds ratio was 1.40 (95% CI 1.03–1.89) for glioma. What does this mean?

4 In the Danish cohort study, for women with the longest mobile phone use, the incidence rate ratio for central nervous system tumors was 0.91 (0.41–2.04). What does this mean?

5 The IARC classifies radiofrequency in Group 2B. What does this mean?

6 What is a "cluster" of disease?

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16

Possible Low-Level Radiofrequency Effects

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16.1 Introduction

Concern over whether low-level nonionizing radiation (NIR) could be linked to adverse health effects began in the middle of the twentieth century and has continued since. This has been particularly true in regard to extremely low frequency (ELF) or radiofrequency (RF) exposures, but questions have been raised in regard to possible low-level effects from the other forms of NIR, including ultrasound. There is always a legitimate concern that insidious health effects may be occurring via subtle mechanisms that remain elusive, but are nevertheless real. The categorization, by IARC, of RF radiation as a "possible carcinogen", as discussed in Chapter 15, strengthens this concern, since the exposures studied in epidemiological studies are everyday exposures, well below the limits discussed in Chapter 13. A number of organizations have, over the years, maintained databases of research papers concerned with RF and ELF bioeffects, including those that appear to occur at low levels. For example, the World Health Organization (WHO) has links to several of these, some containing over 30,000 items in total. Some require subscription but some are free, such as EMF-Portal (http://www.emf-portal.de/), with over 20,000 items. An earlier abstracting service run by the US Office of Naval Research goes back to 1970, at least. The Bioelectromagnetics Society (BEMS) was formed in 1979 and in addition to publishing a scholarly journal, Bioelectromagnetics, also sponsors an annual conference (together with the European Bioelectromagnetic Association, EBEA) covering biological effects relating to the electromagnetic spectrum ranging from static fields through to the high microwave or terahertz (THz) frequencies discussed earlier. Over the years, the emphasis has changed several times: in the early years, concerns were mainly with possible health

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effects from low-level microwaves, radar, and ELF submarine communications installations; interest in power line effects did not really begin until the early 1980s and interest in mobile phone safety is more recent still. Digital mobile phones operate at several frequency bands ranging from 700 to 3500 MHz, which is in the same general part of the spectrum as microwave ovens (2450 MHz), a frequency used in many of the early health effects studies.

Financial support for these low-level effects studies has been from a variety of sources, some governmental (like the European Union Framework Programme for Research and Innovation) and others military or commercial (such as telecommunications companies). The amounts of funding from national competitive research grants bodies (e.g., the National Institutes of Health) have, in general, been modest, but in some countries, such bodies have supported local research programs (an example being the National Health and Medical Research Council of Australia, which has supported programs and specific projects since 1998). Nevertheless, the area has been considered to be out of the mainstream of scientific enquiry and there has been some concern from the mainstream that money set aside for RF bioeffects could be better spent. This has not prevented a large amount of underfunded or even unfunded research from individual scientists who have perhaps had a personal conviction that health effects are possible or even likely. This may have contributed to a problem of lack of replication or inconsistency, since adequate funding is required to ensure that experiments are adequate in scale and in quality control.

16.2 Where Is the Information?

The bulk of the research referred to has appeared in peer-reviewed scientific literature, although some of the journals are only held by a few academic libraries. The recent move to on-line subscriptions has made these research articles more accessible, nevertheless. One of the useful functions of international scientific meetings (such as the annual BEMS/EBEA meeting) is that of encouraging debate, which has often been quite lively. A forum that attracts experts from the biological and physical sciences as well as from medicine is one in which few ideas can go unchallenged and in which inconsistencies between findings are quickly highlighted. One feature of note is that for many years there was reluctance on the part of physical scientists to take the notion of health effects at these low levels seriously, since by their nature, they seem to violate the conventional laws of physics. More recently, however, there has been a realization that because of the special properties of biological tissue, subtle nonlinear effects may occur, although mechanisms of interaction that are theoretically plausible and fit the experimental data are yet to be identified. On the other hand, the physics of tissue heating or nerve stimulation by RF current is reasonably well understood.

Regarding the many thousands of studies on RF bioeffects, several panels of experts have reviewed this literature in recent years with a view to advising on health policy, some on an on-going basis. There have been similar reviews of the ELF literature, which will be covered in Chapter 21.

One challenge has always been to distil this information into a form that would allow legislators and the interested public to form an unbiased opinion. While it is recognized that on one hand the health debate may have been used by interest groups as a general defense against visual intrusions caused by electrical and communications installations, on the other hand, there has been a suspicion that research could be somehow tainted because of the nature of the funding source. Not surprisingly, there has been huge media interest in the question of possible harm from telecommunications equipment, with the inevitable "pitting of expert against expert", highlighting scientific uncertainty. This has led to a certain lack of confidence in statements by government or international health agencies designed to ameliorate concern. This will be discussed further in Chapter 32.

16.3 Thermal and Nonthermal Effects: Formal Definitions

As indicated in Chapter 12, harmful effects of RF radiation have been shown to follow if sustained rises in temperature in living tissue by several degree Celsius are allowed to occur. While some bioeffects may be identified at temperature rises of 1 °C or less, these are not considered hazardous, but the question remains as to whether repeated doses at these levels over many months or years may lead to deleterious effects. Current evidence is that it does not. A thermal effect, then, can be defined as any change in biological structure or function that can be attributed, either directly or indirectly, to a change in temperature. Thermal effects can be quite benign, since the core temperature of the human body has a natural variation of around 1 °C throughout a 24-hour cycle, and the temperature of the skin can rise by several degrees when exposed to the sun or directly contacting a hot object.

A further question is whether a form of RF energy absorption may exist that may not manifest itself in a measurable increase in tissue temperature but could nevertheless be linked to bioeffects. These have been termed athermal or nonthermal effects, but there is also a notion of a resonant absorption mechanism such that modest energy absorption can give rise to an amplification of effect, via cascades of metabolic processes within the cell. An example of this is the way the absorption of a few photons of light in the receptors of the retina ultimately give rise to signals of around 0.1 V, representing an energy gain of the order of around 10^{18}. Such absorption would normally be dependent on frequency (as occurs with sound in resonant cavities, as well as for visual pigments in the eye) but it has also been suggested, in relation to RF, (with some equivocal experimental evidence) that there are "windows" in intensity, whereby modest energy absorption leads to an effect, whereas higher levels do not.

Since demonstrating these putative nonthermal effects unambiguously has proved elusive (despite the volume of reports), other possible explanations for the experimental evidence have been considered. Thus, while there is still the possibility of these effects being due to a local thermal mechanism (a "hot spot"), the term "low-level effects" is preferred. These reported effects could be due to the following:

a) a differential uptake of RF energy by specific cell types or cellular components (hot spots within cells or tissues);
b) nonuniformities in energy absorption patterns within an exposure system (causing hot spots within an organism);
c) an underestimate of specific absorption rate (SAR) due to inadequate computation of energy absorption.

More will be stated on these possibilities (particularly c) later on. In addition, experimental artifact (systematic or methodological errors) or statistical anomaly is always possible in experimental work. Given adequate funding, the number of repeats or checks for systematic errors can be made satisfactorily high.

Whether the mechanism is actually thermal or not, or whether these reported bioeffects are real or artifact, those effects suggesting statistically significant biological interactions at SAR levels well below 1 W/kg need to be replicated satisfactorily, particularly if they are suggestive of harm, before they can form the basis of standard setting. Replication experiments or experiments where analogous results would be expected (even though not replications *per se*) have continued to lack consistency, which has been a feature of this area of research.

Overall, it has been concluded that exposures leading to SAR values below the basic restrictions given in Chapter 13 do not lead to unambiguous biological effects indicative of adverse physiological or psychological function or to increased susceptibility to disease. While these low-level effects have not been established, they cannot be ruled out. The question of what more research needs to be done or indeed can be done is one we will return to at the end of the chapter.

16.4 RF Bioeffects Research: General

ICNIRP, in developing exposure limits, have not ignored possible low-level interactions of high frequency. In the ICNIRP Guidelines, scientific reports up to 1997 were considered and a general conclusion expressed as: "In general, the effects of exposure of biological systems to athermal levels of amplitude-modulated EMF are small and very difficult to relate to potential health effects"

(ICNIRP, 1998, p 508). A revision of the 1998 Guidelines is expected in 2016 or soon after, but it is not expected that the corresponding statement in the revised guidelines will differ substantially from this one.

The studies can be divided into (i) those that attempt to identify any effects of low-level exposure that could lead to specific diseases (in particular, cancer) and (ii) those that study changes in physiological or psychological performance. Although changes in the latter case may not be considered pathological, they would still indicate a previously unsuspected mode of interaction and would be of concern in relation to the capacity of exposed individuals to function optimally. In general, studies of the former type involve exposures over days or months, whereas the latter often involve exposures of a few hours duration.

The WHO maintains a web site summarizing recent work, which is complete or under way relevant to the frequency range covered by this Standard. This can be found via www.who.int/peh-emf/index.htm. This web site also has details of the WHO research agenda and its on-going role in the co-ordination of research (WHO, 2010).

Research into RF bioeffects can be put into the following categories (starting with the smallest scale): *in vitro* (cell or organ studies), *in vivo* (exposure of living complete organisms), human studies (on volunteer participants exposed to RF), and epidemiology (studies of entire populations). The last mentioned was covered in Chapter 15. In addition, there are theoretical studies into possible mechanism of RF interaction and in particular modeling the absorption of RF into particular organs as part of dosimetry assessment.

A detailed assessment of the literature is difficult to do justice to here because of its sheer size, but the summaries provided in recent reviews are highly instructive. In particular, the AGNIR (2012) review and SCENIHR (2015) Opinion can be used to illustrate some broad conclusions that can be made, in relation to *in vitro* and *in vivo* work in particular.

16.5 Summary of *In Vitro* Work

The AGNIR review selected several hundred papers published in the time window of roughly 2002–2010 (this is the period since the previous review published in 2003). In relation to *in vitro* (i.e., laboratory test tube) work, the 179 experimental reports under this category were further subdivided under the following topics:

Genotoxic effects: damage to genetic material (e.g., DNA and RNA) within a cell that could possibly lead to cancer via mutations.

Proliferation/apoptosis: alteration of the rate of division of cells or the process leading to "programmed cell death". Of particular interest is the enzyme ornithine decarboxylase (ODC), which is increased in a number of cancers (and is associated with increased cell proliferation). Reactive oxygen species (ROS) are chemically reactive compounds containing oxygen, which cause mutations and cell proliferation and are produced by a number of environmental factors including ionizing radiation.

Gene expression: the "turning on" (or "turning off") of specific genes to produce particular products, such as proteins. Of particular interest are the "oncogenes" that can cause or contribute to cancer, perhaps by inhibiting "programmed cell death" (apoptosis) and causing cell proliferation.

Stress response/heat shock protein: the production of specific proteins in response to environmental stresses (such as heat), which are designed to help other proteins in the cell cope with the environmental stress.

Membrane effects: cell membranes (which both surround the cells and form an extensive network within cells) have a natural electrical voltage across them, so it has long been assumed that they could be susceptible to external fields.

Intracellular signaling: this can occur both via cascades of biochemical reactions, where some of the various members of the cascade are at particular locations within the cell, or by electrical signals, or both.

Direct effect on proteins: proteins, which form enzymes and structural units within cells, have characteristic folding patterns, which are stabilized by electrical forces. Again, it is assumed that there could be some susceptibility to external fields.

What should be apparent from this list of topics is that there is an underlying assumption that the health concern is cancer, rather than other illnesses, such as cardiovascular disease or metabolic disorders. This is largely driven by early concerns of a possible link between mobile or cell phone use and brain tumors but it is worth bearing in mind that illnesses other than cancer have not been discounted in on-going research.

In a series of tables in the AGNIR review, the outcome of each study is summarized, plus the reported SAR value during the exposure. Of the total, 46% report a significant change due to RF exposure and the remaining 54% report no effect (NE). Figure 16.1 shows the range of SAR values, on a logarithmic scale, for each category, with those reporting an effect (labeled "Effect") separated from those that do not (labeled "NE") on alternate rows. The vertical line represents the SAR limit (10 g average) for the general public. There are a number of observations that flow from this diagram. Firstly, although we are considering "low-level" effects in this chapter; in fact, the majority of studies have chosen SAR values close to the limit. There are only a handful of studies showing significant effects below, say, 1% of the limit (and which would be typical of everyday exposures). Secondly, if the effects of RF occur above a certain threshold, the alternate rows should show a definite separation, with the odd rows (NE) to the left and the even rows to the right. That the median SAR values for the "No Effect" rows are greater than those for the "Effect" rows is indeed curious because it indicates the opposite to what would be expected from the

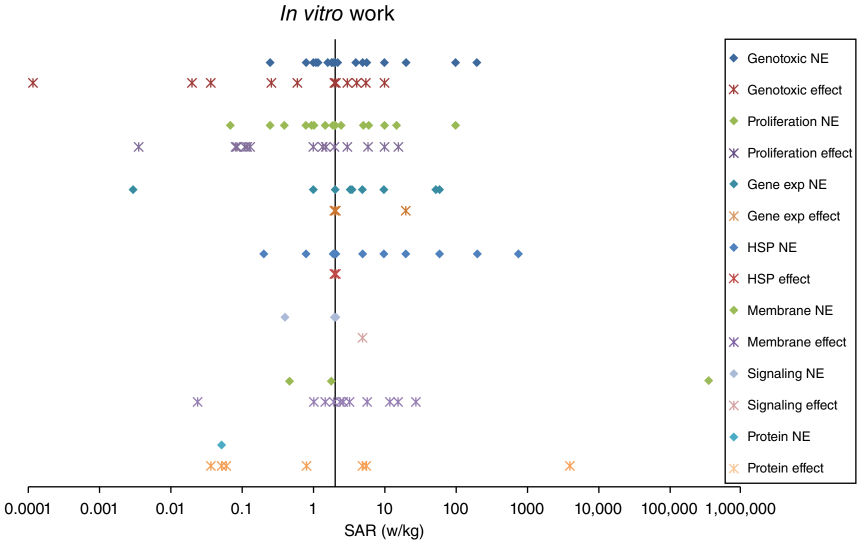

Figure 16.1 Summary of reported SAR values for *in vitro* studies considered in the AGNIR (2012) review. Each row gives values for the types of study shown at right (see text for further explanation), with those showing no effect (NE) and those showing an RF-related effect (Effect) in alternate rows. The vertical line indicates the general public basic restriction.

threshold concept. In fact, the geometric mean SAR for the "no-effect" outcome experiments is around three to four times that for those with "effect" outcomes (see Figure 16.4). Indeed, one would expect all of the outcomes above a certain SAR value (1000 W/kg, say) to represent "effects", due to heating. It is curious that, on the one hand, there is a case in which NE is reported for a SAR value above 10^5 W/kg, while at the other end of the range, a significant effect is reported at less than 1 mW/kg (nine orders of magnitude smaller). Thirdly, there is also no particular type of effect that is showing up as more consistent or more sensitive than the others. It is interesting to note that the first five of these topics represent issues that have had a history of concern, stretching back to the period before 2000. In these categories, the number of "no-effect" results is well in excess of the "effect" results. In the more recent work (topics 6 and 7), the ratio is the other way round. One possible explanation is that attempts at replication, which lag the initial reports by several years, tend to yield a "no-effect" outcome. Investigators are quick to seize an opportunity to apply new biological analysis techniques to "the RF issue", and there is probably a "publication bias" toward those studies reporting effects over no-effects.

In the SCENIHR Opinion (SCENIHR, 2015), there are summaries of 82 studies of *in vitro* work published between 2008 and 2015 (so some of the studies were also represented in the AGNIR review, with a cut-off in 2010).

The method of categorizing the studies was a little different, but the outcomes were very much the same, as is shown in Figure 16.4. Sixty-five percentage of the studies reported NEs.

16.6 Summary of *In Vivo* Work

The AGNIR review considered a total of 176 studies involving *in vivo* exposures: that is, the animals were alive during exposure to RF, even if tissues were subjected to *in vitro* analysis postmortem. In most cases, the duration of exposure was greater than for *in vitro*, including exposures for up to a year or more. Following the AGNIR categories, published work can be divided into two main categories: Brain and nervous tissue effects and secondly, other effects. The first category is further divided into seven topics, the first five concerned with brain processes and the last two with behavioral measures. The seven topics (with brief explanations) are as follows:

Cell physiology, injury, apoptosis: the study of cell shape and function following *in vivo* exposure to RF.

Neurotransmitters: the study of levels of essential chemical messengers in brain and nervous tissue to give clues to possible activation of specific brain pathways.

Brain electrical activity: the characteristics of nerve cell "firing" patterns, including epileptic seizures.

Blood–brain barrier and microcirculation: brain capillaries (the microcirculation) can become abnormally "leaky" allowing toxins to reach nervous tissue following injury and certain diseases. Ionizing radiation can also do this.

Autonomic function: this refers to the part of the nervous system that exerts (mainly) involuntary control over body function (such as heart rate and digestion).

Spatial memory tasks: these memory tasks in animals involve training to remember features of the animals' environments.

General Learning tasks: as above, but involving innate and learned behavior (but excluding those in the above category).

The SAR values reported in these studies (and whether the outcome was "NE" or "Effect") are summarized in Figure 16.2.

16.7 *In Vivo* Studies: Other Effects

The 10 topics are as follows (notice that although cancer is the main concern, possible effects on fertility, development, and other organ systems are also considered):

Endocrine system: this concerns possible RF effects on hormone production or action. Of particular interest is the hormone melatonin, which because of its

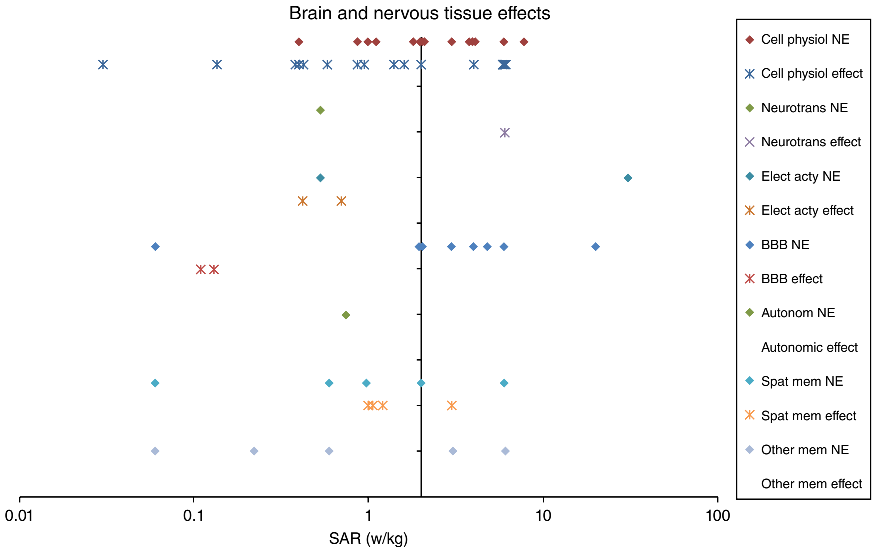

Figure 16.2 Summary of reported SAR values for brain and nervous system experiments. For explanation, see Figure 16.1 and text. N.B. the absence of a symbol indicates that no effects have been recorded for that category.

anticancer properties and susceptibility to light input to the retina has long been considered a candidate for sensitivity to electric and magnetic fields.

Auditory function: since in the area of exposure to mobile phones, the mobile handset is placed close to the ear, investigation of possible deficits in hearing and balance has been a research priority.

Genotoxicity and mutagenesis: as in the case with the *in vitro* topic of the same name above, DNA and RNA damage resulting from *in vivo* exposure is studied.

Tumor incidence – normal strains: typically this involves daily exposure over several months, with examination postmortem for size and number of specific tumors.

Tumor incidence – tumor-prone strains: as above, but using genetically modified animals with unusually high incidence to particular cancer types.

Cocarcinogenesis: refers to experiments in which the animals are treated with RF together with chemical agents known to induce or accelerate the development of cancers to determine whether there are any synergistic effects between these chemical agents and RF.

Implanted tumors: here the presence or absence of RF exposure is studied in the relation to the ability of these implanted tumors to invade healthy tissue.

Immune system and hematological system: looks at RF exposure in relation to blood formation and the components in blood that form part of the "immune response" – the production of specific antibodies.

Testicular function: effects particularly on sperm production and motility.

Pregnancy and fetal development: outcomes such as low birth weight, premature delivery, and birth defects.

Figure 16.3 summarizes the SAR values reported in these studies.

The AGNIR review perhaps does not fully capture the work of several research groups, including that at Oxford University, on the possible role of retinal cryptochromes and associated free radical lifetimes in avian magnetoreception. This work is important and continues to provoke debate (Solov'yov and Schulten, 2009). The link with RF is experimental data showing altered flight patterns in birds exposed to RF in the low megahertz region, supported by theoretical analysis (Henbest et al., 2004; Timmel and Henbest, 2004). However, the relevance of this work to mobile telecommunications frequencies is unclear.

The results of the *in vitro* and *in vivo* data are summarized in Figure 16.4. This emphasizes that there is almost complete overlap between reported SAR values in those experiments producing RF-related effects and those producing no significant effects. If anything, the "no-effect" SAR is higher than the "effect" SAR. This must call into question the contention that the general public guideline limit of 2 W/kg is somehow inadequate, unless, of course, effects occur within specific "windows", which has been suggested in the past and would occur in highly resonant system. However, no mechanism for resonant absorption at low levels of SAR has been identified.

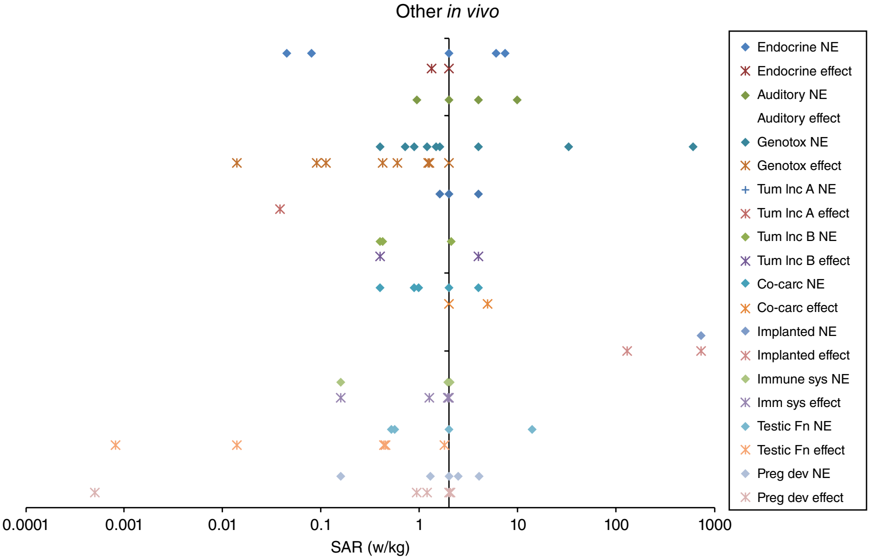

Figure 16.3 Summary of reported SAR values for "other *in vivo*" experiments. For explanation, see Figure 16.1 and text.

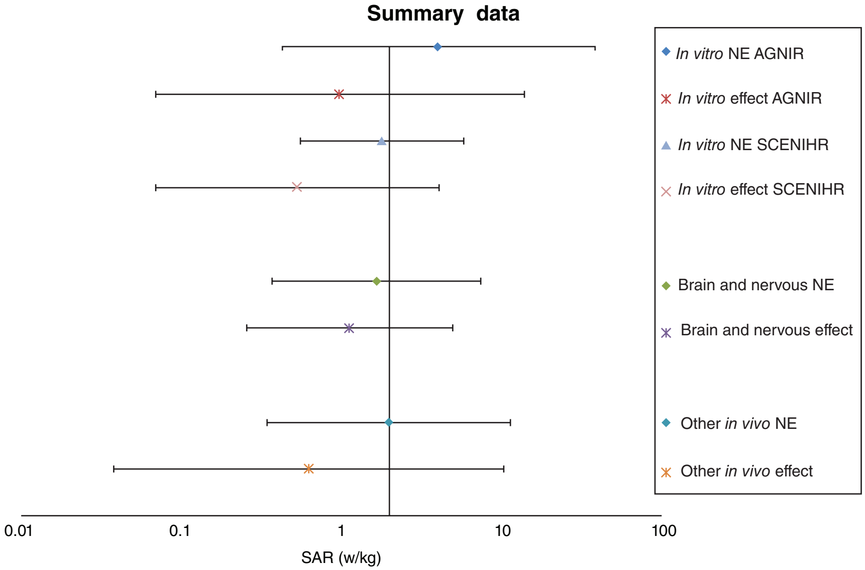

Figure 16.4 Average (±SD) SAR reported for the types of experiment shown at right. Individual values shown in Figures 16.1–16.3 (except for the SCENIHR data, which is not shown).

16.8 Animal Whole of Life Studies

Experiments, mainly on rodents, comparing histopathology following long-term (usually lifetime) exposure to RF (compared to animals with sham-exposure) have been carried out for over two decades. Some experiments have used genetically modified animals with a susceptibility to certain types of cancer and yet others have used RF as a coexposure to chemical carcinogens or ionizing radiation. Studies up to 2012 have been reviewed (Repacholi et al., 2012), with an overall conclusion in relation to these types of study:

> … our results from evaluating brain tumor and brain tumor promotion studies do not show a consistent relationship between RF exposure and the incidence of brain cancers or other head tumors, or their promotion in animals induced with chemical carcinogens.

Similar conclusions were reached by both of the reviews referred to earlier; however, a report just released by the US National Toxicology Program (NTP) (Wyde et al., 2016) shows evidence of raised incidence of both precancerous and malignant lesions in both brain and heart of male rats (but incidence in females was essentially normal). The survival rates of the control (unexposed) male rats was relatively low compared to other studies run by this NTP group, raising the possibility of a lower than normal incidence of cancers in this group (because they did not survive long enough to develop them). The exposed groups consisted of two forms of RF radiation (GSM and CDMA) and at three different SAR values each. Since at the time of writing only partial results are available, it would be prudent to regard these findings as preliminary and to follow up on subsequent reports to evaluate their overall significance in terms of human long-term health assessment.

16.9 Human Volunteer Studies

Since RF basic restrictions have largely been determined by thermal effects in tissue, it is important to investigate whether performance (memory, cognitive processing speed or accuracy, sleep quality, and so on) could be affected by exposure to RF at lower levels (where there could be enhanced sensitivity in certain organs, particularly parts of the central nervous system). While some of these experiments have involved exposing specific regions of the head at the 10 g average spatial peak SAR limit, some have used commercial mobile phone handsets, where the peak SAR values are in general much lower (around 10% of the SAR limit). Thus, it is argued that any bioeffects, however innocuous, are biologically significant because they would be indicative of an effect outside of the “thermal” paradigm and which would require further investigation, even if only to identify the causative mechanism. It is certainly recognized that any degradation in cognitive function during a commercially or politically sensitive phone-call could have severe consequences.

Despite a large number of separate studies on cognitive and general performance of volunteers, the overall conclusions from reviews are similar to those for *in vivo* and *in vitro* studies: results are inconsistent and mixed. Apart from the AGNIR review and SCENIHR Opinion, there have been many other reviews of the literature relating to human volunteer experiments. Within my own group we have been active in this area for many years and in a review carried out by a colleague and myself in 2002, we noted that if there was any consistency in outcome at all, then it appeared that a certain feature of brain electrical activity (the so-called alpha waves in the electroencephalogram or EEG) appeared to be enhanced in response to RF mobile phone-type exposure (Hamblin and Wood, 2002). Subsequently, we compiled the precise range of alpha frequencies for which a statistically significant enhancement had been reported (Figure 16.5). This shows a high degree of variability, emphasizing the difficulty of characterizing an effect, if indeed it does exist. However, results from the University of Wollongong (Loughran et al., 2012) do appear to be more consistent when participant variability is specifically taken into account.

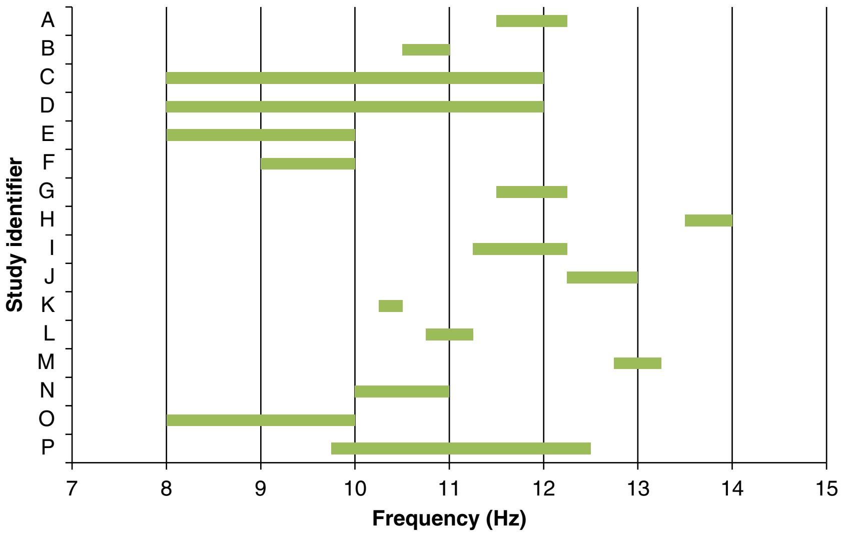

Figure 16.5 Ranges of frequency over which enhanced electroencephalographic alpha wave power has been reported in 16 separate studies (identified as codes A–P: see for further details on some of these). Source: Wood et al., 2008. Reproduced with permission of Elsevier.

16.10 Other Issues Relating to Mechanism of Interaction of RF with Biological Systems

The levels associated with epidemiological studies and with self-reported hypersensitivity are those encountered in daily life, so properly belong in a discussion of "possible low-level" effects. However, both are covered in other chapters (Chapters 15 and 24) so no further comment needs to be included here, except to observe that the time scale of exposure is much longer than in most laboratory studies (except that in terms of life span, 2 years in a rodent experiment is equivalent to 80 years for a human).

There are numerous reports of thermal levels of RF being used voluntarily in humans. For example, short-wave diathermy or microwave applicators have been used to alleviate muscle and joint pain and as an adjunct to radiotherapy or chemotherapy for many years (Wood, 2012). The study of Detlavs et al. (1996) is unusual in that it claims improvement in the rate of healing of soft tissue injury at nonthermal levels of modulated microwaves in the 40–55 GHz band. These experiments require independent replication before it can be accepted that there truly is a nonthermal mechanism operating.

The effect of RF exposure on thresholds to other agents: Verschaeve and Maes (1998) have reviewed evidence of possible synergistic effects between RF exposure and exposure to toxic chemicals or other agents. The question of the effect of concurrent thermal levels of RF exposure on the toxicity of industrial solvent has been studied by Nelson et al. (1998), but since thermal levels of RF exposure are used, this study does not address the question of nonthermal mechanisms.

Isothermal exposure (i.e., exposure to levels of RF that would cause an appreciable rise in temperature, but in which the temperature of the experimental system is deliberately kept at a fixed value) has been studied by Cleary for a number of years (see, e.g., Cleary et al. (1997)). A number of anomalous results point to a possible nonthermal mechanism operating. However, significant nonuniform temperature distributions within exposed cell cultures cannot be ruled out, particularly with the very high SARs used in the experiments.

16.11 Modeling and Dosimetry

One of the difficulties in identifying low-level effects is that of unambiguously eliminating the possibility of significant rise in temperature in localized areas in the biological system under study. Chou et al. (1999) have shown that the ratio of maximum to average SAR in the brain tissue of small mammals exposed to a mobile phone simulator is 2:1, and in the scalp, this ratio is 10 times the brain average. SAR distributions within cell and tissue samples in exposure systems commonly used for *in vitro* experiments have been extensively studied by Guy, Chou, and McDougall (1999). Ratios of maximum to average SAR values range from 3 to 15, depending on the exact configuration. Effects that may appear to be athermal based on the average SAR value may thus be due to a localized elevation in absorption.

16.12 Unanswered Questions

There are a number of issues that still need to be clarified in terms of their possible implications for health and welfare.

Alterations in blood–brain barrier permeability could lead to inappropriate exposure of neural tissue to blood–borne pathogens; thus, it is important to discover, where this is reported, that it is not a consequence of tissue heating at SAR levels above the basic restrictions, due to local SAR variations. Similarly, changes in gene expression may also be a consequence of thermal effects, but it is important to continue to refine methods for determining local SAR and to evaluate whether any changes have any serious health implications.

Neuropsychological and neurophysiological testing may suggest that altered human responsiveness may result from RF levels just below the basic restrictions, but it remains to be unambiguously demonstrated that this is the case and that any alterations would have serious implications in terms of well being.

Although the uncertainties in determining the exact RF "dose" were highlighted earlier as possible confounders, these are unlikely to provide a complete explanation of why effects are reported at levels well below the general public limit. However, they do highlight some of the difficulties in regarding these putative "effects" as having been established.

In summary, it would appear that although nonthermal effects or mechanisms cannot be ruled out, the evidence for them is inconsistent and further confirmatory studies need to be carried out, particularly in relation to SAR estimations.

16.13 What More Needs to Be Done?

Since 2000, there have been a number of nationally and internationally funded research programs in relation to the safety of mobile telecommunications, many having an *in vitro*/*in vivo* component. Many of the themes continue the issues discussed above and have been informed to a certain extent by the WHO RF Research Agendas (the most recent being (WHO, 2010)). In addition, there have been some significant advances in the study of possible mechanisms for nonthermal effects, bioeffects, and applications of millimeter waves and THz radiation.

In view of the wide-spread use of MRI systems, it is important to pay attention to any reports of adverse effects associated with the RF exposure in these systems, including, for example, a suggestion of genotoxicity Lee et al. (2011). However, more recent work, reviewed by Vijayalaxmi, Fatahi, Speck (2015), indicates that although most investigations do not show significant effects, there are sufficient gaps in knowledge to merit further research, using standardized protocols.

There has also been considerable recent interest in the frequencies above 30 GHz and extending to the THz range. These frequencies are used in some types of airport scanner and are being investigated for medical imaging applications. In addition to the commentary included in the SCENIHR Opinion, which recommended "more research focusing on the effects on skin (long-term, low-level exposure) and cornea (high-intensity, short-term exposure)," a review by Ziskin (2013) covers some of the work at millimeter waves, and there is generally a growing database of studies at THz.

Clearly, the outcomes of these types of experiments continue to be mixed, with no obvious explanation of why under almost identical exposure circumstances different results are obtained in different laboratories. There is a tendency for replication studies to fail to reproduce the RF-related effects in the original study.

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Part V

Extremely Low-Frequency (ELF) Electric and Magnetic Fields

17

Electric and Magnetic Fields and Induced Current Hazard

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17.1 Introduction

In Chapter 12, we saw how electric and magnetic fields (EMFs) in the form of radiated waves can induce electric currents within the tissues these waves interact with. We saw that the mechanism of interaction is distinct from the heating effects of radiofrequency (RF) waves, and that for frequencies below 100 kHz, the heating effects are negligible. In this chapter, we will be concerned with frequencies below 3 kHz, but above 0 Hz, that is, the fields are time varying. The special case of static fields (0 Hz) will be dealt with in Chapter 22. Fields in this low-frequency range are arguably not correctly categorized as radiation, since the characteristic wavelength is several kilometers, very much larger than the equipment associated with the fields. In NIR that is radiated (such as radiowaves and visible light), the EMFs are in strict ratio. The EMFs considered here are determined by separate processes and they are more or less independent of each other. The particular form of hazard in this range of frequencies is electrostimulation, that is, inappropriate activation of nerves giving rise to unpleasant or annoying sensations. At higher levels of exposure, the fields can cause severe shocks that can interfere with heart function or breathing; this is almost identical to the kind of shocks received from direct contact with a live electrical conductor.

17.2 What Other Hazards Need We Consider?

In the human body, the cells that compose the tissues of the various organs can be divided into those that are excitable and those that are nonexcitable. Cells in

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the former category, which consists of nerve and muscle cells, are able to conduct electrical impulses as part of their normal functioning. These impulses, which consist of momentary reversals of the normal 0.1 V or so which exists across the cell membrane, are the mode by which messages are passed within one nerve cell to the next and by which muscle cells co-ordinate their contraction. In order to assess whether an electric or magnetic field will cause electrostimulation, it is necessary to determine the amount of current that the external fields induce within the tissues of the body and how the nerves and muscles are arranged within the particular tissue. Excitable tissue shows the phenomenon of *threshold*, that is, no stimulation response will occur at all if the stimulus is below a certain level, or threshold. If the stimulus is above this threshold level, the response will be of the same magnitude, regardless of how big the stimulus is. This has been termed the "all-or-nothing" effect. This is particularly important when considering the effects of low-level EMFs. It implies that generally there are certain threshold levels below which no electrostimulation would occur and thus, no modifications in the way the nerve cells communicate with one another or in the way the heartbeat is controlled. In order to have a clearer understanding of what determines the level of threshold and whether a particular level of EMF would be sufficient for this threshold to be reached, the process of initiating a response will now be described.

17.3 The Initiation of an Action Potential

An action potential is the name given to a nervous impulse; similar impulses occur in muscle cells in the moments preceding contraction, but nerve cells will be described first. A nerve cell or *neuron* consists of a cell body (*soma*), with branches or *dendrites* and a long cylindrical *axon* (diameter: 1–15 millionths of a meter or micrometer; length: up to 0.5 m – see Figure 17.1). The axon is like a wire joining one neuron to the next; an axon from one cell joins on to a dendrite of another cell.

Information is carried along nerves as a series of impulses consisting of reversals in electrical potential difference across the axon membrane; these impulses travel at constant speed and the magnitude does not diminish during travel. Some axons have an insulating sheath of *Schwann cells* (whose membranes consist chiefly of myelin (fatty membranous material) wrapped around in several layers). These are called myelinated axons. The conduction velocity increases with increasing axon diameter. Unmyelinated axons lack this layer; in this case, conduction velocity varies with the square root of diameter. Using microelectrodes, the voltage across the cell membrane can be measured quite accurately. When the axon is not carrying nervous impulses, the membrane potential remains constant at between 0.06 and 0.1 V, with the inside negative. Membrane potentials are usually referenced to the outside, so this "resting potential" is negative. This voltage is maintained by a metabolic pump within

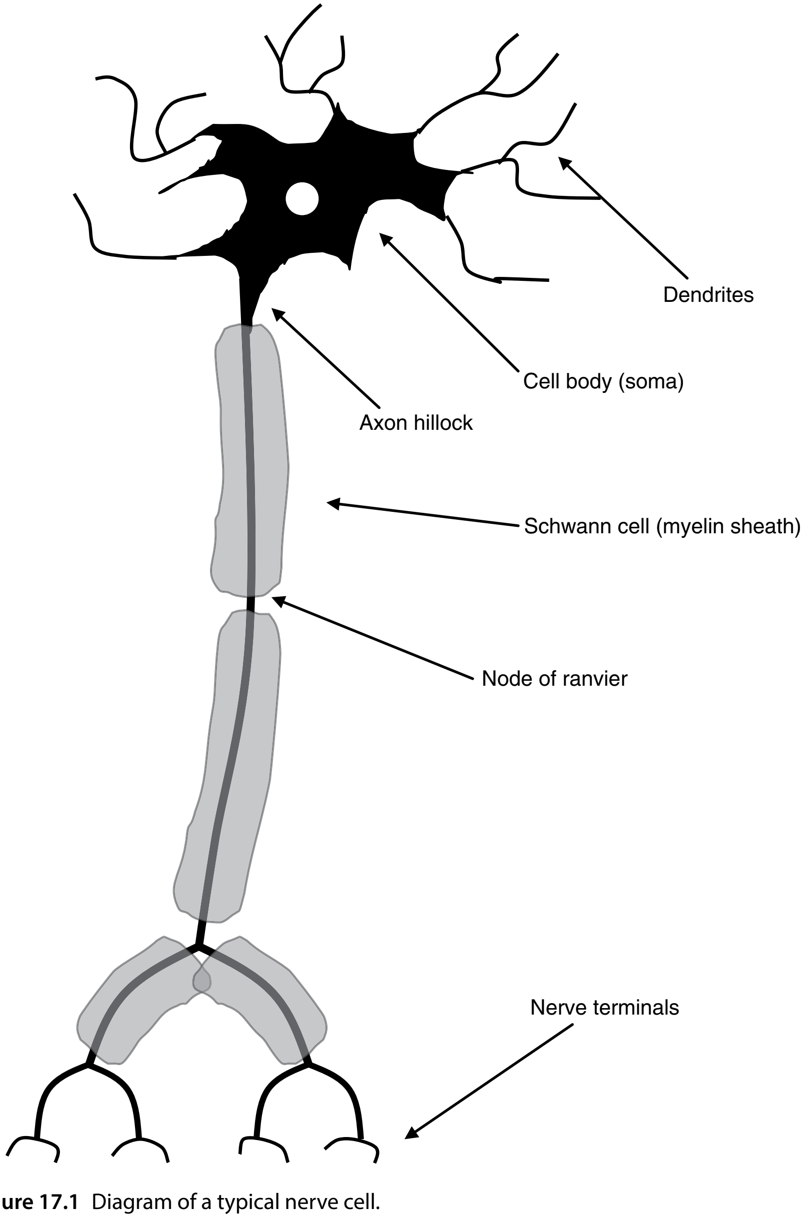

Figure 17.1 Diagram of a typical nerve cell.

the membrane, which takes sodium ions from the interior of the cell, where its concentration is low, into the surrounding medium, where it is at least 10 times higher in concentration. The membrane, during this time, is 20 times more permeable to potassium in the surrounding medium than to sodium, so the voltage reflects this.

The nervous impulse or action potential consists of a sudden change in membrane potential to around 0.03–0.04 V, now with the inside positive. This actually reflects the membrane now becoming 20 times more permeable to sodium than to potassium for less than 1 ms. In general, the information the nerve carries is coded as the number of impulses per second. The action potential is propagated along the axon at constant speed and it does not attenuate as it proceeds along the axon. In order to reach threshold (and for the axon to "fire" or form an impulse), the stimulus has to be sufficient to change the membrane potential by a certain amount, usually about 0.015 V or so less negative than the resting potential. This is referred to as a depolarization. If the membrane potential is changed very slowly, the membrane adapts to this change, so that a larger depolarization (i.e., more than 0.015 V) then becomes necessary for threshold to be reached. In fact, if the membrane potential is changed too slowly, the axon will never fire. This is relevant to situations where the stimulating current varies in a sinusoidal manner at frequencies lower than 20 Hz and will be elaborated on later. For rectangular or square wave stimulating pulses, there is a relationship between the strength of the stimulus and the duration of the pulse. In fact, for an infinitely long duration of pulse, a certain minimum stimulus strength is required for the axon to fire. As the duration gets shorter, the strength needs to be increased in order for the axon still to fire. A plot of the strength versus duration for just sufficient stimuli follows the form of a rectangular hyperbola, shown in Figure 17.2,

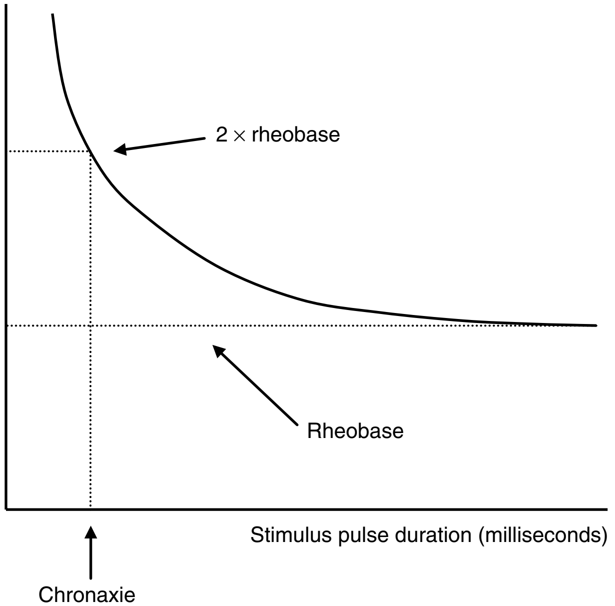

Figure 17.2 Strength–duration curve for an excitable cell.

which can be represented approximately as $I = K/D$, where I is the stimulating current, D is the duration, and K is a constant. This indicates that the amount of positive *charge* withdrawn from the membrane (which is proportional to $I \times D = K$) is the relevant determinant of whether a stimulus will be effective or not. The minimum stimulus of infinite duration referred to above is known as the rheobase and the minimum stimulus duration for effective excitation at twice the rheobase as known as the chronaxie. Plots of minimum effective stimulus strength versus respective stimulus duration are known as strength-duration curves.

The action potential is self-propagating; the inrush of sodium, which occurs at the point of potential reversal, withdraws charge from areas of the membrane ahead of this region. The threshold is reached at these regions ahead, so the potential reversal moves along to that point. The magnitude of action potential does not diminish with distance; it is thus also self-reinforcing. As the action potential passes, the membrane is left refractory (i.e., with a diminished ability to respond) for a few milliseconds or so. This places an upper limit on the number of impulses per second the axon can carry. The refractory period is divided into *absolute* refractory (where no matter how large the stimulus is, a second action potential cannot be elicited during this time) and *relative* refractory (where if the nerve is stimulated by a pair of stimuli, a second response will be obtained after the first only if the second stimulus is much stronger than usual). This is equivalent to saying that the threshold moves further away from the resting potential following stimulus and takes a few milliseconds to return to the original level.

In myelinated nerve, the depolarizations occur only at the nodes of Ranvier, which are the gaps between adjacent Schwann cells. The inrush of sodium at one node causes withdrawal of charge from the next node and so the impulse goes via a series of jumps from one node to the next. This is called saltatory conduction.

The membrane thus takes a certain length of time to respond to a depolarization, and this time is of the order of milliseconds. If we apply a stimulating current in the form of a sinusoid, we find that as the frequency rises from 20 Hz to several kilohertz, it becomes less effective. In fact, currents at 3 kHz are at least double those at 30 Hz to cause stimulation. It is, perhaps unfortunate, that the frequency best suited to nerve and muscle stimulation is 50–60 Hz!

Finally, it should be noted that if a number of impulses pass along an axon, the sodium ion concentration inside the axon rises and the potassium concentration falls, to such an extent in some cases that the nerve fatigues and ceases to fire. The pump referred to above will gradually restore the initial conditions if the nerve is allowed to rest. Each time an action potential occurs the axon loses around 43 nmol/m^3 of potassium and gains around the same amount of sodium. It would require several million action potentials to change the concentrations significantly, however. It has already been mentioned that the pump used in the restoration is *electrogenic*, that is, it contributes to the 0.1 V across the membrane. In some ways, the pump is like a battery, but since the axon membrane is only 0.01 μm thick, this represents a very large voltage gradient. In fact, the electric field in the membrane, which is voltage across the membrane divided by its thickness, is 10 million volts per meter (10 MV/m). This level of field in other materials is sufficiently large to cause electrical arcing ("dielectric breakdown", when an insulator becomes a conductor) and this emphasizes the unique nature of biological structures. Because of this extremely large electric field, relatively large external fields are required to significantly perturb the voltage across the membrane, let alone cause a depolarization that would reach threshold.

17.4 Endogenous and Exogenous Currents

One consequence of action potentials or voltage reversals traveling along axons is that the accompanying flows of sodium and potassium (the first occurs shortly before the second) represent currents flowing in the spaces between adjacent neurons and muscle fibers. If several thousands or millions of fibers are being activated simultaneously (as happens in the heart muscle), the current will flow through adjacent tissues. For this reason, it is possible to measure the electrical activity of the heart itself by applying electrodes to the wrists and ankles, as in the heart monitor or electrocardiogram (ECG). The electrical voltages due to currents flowing in the brain can similarly be measured from scalp electrodes, as in the electroencephalogram, or EEG. Biophysical modeling allows estimation of the magnitude of these currents in adjacent tissues. The issue of whether there could be inappropriate firing of neurons due to electrical activity in adjacent neurons has also been studied in detail. These currents, which form the normal environment in animal tissues, are called endogenous currents. The currents induced by external EMFs are referred to as exogenous currents. There is a view that unless exogenous currents exceed endogenous currents, they cannot give rise to inappropriate responses and the EMFs generating them would therefore be safe (Wachtel, 1992). However, the exogenous currents tend to be different in character; At power frequencies they vary sinusoidally over a 20-ms period rather than an irregular impulse of 1 or 2 ms. Secondly, the currents are of a similar magnitude ranging over large volumes of tissue rather than localized to individual neurons or muscle fibers. In response to this, we should understand that arbitrary waveforms such as the nervous impulse can be expressed as a sum of sinusoidal variations (Fourier components). The range of frequency variation of endogenous currents due to heart activity is similar to exogenous currents due to external power-frequency magnetic fields (when harmonics are included).

17.5 Sensation Thresholds

The five senses of sight, hearing, touch, taste, and smell involve the conversion of several forms of energy (light, sound, pressure, dissolved chemicals, and airborne chemicals) into electrical impulses. The cells that do this are referred to as receptors. Some animals, such as species of fish and monotremes, are able to directly sense electrical fields. Others such as birds, honeybees and certain diatoms (type of single cell algae), and bacteria are able to respond to magnetic fields (to form a biological compass), but in this case, there is no direct conversion to electrical impulses. The electrical responses of cells involved in sensation can be elicited by direct electrical stimulation. For example, passing a current between two points on a finger can give rise to a tingling sensation, or passing a current from one side of the eye to the other can cause the impression of pin points of light (electrophosphenes) due to individual retinal receptor cells being stimulated. There is still a need for the strength of stimulation to be above a certain threshold for any response to be detected (or in this case, sensed), but above this threshold, the response is *graded*. That is, as the strength of the stimulus current is increased, the number of impulses per second in the nerve attached to the sensory cell will increase (Figure 17.3).

The retinal cells of the eye are extremely sensitive to electrical current; the current can be caused by direct application to the skin on either side of the eye or it can be induced by an external varying magnetic field. In this case, the visual sensation is called a magnetophosphene, but there is every indication that the origin of this phenomenon and that of the electrophosphene is the same; a current above a certain threshold flowing in the retina. As an external time-varying magnetic field is increased in value, the phenomenon of magnetophosphenes is the first one to be experienced. As we will see, the guidelines and standards for magnetic fields have the prevention of magnetophoshenes as their basis. It could be argued that this phenomenon does not represent a health hazard but is merely annoying. There is at least one report of tiredness and eye muscle fatigue following experimental sessions in which magnetophosphenes were induced (Lovsund, Oberg, and Nilsson, 1980). As a matter of prudence, the fact that any inappropriate response is occurring might be taken as indicating the possibility of harm, particularly with long-term repeated stimulation or vulnerable individuals within the community taken into account.

We have seen that external time-varying magnetic fields can induce currents inside the body similar to those produced by direct application of current via points on the skin (contact currents). Similarly, electric fields can induce currents without the need for electrical conductor contact with the skin. If, for example, the wrist is placed between two conducting plates and a large voltage is applied between them, it is possible to stimulate the nerves within the wrist. However, the voltages necessary to do this are not commonly encountered

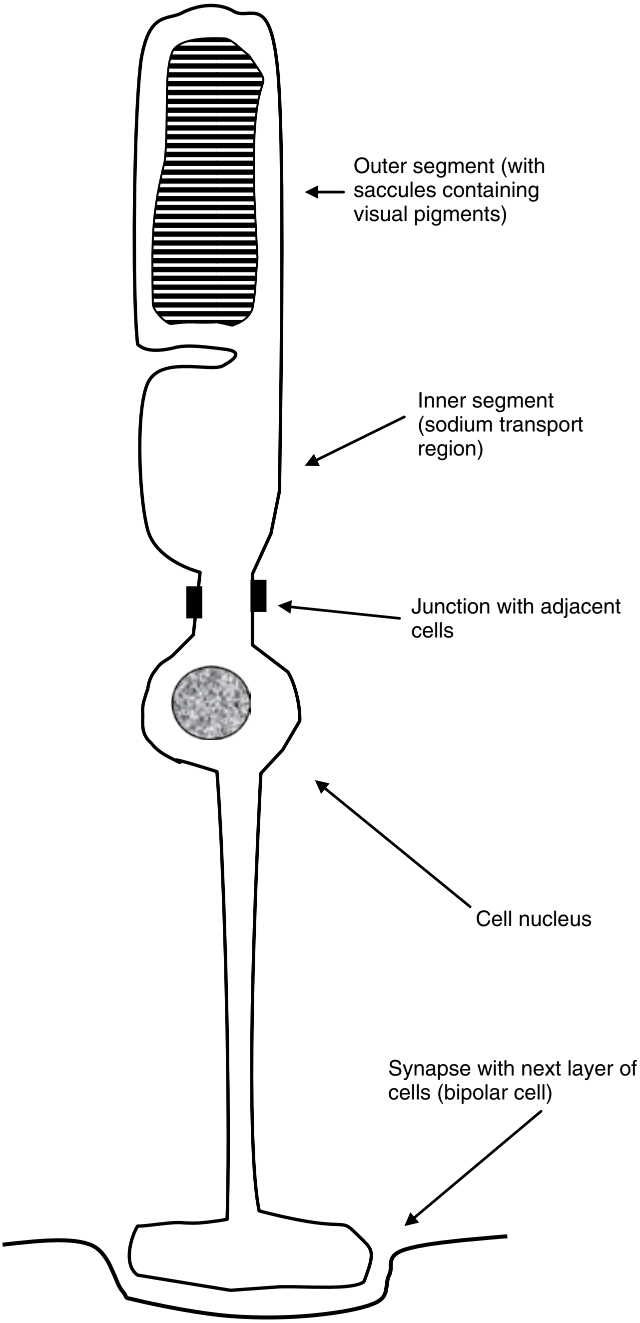

Figure 17.3 A sensory cell such as a retinal rod cell.

(400,000 V, typically), and there are hazards that occur at lower voltages due to other mechanisms, which will be discussed in the following section. For the moment, we will discuss mechanisms of the induction of currents within the body and discuss what the hazards might be if these currents become excessive.

17.6 Effects of Contact Currents

Electric shock refers to receiving sufficient current through regions of the body to cause nerve or muscle stimulation. If this is sufficiently large or sustained, cessation of breathing may result, leading to electrocution. At lower levels, stimulation of muscles in the hand is such that it becomes impossible to release a grasp on an electrical conductor. This occurs above a threshold known as "let-go" current, which was determined experimentally over 50 years ago to average at 16 mA for men and 10 mA for women, applied hand-to-hand. Currents at these levels and fields that would produce them are obviously hazardous; there is little to remark on except that for 1% of the female population these can be as low as 6 mA. This level of variability is also found in the level above which some form of sensation is reported (i.e., the recipient can tell that a current is flowing), which ranges from 0.5 to 2 mA in this hand-to-hand situation. It should be pointed out that receiving a mild shock from electrostatic buildup from carpets and clothing is a fairly common occurrence. Receiving shocks of a similar magnitude from conductive parts of electrical plant or equipment is indicative of poor design or faulty connections and should be prevented. In intensive or emergency medical care, indwelling venous infusion devices or metallic pacemaker leads represent high conductance paths to the heart. Currents as low as 10 µA flowing through the heart are sufficient to cause fibrillation or chaotic movements of the heart.

The study of sensation thresholds from contact currents is important to determine what level of noncontact electric or magnetic field might lead to similar effects. Since the current between two points of contact can take a number of distinct paths, depending on how big the area of contact is, the important metric is in fact the amount of current per unit area or current density. This is correctly expressed as amps per square meter (A/m^2), but is often given as milliamps per square centimeter, since a square centimeter is a more appropriate contact area. Clinical instruments are designed to measure the skin current perception thresholds at frequencies corresponding to the three main categories of sensory nerve. The lowest thresholds are obtained for 5 Hz, with current densities as low as 160 µA for a 1-cm^2 disk electrode. This corresponds to 1.6 A/m^2 and is a direct measure of the order of magnitude of current densities in bulk tissue necessary to stimulate nerves. This is in accordance with estimates of 1.2 A/m^2 based on mathematical models of individual nerve activation (Reilly, 1989; Reilly and Diamant, 2002). We should thus treat a current density in the body of around 1 A/m^2 with some concern, as it would most likely lead to nerve stimulation and annoying sensations, especially if flowing through the skin.

17.7 Inducing a Current in Tissue by an External Magnetic Field

Currents can be induced in the body by the action of external fields as well as through direct contact with charged objects or conducting surfaces. The coupling of external magnetic fields is perhaps a little simpler than electric fields and will be dealt with first. A current is induced in tissue whenever an external magnetic field *changes*, and the magnitude of this current is proportional to the rate of change of magnetic field. For sinusoidally varying fields, as the frequency of the variation rises, the rate of change rises too. Fields of 1 kHz thus induce higher currents than fields of, say, 100 Hz. Actually, what the changing magnetic field induces is an internal *electric* field, which vibrates with the same frequency as the external field. It is this internal field rather than induced current density that determines whether or not a nerve will be affected. If a region of tissue can be considered as homogeneous (which is rather a big assumption), then the induced current density is just the internal electric field (E_{int}) multiplied by tissue conductivity in Siemens per meter (a Siemens is a "reciprocal ohm"). Many tissues have conductivity values of approximately 0.2 S/m^2, so an induced current density of 1 A/m^2, which as we have seen might lead to nerve stimulation, would result from an induced internal field of 5 V/m. It is actually quite an easy matter to estimate what this induced electric field will be; it is given by the formula

$$E_{\text{int}} = r\left(dB / dt\right)/2$$

For sinusoidal fields, $dB(t)/dt = 2\pi f B(t)$, where f is the frequency of the field.

In words, this is the distance (r) from the center of the object (in the direction at right angles to the field) times the rate of change of field (dB/dt) divided by 2. The symbol B denotes the magnetic flux density of the field, which is measured in tesla (T) or gauss, the latter being an older unit. The rate of change dB/dt is usually given as tesla per second (T/s). If we regard 5 V/m as the induced field (E_{int}), which might lead to nerve stimulation, then for a torso of radius 0.2 m (20 cm), a field changing at 50 T/s would be sufficient to do this. Figure 17.4 shows the direction of the induced currents in the torso for a spatially uniform horizontal time-varying magnetic field. For a sinusoidal field, the rate of change is given by $2\pi f B$, where f is the frequency. Thus, at a frequency of 50 Hz, the magnitude of field that could stimulate nerves is 0.16 T, approximately. This is a very powerful field and is about 1 million times greater than one would experience at home or 10,000 times the field under the highest rated power transmission lines. In fact, in medical diagnosis, transcranial magnetic

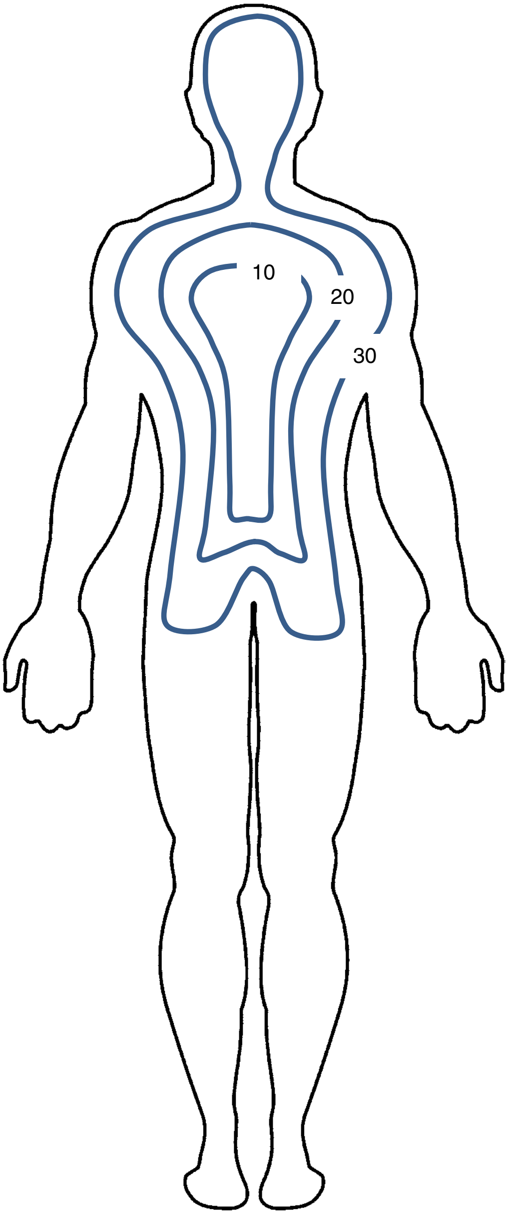

Figure 17.4 Induced electric field lines within the body of a person subjected to a 1 mT spatially uniform time-varying magnetic field directed front to back. Units: mV/m.

stimulation is given to specifically stimulate nerve cells in brain and other nervous tissue. Typical dB/dt rates are upward of 20,000 T/s rather than the 50 T/s just estimated. There is thus little likelihood of nerve stimulation from environmental sources. There is, however, concern that magnetophosphenes, mentioned above, might indicate potentially hazardous changes in other tissues, and these are known to occur at much lower values of B. In fact, sinusoidal fields of 0.008 T at 20 Hz and 0.014 T at 50 Hz (corresponding to E_{int} values of 0.05 and 0.2 V/m, respectively) are the approximate thresholds for this phenomenon. This would imply that a threshold current density at 50/60 Hz (assuming 0.1 S/m for retinal tissue) would be somewhere between 10 and 20 mA/m^2. In fact, if we assume the eye to be an isolated sphere, radius 10 mm, the threshold could be even lower. Experiments on humans in which currents were applied directly to the temples showed that the phosphene threshold was about 0.3 mA at 50 Hz and about 1/10 of this at 20 Hz. If it is assumed that this current distributes uniformly across the head (cross-sectional area of 0.025 m^2), then this represents 12 mA/m^2. At 20 Hz, it would be only 1 mA/m^2. Again, it is uncertain whether the local current density in the retina would be greater or less than this average value. Since the sclerotic layer of the eyeball is poorly conducting, it could be argued that the local current densities would be less. However, Lindenblatt and Silny (2001) reported evidence that blood vessels entering the eyeball provide a low resistance pathway making the effective cross-sectional area over which the current distributes much less. In summary, there is good reason to believe that at power frequencies, magnetic fields have the capability of producing the rather startling magnetophosphenes at around 0.01 T at extremely low frequency (ELF) frequencies and that this would represent local electric fields (E-fields) (E_{int}) of 0.05 V/m or more. Retinal thresholds are discussed further in Wood (2008).

17.8 Effects of External Electric Fields

Electric field effects on the body are a little more complicated than magnetic field effects. There are two chief ways in which electric fields, or E-fields, interact: effects on the surface of the skin and effects of induced currents within tissue. Dealing with the second mechanism first, as in the case of magnetic field stimulation, an external electric field will produce (or induce) a local, internal, electric field. This will in turn produce a current whose density is equal to this induced field times the local tissue conductivity. Because the tissues are relatively good conductors of electricity (due to their salt content), the induced E-field is very much less than the external E-field, around 100 million times less, in fact. We will denote these electrically induced E-fields as E_{int}^{E} to distinguish them from magnetically induced fields E_{int}^{B}. The complication in the E-field situation is that although the body does not perturb the direction of the external magnetic field (B-field) lines, it has a profound effect on the external E-field lines. If the body were to contain significant amounts of magnetically susceptible materials (e.g., such as soft iron implants), the B-field lines would be similarly affected. The distortion of E-field lines near the surface of the body is shown in Figure 17.5. The particular features worth noting are that the (imaginary) field lines enter the surface of the body at right angles and the field lines are crowded together (indicating a higher field value in V/m) close to pointed regions such as an upraised arm or finger.

The effect of this "crowding" of field lines is that in certain regions of the body, the external E-field is enhanced by up to 500 times, causing E_{int}^{E} to be similarly enhanced. As before, the induced current density is obtained by

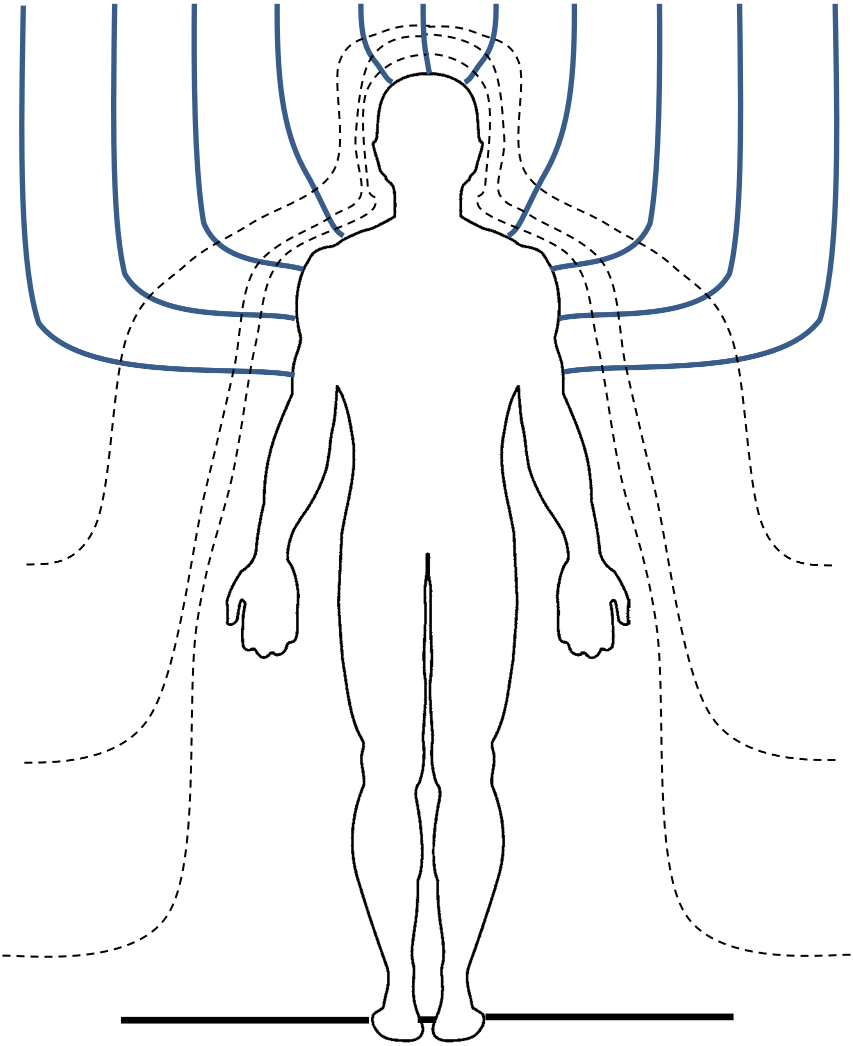

Figure 17.5 Electric field lines (full) and isopotentials (dotted) for a person subjected to an electric field.

multiplying E^E_{int} by the local tissue conductivity. If we regard the induction of phosphenes as the phenomenon that is indicative of possibly hazardous bioeffect, then in order to induce E^E_{int} 0.05 V/m, a minimum external field of 10 kV/m would be required. The fact that volunteers placed in 10 kV/m 50/60 Hz fields do not experience phosphenes would emphasize that a large safety margin obtains. However, there is another phenomenon due to induced current, which would tend to place a practical limit on E-field exposure, that of microshock. If a person is placed in a strong E-field and they touch an ungrounded metal object (or another person, even), they may experience a shock at their point of contact. This might happen if a person touches a wooden fence with a metal rail parallel to an electrical transmission line. This shock is similar to the "static" shock a person may experience after crossing a synthetic carpet or getting out of a car with synthetic upholstery. Although these microshocks are not in themselves dangerous, they are startling and can be quite painful. As we have seen, if the induced current is made to flow through a small area of skin (if, e.g., a person with bare feet steps off a wooden ladder on to a metal surface), the local current density and hence E^E_{int} can be high. The following formula was developed to estimate the current that would be induced in the body in this situation (Deno, 1975):

$$I = 9 \times 10^{-11} \times f \times h^2 \times E \tag{17.1}$$

Here, f is the frequency (Hz), h the person's height (m), and E the external electric field (V/m). In this case (10 kV/m), a current of around 130–160 μA would flow through the area of contact, which, as we have seen above, would be sufficient to elicit sensation if the area were 1 cm^2 or less. Modeling studies have shown that as a person continues to stand barefoot on a conducting surface in a 10 kV/m field, a current density of 20 mA/m^2 flows in the ankles and 5 mA/m^2 flows through the neck. While in the retina, as we have seen, the current densities will be lower (the E-field threshold for this phenomenon seems to be of the order of 1000 kV/m), current densities of 10 mA/m^2 were of concern when considering external magnetic fields.

The other mechanism of interaction referred to above is that of effects on the skin. As an external E-field is increased in value, the first phenomenon people perceive is vibration of skin hairs. While of itself this does not indicate harm, it would act to warn members of the general public of danger of a close approach. It might also provide an explanation of behavioral responses in laboratory or farm animals. Tests on humans have shown that at 50/60 Hz, if a hand is raised above the head, the threshold is around 7 kV/m for an unperturbed field. This would equate to a local external E-field of many times this value if the enhancement effect shown in Figure 17.5 is taken into account. A related phenomenon is the perception of vibration if a person insulated from the ground moves a hand over a painted or otherwise insulated metal surface. There are good explanations for this phenomenon, which will occur even under moderately high-voltage electrical transmission lines.

Those living near high-voltage lines often complain about noise due to corona discharge near insulators on the line. In particular during foggy or rainy conditions, spark discharge accompanied by crackling and fizzing sounds (which is a miniature version of lightning and thunder in storms) is due to a process known as dielectric breakdown. Some ozone is released during this process, but the quantities are not sufficient to warrant concern. Tests have also been carried out on pointed leaves such as fir tree leaves without any clear evidence of altered growth patterns near high-voltage transmission lines.

17.9 Sources of EMFs: Electricity Transmission and Distribution Systems

We have noted that high *E*-fields are experienced near high-voltage electrical transmission lines. Voltages (or electrical pressures as they are sometimes called) are typically in the range 33,000–500,000 V. The electric field associated with these transmission lines exists in the space between the cables and the ground and is directed from the cables down to the ground (or vice versa). However, the strength of the electric field is inversely proportional to the distance between the wires and the ground level. Thus, as far as public exposure is concerned, the greater height of the transmission line poles compared to the distribution system poles (for the 110/240 V supply) means that the electric fields associated with the former are not necessarily orders of magnitude larger. In addition, trees and other tall objects tend to significantly reduce electric fields experienced by the public outdoors. The values of voltage of the three main sets of wires of a transmission line at any given instant can be positive or negative and in fact, the sum of the three voltages is always close to zero (Figure 17.6). A person standing on the ground beneath a transmission line experiences an electric field because he or she is closer to one set of wires than the other two. This "phase cancelation" is another reason why electric fields due to utility installations experienced by the general public are at best modest. Indoors, the building itself provides additional shielding from external electric fields.

Inside the home, the values usually encountered are of the order of several tens of volts per meter. Directly under a 275,000 V power line, fields of 500 V/m are possible. The values of electric field measured indoors are more than likely to be due to sources within the building rather than external to it. A Canadian study (Levallois et al., 1995) measured an average 26 V/m in homes within 85 m of a 735,000-V transmission line. They found that in homes away from the line the *E*-field values were only about half of this value. Table 17.1 lists some typical values of *E*-field in domestic and occupational settings, drawn from data from around the world.

Magnetic fields beneath electrical power distribution lines in residential streets are typically between 0.2 and 2 μT (2 and 20 mG) at 1.5 m above ground

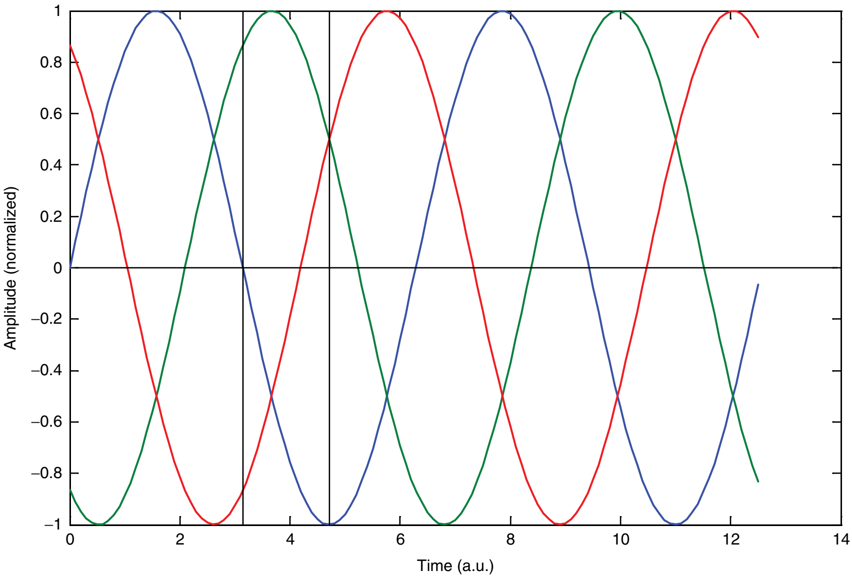

Figure 17.6 Phase cancelation effects: each of the three sine waves is delayed by one-third of a cycle (relative to the previous one). If these three sine waves represent current in the three transmission line conductors, note that at each instant the net current is zero (the first vertical line has values +0.9, 0, −0.9; the second one +0.5, +0.5, −1.0). At positions remote from the transmission line, the magnetic field is determined by the sum of the currents: effectively zero.

level. Corresponding levels at easement boundaries of transmission lines are between 0.2 and 5 μT (2–50 mG). Directly underneath 500,000 V lines, *B*-fields can be as high as 18 μT (WHO, 2007). *B*-fields are somewhat more variable with time because they depend on the amount of current flowing in the lines, which is a function of demand. The maximum current is of the order of 1000 A, but because of the phase cancelation referred to above, the fields due to the separate conductors carrying the different phases tend to cancel each other out. As an illustration, if 1000 A was carried by a single conductor 12 m from the ground, the *B*-field 1.7 m above ground (head height) would be 20 μT, whereas fields of 1/10 of this or less can be achieved through careful engineering design such as "reverse phasing", which is explained in Chapter 25. Typical *B*-fields are listed in Table 17.1.

17.10 Home Appliances and Industrial or Commercial Sources of EMF

As indicated in Table 17.2, the median *B*-fields are of the order of 0.1 μT in the home and with similar levels in an office environment. For example, in office

Table 17.1 Typical values of magnetic fields measured near powerlines and substations.

Source	Location of measurement	Range of measurements (μT)[a]
Distribution line	Directly underneath	0.2–3
Distribution line	10 m away	0.05–1
Substation	At substation fence	0.1–0.8
Transmission line	Directly underneath	1–20
Transmission line	At edge of easement	0.2–5

Source: http://www.arpansa.gov.au/radiationprotection/factsheets/is_magfields.cfm.

a) Levels of magnetic fields may vary from the range of measurements shown.

Table 17.2 Typical values of magnetic fields measured at normal user distance.

Appliance	Range of measurements (μT)[a]
Electric stove	0.2–3
Refrigerator	0.2–0.5
Electric kettle	0.2–1
Toaster	0.2–1
Television	0.02–0.2
Personal computer	0.2–2
Electric blanket	0.5–3
Hair dryer	1–7
Pedestal fan	0.02–0.2

Source: http://www.arpansa.gov.au/radiationprotection/factsheets/is_magfields.cfm.

a) Levels of magnetic fields may vary from the range of measurements shown.

environments, 55% of time is spent at magnetic field exposure levels of less than 0.1 μT (WHO, 2007).

Appliances and machines that operate via an electric motor (vacuum cleaners, washing machines, hair driers, electric shavers, bench grinders, and overhead projectors) are associated with fairly strong B-fields, but these fall off with the inverse cube of distance ($1/R^3$). Fork-lift truck operators and sewing machine operators are normally in close proximity to electric motors and their levels of exposure to parts of their body is quite high. Other workers, such as welders, can be using cables carrying high currents at a variety of frequencies. Concern has been expressed that these workers could receive levels in excess of those set as basic restrictions (Nadeem et al., 2004). A range of utility workers are exposed to high levels of both E- and B-fields: these include bare-hand live-line workers, electrical switchyard workers, and telephone linemen (who work on poles in which telephone lines are colocated with energized electrical distribution cables). Several health and exposure surveys have been carried out on these types of worker.

Many libraries and shops use electronic surveillance systems at checkouts or at exits to detect theft. These operate at a variety of frequencies, usually as a series of pulses, with field levels of several hundreds of microteslas.

17.11 Transportation Systems

Since electric motors and supply cables to them are associated with strong, but localized, *B*-fields (as we have just seen), it would be expected that exposure levels in trains, trams, and other electric transporters might be high. It should be pointed out that many transportation systems employ direct current, and the static fields associated will be dealt with in Chapter 22. Others use alternating current supply, often at a different frequency from the electricity grid. For example, the Swiss railway system uses 16.7 Hz supply. A survey (Minder and Pfluger, 1993) measured up to 6,200 μT in the legs of engine drivers, with an estimated annual time-weighted exposure of 250 μT. Other transportation systems involve magnetic levitation (Maglev) in which exposure of passengers is to a variety of frequencies and to levels up to 25,000 μT (WHO, 2007).

17.12 Therapeutic Uses

A number of therapeutic devices employ pulsed or sinusoidal currents applied via stick-on electrodes. As we have seen, this is equivalent to field stimulation in terms of induced current. Others employ pulsed magnetic fields and as such do not need to contact the skin. These devices can be divided into those that are specifically designed to stimulate nerves and those that are not. The former include devices such as transepithelial neural stimulators (TENS) for pain relief and transcranial magnetic stimulation (TMS) units, which are used experimentally for treatment of psychiatric illness and for diagnosis (which was discussed earlier). These are capable of delivering brief current densities of 1 A/m^2 or more. The latter category includes bone growth pulsed magnetic field stimulators (for the treatment of intractable fractures) and contact current interferential units (used in physiotherapy). These appear to induce several hundreds of milliamperes per square meter, but in view of the electrical properties of, in particular, bone, it may effectively be much less than this. The mechanism of action is unclear and evidence of their efficacy is limited.

17.13 Effect on Pacemakers and Other Implantable or Body-worn Electronic Medical Devices

A heart or cardiac pacemaker consists of a small battery-driven control unit and a stimulus generator, which is implanted below the skin, with a long metallic lead that senses the level of electrical activity in the heart and delivers a short "shock" at the appropriate moment directly to the heart itself. If the lead senses interference from external *E*- or *B*-field, the pacemaker can respond inappropriately, particularly if it is an older unit of the unipolar (as opposed to a bipolar) kind. Manufacturers have been aware of this possible problem for many years and have designed units to be immune to 50/60 Hz fields in particular. However, some of the surveillance systems just referred to operate at pulsing frequencies other than 50/60 Hz and may affect a greater range of pacemakers. Manufacturers of other electronic devices, such as implantable nerve stimulators or infusion pumps, have also sought to provide immunity from inappropriate responses. Specialist laboratories test the level of immunity of specific medical devices from ambient fields both at ELF and RF.

17.14 Electro and Magnetobiology

Certain fish possess an ability to detect fields as small as around 1 μV/m. They sense the tiny changes in *E*-field produced by prey, even though they may be submerged in silt. However, these fish possess unique sensory organs that are able to amplify and detect these small signals by a combination of spatial and temporal coherences in nerve firing rates. Monotremes such as the platypus are able to sense small ac fields up to around 160 Hz (Gregory et al., 1988; Fjallbrant, Manger, and Pettigrew, 1998) Humans do not possess these "electrical" sensory organs. Similarly, the ability of humans to detect the earth magnetic field has not been established scientifically. Birds, honeybees, certain fish, and certain bacteria, on the other hand, possess regions containing biogenic magnetite (a magnetic ore), which are thought by some to provide the basis for their direction-finding capabilities. Others have investigated a role of cryptochromes in photoreceptors as producing a way for birds to "visualize" the magnetic field (Ritz, Adem, and Schulten, 2000; Ritz, Dommer, and Phillips, 2002) As an example of magnetosensitivity, there is evidence of birds being able to distinguish fractions of a degree of latitude in choosing a migratory route across the oceans.

17.15 Glossary and Further Definitions

17.15.1 Electric Fields

Electric fields exist wherever there is a difference of electric pressure, or voltage, between two objects or between a single object and ground. In an analogy with the domestic water supply, there is pressure in the water pipes whether the taps are on or not (due eventually to the height of the water-tank or reservoir). Similarly, there are electric fields present wherever there is energized electric wiring, whether the electrical plant or appliances are switched on or not. In regard to electrical utility installations, electric fields are associated with power transmission and distribution lines, with transformer substations and with power stations and switch yards. Electrical fields are associated with such natural activities as combing one's hair or rubbing a glass surface with a dry cloth. Static electricity is a well-known phenomenon associated with getting out of a fabric car seat or walking across a polyester carpet. The small shocks and crackles observed when removing polyester clothing or touching metal objects after collecting "static" are associated with very high momentary electric fields. People tolerate these electric phenomena as part of everyday living usually without comment.

17.15.2 Magnetic Fields

Magnetic fields are associated with magnetic materials such as magnetite (an iron ore) and with flowing electricity. The earth has a static magnetic field that has formed the basis for navigation for several centuries. Magnetic materials are incorporated into such familiar items such as fridge magnets and door closers to provide an attractive force. Strong magnets form the basis of devices such as electric motors and magnetic resonance imaging (MRI) machines (which are used in hospitals to produce detailed images of the body, especially the brain). When electricity flows in a wire or other conductor to form a current (measured in amperes, or amps, for short), this will set up a magnetic field. Magnetic fields are associated with natural flows of current within the human body associated with processes such as the heartbeat and the functioning of the brain. In general, the larger the current, the greater the magnetic field. If the current flows in a straight wire, such as a transmission or distribution line, the magnetic field is directed in a circle around the wire or cable. The strength decreases with distance from the cable. Unlike the electric field, the magnetic field is not diminished by trees or by the presence of other nonmetallic buildings. In general, magnetic shielding is quite difficult (and expensive) to accomplish effectively. However, phase cancelation (see Section 17.15.1) also acts to reduce magnetic field intensity in electrical power transmission and distribution systems.

17.15.3 Units for Magnetic Fields

The basic unit for magnetic field intensity is amps per meter (A/m). However, since different materials have different susceptibility to this magnetic intensity, the flux density (in tesla) is a more appropriate measure when considering effects on objects, including the human body. For nonmagnetic substances such as the human body, $1\,\mu\text{T}$ (one millionth of a tesla) is equivalent to

0.796 A/m. For magnetic substances (such as iron), this amount of magnetic field intensity would produce a much larger flux density, several milliTesla, in fact. An older unit, the gauss, is still in use. One microtesla is equal to 10 mG (1 mG is one thousandth of a gauss). Within the home, values of a few milligauss (mG) are common. The fields at normal operating positions of some household appliances, such as hair driers and electric shavers, can be over 30 mG. At a personal computer, fields of up to 20 mG can be recorded.

Tutorial Problems

1 If it is assumed that the magnetic field directly below a transmission line is 5 μT (root mean square value, RMS), directed horizontally, estimate the maximum induced electric field in the body of someone standing in this position, given the shoulder to shoulder distance to be 40 cm and a frequency of 50 Hz.

2 Use the Deno formula $I = 9 \times 10^{-11} \times f \times h^2 \times E$ to show that the total induced current in a 1.7 m high person standing on the ground in a 10 kV/m 60 Hz field is 0.16 mA. If the person stands on one leg and this current flows through an ankle, diameter 75 mm, estimate the current density in the ankle. Further, estimate the induced electric field E_{int} using an average tissue conductivity value of 0.2 S/m.

3 In the previous example, since the neck has relatively low conductivity, the head can be approximated to an isolated sphere, radius 80 mm. Estimate the 60 Hz current in the neck, given that the capacitance of a sphere is $4\pi\varepsilon_0 r$ and that the current is given by $2\pi f C \cdot V$, if the space potential at the head is 10 kV.

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18

Extremely Low-Frequency (ELF) Guidelines

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18.1 Introduction

In the chapter on radiofrequency (RF) guidelines (Chapter 13), some of the issues of defining basic restrictions (BRs) and maximum permitted exposures (MPEs) or reference levels (RLs) were reviewed. For the extremely low-frequency (ELF) range of frequencies, again the two main international bodies producing standards/guidelines are the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronic Engineers (IEEE). At one time, the two sets of exposure limits were considerably different, but with the revision of the ICNIRP guidelines in 2010 (ICNIRP, 2010), these differences are now less, but are still quite significant.

Although the ELF part of the spectrum covers the region from static fields to frequencies of several kilohertz, the frequency of most interest is 50/60 Hz, the frequency of the electric power supply. The fields associated with the generation, transmission, distribution, and use of electricity pervade most inhabited areas and to a certain extent, uninhabited areas in more or less every country on the globe. Tables 17.1 and 17.2 give some typical values of power frequency electric and magnetic fields (EMFs) associated with particular installations and appliances. These values vary in only a minor way between countries. Personnel involved in maintenance work of high-voltage transmission lines and substations are exposed to high fields, but less obviously, those working in some machine shops and in electric arc welding are exposed to similar high levels. Some of the highest measured exposures are of train drivers, where the frequency used may be other than 50/60 Hz, often 16.67 Hz. Many of the waveforms are quite complex, so the sensitivity of tissue to the higher frequency harmonics needs to be carefully considered. A basic issue in considering

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Table 18.1 Comparison between basic terminology from the ICES standard and the ICNIRP guidelines: where no formal definition is given, parts of the relevant text are paraphrased in brackets.

IEEE (ICES)	**ICNIRP**
General public All individuals who may experience exposure, except those in controlled environments	*Public exposure* All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures
Controlled environment An area that is accessible to those who are aware for the potential of exposure as a concomitant of employment, to individuals cognizant of exposure and potential adverse effects, or where exposure is an incidental result of passage through areas posted with warnings, or where the environment is not accessible to the general public and those individuals having access are aware of the potential for adverse effects	*Occupational exposure* All exposure to EMF experienced by individuals in the course of performing their work
Basic restriction Limitations on the *in situ* electric forces that avoid adverse effects and with an acceptable safety factor	*Basic restrictions* For 1 Hz to 10 MHz: restriction on current density to prevent effects on nervous system functions
Maximum permitted exposure (MPE) levels The RMS and peak electric and magnetic fields and contact currents to which a person may be exposed without an adverse effect and with acceptable safety factors	*Reference levels* Obtained from basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies
Safety factor A multiplier (≤1) used to derive MPE levels, which provides for the protection of exceptionally sensitive individuals, uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in reaction thresholds, and uncertainties in induction models	*Safety factor* In range few hertz to 1 kHz; applied to basic restriction – factor of 10 below threshold for neurostimulation for occupational and a further factor of 5 to derive the general public basic restriction

protection against harmful effects of ELF fields is to identify exactly what these harmful effects might be, in other words: what precisely are guidelines designed to protect people against? In Chapter 17, there is a discussion of some of the immediate effects of elevated ELF fields, such as various forms of nerve stimulation, including unpleasant sensations. Beyond the levels of sensation, they become gradually more annoying until they become intolerably painful. The

Table 18.2 Occupational/controlled environment maximum permitted exposures (IEEE) or reference levels (ICNIRP) for *B*-fields at 50 Hz and 3 kHz.

	BR (mV/m)	RL (mT)	Model (mV/m/mT)	Effect threshold (E_{int} mV/m)	Margin
50 Hz					
IEEE	44 (CNS)	2.7	15.8	130	3
ICNIRP	100 (CNS)	1.0	3×33^a	100	1
3 kHz					
IEEE	2100 (PNS)	0.687	3.07	6300^b	3
ICNIRP	800 (PNS)	0.1	3×3.6^c	4000	5

The RL is derived by dividing the second column by the fourth.

a) Modeling gives 33 mV/m/mT, but this is increased threefold to allow for uncertainty in modeling.

b) This value is the sensation threshold multiplied by 1.45.

c) Here, the 50-Hz estimate is multiplied by the ratio of frequencies (3000/50) to give 3.6 V/m/mT and then increased by threefold as before. The fifth column gives the value for tissue electric field, which is considered detrimental and the final column the effective margin. For the general public, the margin is greater.

question is – when do the levels become unacceptably annoying? Is mere perception unacceptable? It needs to be borne in mind that "static" discharges, which can be quite painful, are often experienced in everyday life: touching a car door after rubbing against the seat material on alighting; touching a plastic chair after crossing a carpeted floor; removing clothing made from synthetic fabric; and so on. These can be very annoying, but are perceived as "natural" and therefore acceptable. The same sensations experienced when touching a metal fence or other object close to an electric transmission line would be perceived as being the product of human activity, so therefore more preventable or controllable and therefore the occurrence unacceptable.

A related question is how do we protect the most vulnerable members of the community and who might these people be? The very young, the very old, and those pregnant or on particular medications are candidates for special protection, but some understanding of why these categories might be at greater risk is necessary. Some of the considerations in Chapter 17 would indicate that vulnerability might be related to body size, which is not an attribute that would spring naturally to mind. Since some standard-setting bodies have questioned the need for a "two-tier" standard (i.e., two sets of limits based on some attribute of the exposed person or the environment in which a person is in), some discussion on the differing philosophies will be presented.

Chapter 20 discusses some of the epidemiological evidence of an association between childhood leukemia and elevated 50/60 Hz magnetic fields. A crucial issue in standard-setting is the question of whether causality has been established and hence to what extent the limit values are determined by this evidence. As in the case of RF fields, there are uncertainties and inconsistencies in the science, which would lean toward to a cautionary approach being taken in standard setting. A fuller discussion of the place of precautionary measures will be postponed until Chapters 25–27.

18.2 Standard or Guidance Levels?

In some areas of NIR protection, limits are quite precise and the consequences of exceeding them are easy to predict. For example, overexposure to RF radiation produces heating of tissue beyond the range of internal compensation, which could lead to irreversible denaturation of proteins. It is therefore necessary to prevent deliberate overexposure and to minimize the risk of accidental overexposure by the various control mechanisms discussed in Chapter 13. In the area of ionizing radiation protection, allowing a person to be overexposed (e.g., to X-rays) is a quite serious offense, which can lead to legal proceedings or a heavy fine. There is little support for similar penalties to be applied in the case of ELF. There is no evidence that occasionally exceeding the present limits by, say, 10-fold, would lead to permanent damage or serious health consequences. On the other hand, there is no compelling evidence to suggest that complying with the present limits will be sufficient to protect against increased risk of serious illness, such as cancer. Thus, there is a range of scientific uncertainty that has made regulators disinclined to be over-prescriptive regarding ELF.

Sections of industry, on the other hand, have developed "best practice" standards based on what is practicable but also on what they judge society demands with regard to safety. Electric power utilities have guidelines on power line and switchyard design based on engineering principles but with wider safety issues taken into account. For example, the width of transmission line easements takes into consideration the lateral movement of conductors in high winds rather than a requirement to limit EMFs exposure to humans (EPRI, 2008). The distance of transformers and switchyard gear from the perimeter fence is to prevent the possibility of flash-over or induced current shock.

There is thus a question of whether or not a standard is actually needed, since sections of the industry are effectively and responsibly self-regulating, and people are receiving what is deemed to be adequate protection. Most high fields occur in areas where a degree of control (e.g., the restriction of access) is maintained. The number of reports of people, including workers, receiving injury as a direct result of high *field* exposure (i.e., exposure to fields rather than contacting conductors) is virtually zero. The average magnetic field values most members of the general public experience are around 1000 times less than those experienced by some maintenance workers on transmission plants. Studies of the health of these workers have not revealed any unequivocal increases in mortality or morbidity. However, the literature reviewed in Chapter 20 indicates that harm due to higher than usually encountered environmental EMFs in the long term cannot be ruled out, particularly in children, which would point to a need to be cautious. Some bodies, such as state and local councils in particular, have reacted to public pressure by setting unrealistically low EMF standards. Although the European Union directive (EU, 2013) (which came into force in 2013) makes it mandatory for member states to adopt (specifically) ICNIRP guidelines into legislation, this does not preclude states from adopting stricter guidelines if they feel the need to. Adoption of limits-based standards, or at least guidelines, seems to be a direction many jurisdictions are now heading. In the absence of guidelines based on scientific analysis, there could be a tendency for the outcomes of legal proceedings to dictate the "de facto" limits for power-frequency magnetic fields in particular.

Before discussing particular standards, an important distinction has to be made. These standards are to protect against harmful effects of being exposed to EMFs rather than the consequences of touching uninsulated current-carrying conductors. A slightly gray area concerns conductors that gain a charge due to their presence in an electric (or magnetic) field. A person may experience a discharge on touching this conductor, but because this discharge current is a consequence of the conductor being within the field, the ELF standards are designed to limit the field to prevent the discharge being harmful.

18.3 Guidelines/Standards: History

Historically, before 1980, it was generally agreed that there was no need for electric field (*E*) or magnetic flux density (*B*) restrictions for frequencies below a few kilohertz. The lower limit of RF standards had been set by the American National Standards Institute (ANSI) at 10 MHz in 1966 and then lowered to 300 kHz in 1982. The US Environmental Protection Agency then produced a number of protection options down to 10 kHz in 1986. Startle phenomena from touching grounded conductors had been recognized as an ELF hazard long before then (Deno, 1975) (Dalziel, 1973). This gave rise to recommendations to limit the amount of current flowing in the body to prevent startle phenomena from happening in high electric field situations. The International Radiation Protection Association (IRPA) saw a need to issue guideline limits for fields at 50/60 Hz in 1990. The range was extended to provide continuous coverage from 0 Hz to 300 GHz in 1998 (by a specialist group within IRPA, which was by this time known as ICNIRP) (ICNIRP, 1998). Previous to this, expert groups under the auspices of WHO/ILO (the International Labour Office) reviewed the science during the mid-1980s, producing Environmental Health Criteria (EHC) monographs on ELF Fields (UNEP/WHO/IRPA, 1984) and magnetic fields (UNEP/WHO/IRPA, 1987).

In the United States, in 1991, the American Conference of Government Industrial Hygienists (ACGIH) issued a threshold limit value (TLV) of $60/f$ (mT) for magnetic (*B*) fields below 30 kHz (f being the frequency in Hz) and

60 mT below 1 Hz. For electric (*E*) fields, the limit was 25 kV/m from 0 to 100 Hz, then $2.5 \times 10^3/f$ kV/m up to 4 kHz, and 0.625 kV/m up to 30 kHz. The values at 60 Hz were therefore 1 mT and 25 kV/m for magnetic fields and electric fields, respectively. Also at this time, there was a concern that the high fields associated with power lines could affect the operation of cardiac pacemakers. However, since this is primarily an effect of fields on the operation of electronic circuitry, rather than the human body, the pacemaker designs were modified to give some immunity, but wearers were instructed to avoid areas where high fields were likely.

The IEEE standard-setting process (with links to ANSI) was broadened to encompass international input. This new body, the International Committee on Electromagnetic Safety (ICES), issued an RF standard in 1999 (C95.1™-1999) (replacing one issued in 1991) with a lower frequency limit of 3 kHz. In 2002, the same body issued C95.6™-2002, covering the range 0–3 kHz (IEEE, 2002).

There is plainly a divergence of view on what international standards (ICNIRP or IEEE) should prevail.

18.4 Basic Restrictions and Reference (or Maximum Permitted Exposure) Levels

Before discussing the differences in approaches between ICNIRP and IEEE (see Table 18.1), the major aspects they have in common will be discussed. Firstly, they both distinguish between members of the public and those who perform work in which EMF exposure is likely. The two bodies have divergent views on how the latter category is to be managed. ICNIRP defines "occupational exposure" as "all exposure to EMF experienced by individuals as a result of performing their regular or assigned job activities". ICES/IEEE restricts this category to those members performing work that involves a specific component of electrical technology and with which the worker would have some knowledge of potential hazards. It also designates the *environment* as being a separate category rather than the individual, designating it a "controlled environment", with methods of restricting access. Secondly, they both distinguish between a restriction that is related to the susceptibility of biological tissue for adverse effects (the BR) and external field-related parameters that are amenable to measurement using meters that can be positioned where the body would normally be. These relatively easy-to-make measurements serve to assess whether the BRs are likely to be exceeded. In ICNIRP, these are known as RLs and in IEEE MPE levels. In both approaches, the RLs or MPE values can be exceeded if it can be demonstrated that the BRs will not be exceeded. It should also be emphasized that the RLs are conservatively derived so that meeting them has some degree of certainty that the BRs will be complied with.

18.5 Basic Restrictions

18.5.1 The ICNIRP Approach (1990/1998)(Now Superseded)

The BRs were on current density in tissue averaged over a 1 cm^2 perpendicular to the direction of the current flow. It was recognized that above 100 $\mathrm{mA/m}^2$ thresholds for acute effects such as nervous system excitation would be exceeded. Following the rationale elsewhere in the frequency range, a factor of 10 was introduced to derive a limit for occupational exposure. The frequency range 4–1000 Hz, the range for which nervous tissue is most susceptible to excitation, was selected for this limit (10 $\mathrm{mA/m}^2$) to apply. Above and below this range, the restriction was allowed to rise. In 2010, this approach was revised and these revisions are described later.

18.5.2 The IEEE Approach (2002)

In the IEEE Standard, the BRs are on induced electric field (rather than current density), specifying the distance over which this is to be evaluated as 5 mm in any direction within particular tissue types (brain, heart, extremities, and other tissue). Within each tissue, two parameters specify the restriction: the transition frequency f_e (which is related to the inverse of the characteristic time constant or chronaxie of the tissue) and the minimum field strength E_0 or rheobase. These terms were described in Chapter 17. IEEE argued that the electric field is the more fundamental quantity compared to current density in determining whether neural cells are excited or not. The two quantities are related as follows:

$$E = J / \sigma \tag{18.1}$$

where E is the electric field (in V/m) at the point of interest within the tissue, J the current density (in $\mathrm{A/m}^2$), and σ the electrical conductivity of the tissue concerned (in S/m). The dependence of BR value (E_{int}) with frequency is shown in Figure 18.1a for occupational/controlled environment groups. The inflection at 20 Hz reflects the f_e value for synaptic effects in the brain: above this frequency $E_{\mathrm{int}} = E_0 f/f_e$, so the value increases until the possibility of peripheral nerve stimulation becomes more important. There is a brief flat section above 2.4 kHz where this occurs (there is a region above 3.35 kHz where the limits rise as $E_0 f/f_e$, where f_e has this value and E_0 is 2.1 V/m, but since the standard is restricted to the range 0–3 kHz, this is not shown in Figure 18.1).

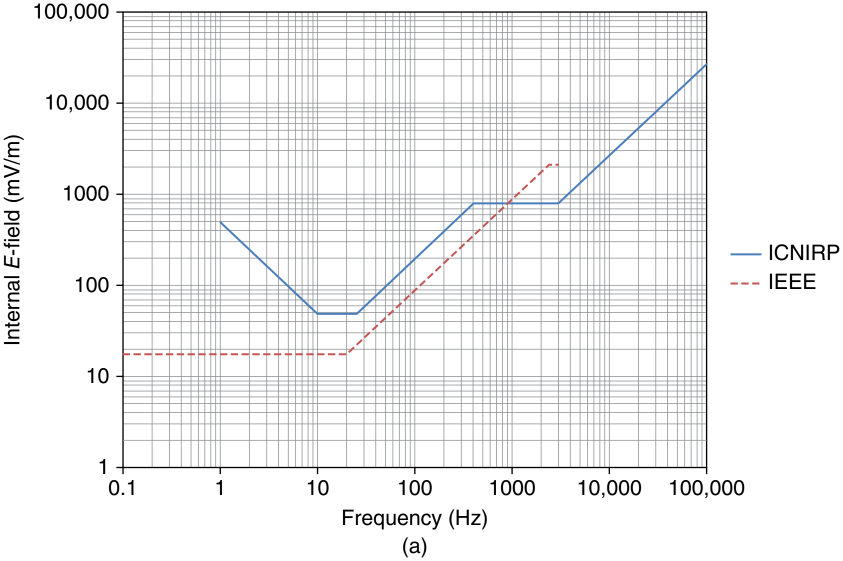
The basis of the E_0 values for the various tissues is reported experimental and modeling values for excitation thresholds. Of particular interest (because it determines MPE levels at 50/60 Hz) is the value for brain, which effectively refers to effects on the synaptic connections of the photoreceptor cells in the retina. This is given as 5.89 and 17.7 mV/m for the general public and the "controlled environment" (or occupational exposure) situation. These values (which are different by a margin of 3) are in turn related to the E_{int} of 75 mV/m (peak) estimated as being sufficient to cause the phenomenon of magnetophosphenes (when delivered as a step). This figure was estimated from data given in a series of papers from a Swedish laboratory. This peak value is divided by a factor of √2 to give an RMS value of 53 mV/m. This is then multiplied by a "probability multiplier" (F_{p}) of 1/3 to derive the "controlled environment" value of 17.7 mV/m. The F_{p} value is justified as follows: since the 75 mV/m was a mean or median value for a group of volunteer subjects, and the thresholds were log-normally distributed, only 1% of thresholds (and therefore people) would be below 1/3 of the median value (the median value being that for which 50% of people would have thresholds below it). Whether 1% is low enough is a matter of some discussion.

The corresponding BRs for the General Public are shown in Figure 18.1b. Note that for part of the range (above 2250 Hz), the levels are identical to the controlled environment values, but in general, they are three times less. As mentioned, above around 800 Hz, peripheral nervous system (PNS) stimulation becomes a greater concern than phosphene generation, Cardiac excitation is always around an order of magnitude less sensitive than either phosphene generation or peripheral nerve stimulation.

18.5.3 The ICNIRP Approach (2010)

As mentioned above, the ICNIRP committees revised their guidelines in 2010 to follow the IEEE approach just outlined with BRs on tissue electric field E_{int} rather than current density. The rationale for this change was that the newer electrophysiological data had indicated that the better indicator of whether or not a nerve would "fire" was the local electric field rather than a current density averaged over an area of a square centimeter. There still does need to be some spatial averaging in considering a value of E_{int}, and the recommendation is to perform a vector averaging (that is, taking field direction as well as magnitude into consideration) over a volume of $2 \times 2 \times 2\,\text{mm}^3$ of contiguous tissue. There is then a tissue average performed with the 99th percentile value taken as the value to compare against the BR. This is recognizing that E_{int} is usually estimated via mathematical modeling rather than direct measurement and the modeling algorithms are prone to giving occasional spuriously large values.

The shape of the BRs for occupational exposure and general public exposure is shown in Figure 1a,b, respectively. The "U"-shaped characteristic between 1 Hz and a few hundred hertz reflects the experimental work on electro- and magnetophosphene generation in human volunteers, in which the most sensitive frequency was 20 Hz, but the threshold was higher on both sides of this frequency (Lovsund, Oberg, Nilsson, 1980). As mentioned previously, the magneto- and electrophosphene 20 Hz thresholds are both thought to have the value of approximately 50 mV/m within retinal tissue, so this is set as the occupational limit. There is thus no safety margin because the effect is thought to



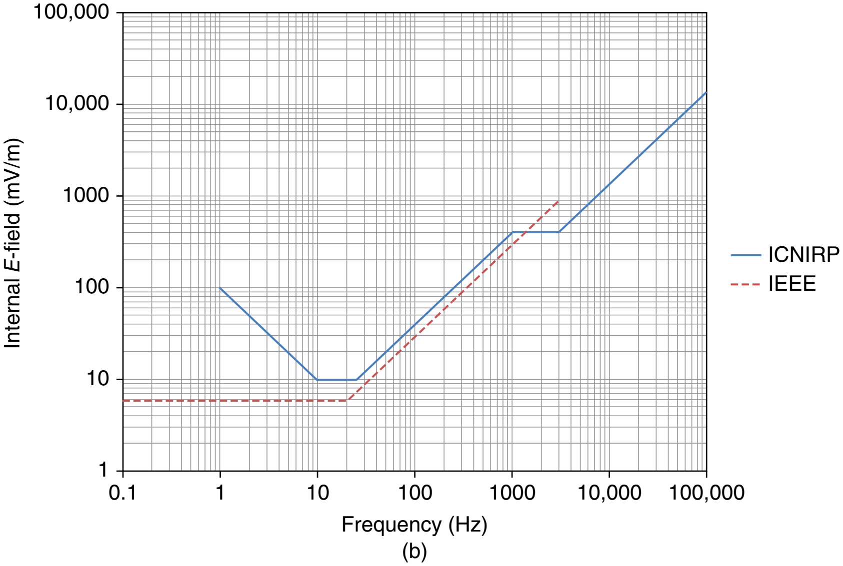


Figure 18.1 (a) Basic restrictions on internal electric fields (E_{int}) for occupational exposed persons (ICNIRP) or controlled environments (IEEE). (b) Basic restrictions for the general public. Where exposure does not involve the CNS, the PNS restrictions apply throughout (which means a "flat" restriction of 2.1 or 0.9 V/m for IEEE and 0.8 or 0.4 V/m for ICNIRP down to 0.1 and 1 Hz).

be annoying rather than indicative of harm. Nevertheless, it is taken as a surrogate for central nervous system (CNS) effects in general. At higher frequencies, the possibility of stimulating nerves in the PNS is more likely, so in a similar manner to IEEE, there is a flat portion (which can be extended down to 1 Hz if the CNS is not exposed, but with a rising portion above 3 kHz – this frequency is slightly different from IEEE). Note that the range in the title of the ICNIRP ELF guideline extends to 100 kHz, but in fact, the BR table provided in the guideline extends further, to 10 MHz, but with a rider that heating effects need to be considered above 100 kHz.

The general public BRs are five times less than the occupational for CNS effects, but only two times less for PNS effects, hence the different ICNIRP inflection points for Figure 18.1a,b.

18.6 MPEs/RLs for Electric (*E*) Fields

18.6.1 *E*-Field MPEs – The IEEE Approach

The MPEs for *E*-field exposure are given in Tables 18.2 and 18.3. At frequencies below a few hundred hertz, the limits are designed to avoid painful discharges from touching earthed objects when isolated from ground or touching isolated objects (charged by the field) while barefoot or otherwise connected to ground. An example of the first situation is a person on a wooden ladder close to a high-tension power line and then touching a metal drain pipe and of the second, a person touching a large vehicle parked or unearthed fencing under a high-tension power line. The MPEs are thus not derived from the BRs but from practical considerations of how to limit *E*-field values to reduce the chance of these annoyances. It is noted that even at the general public limit of 5 kV/m, 7% of adults will experience painful discharges in the abovementioned scenarios.

Table 18.3 Power frequency (50 and 60 Hz) limits compared.

	Occupational			**General public**		
	BR (mV/m)	**RL (mT)**	***E*-Field RL (kV/m)**	**BR (mV/m)**	***B*-Field RL (mT)**	***E*-Field RL (kV/m)**
50 Hz						
IEEE	44	2.7	20	14.3	0.9	5 (10)
ICNIRP	100	1.0	10	20	0.2	5
60 Hz						
IEEE	53	2.7	20	18	0.9	5 (10)
ICNIRP	120	1.0	8	24	0.2	5

The controlled environment MPE is 20 kV/m (where protective measures are assumed) and within power line rights-of-way the general public limit is relaxed to 10 kV/m because it is assumed that the risks of the abovementioned scenarios are appropriately managed.

Above 272 Hz (controlled environment) and 368 Hz (general public), the limits are determined by restrictions on the amount of touch current permitted, which is 1.5 and 0.5 mA for the two situations, respectively. The Deno formula (Deno, 1975) links the external electric field E with the current I_c at frequency f, which can flow to earth in a touch contact (with the foot) for a person of height h.

$$I_c = 9 \times 10^{-11} h^2 fE \tag{18.2}$$

For a person 1.75 m tall, substituting the I_c values above gives E/f of $5.44 \times 10^6/f$ and $1.84 \times 10^6/f$, respectively.

The standard does not extend beyond 3 kHz but there is an implied flattening of the limit value (in a similar manner to ICNIRP, which will now be discussed).

18.6.2 *E*-Field RLs – The ICNIRP Approach

The low-frequency limits are identical to IEEE, with a similar rationale of avoiding painful discharges. The rationale for the downward sloping part above 25 Hz (occupational) and 50 Hz (general public) is not given in detail (beyond a need to prevent shocks and burns), but there is over a 10-fold margin of conservatism of ICNIRP compared with IEEE. Modeling studies have shown that at 50 Hz the induced E_{int} value is 3.42 mV/m/kV/m in spinal cord, which translates to 29.2 kV/m for the occupational BR of 100 mV/m (and 5.84 kV/m for the general public). However, as with IEEE, the need to prevent the indirect effects of microshock is more stringent than these direct effects on PNS stimulation. At 50 Hz, there is thus a limit of 10 kV/m for occupational exposure and there is no relaxation for the general public in power line easements (rights-of-way). At 60 Hz, the limits are 8.33 and 4.17 kV/m, respectively. The margin of 2 between occupational and general public categories is maintained from 50 Hz up to the end of the range (which is actually 10 MHz, even though the guideline title gives the range as up to 0.1 MHz).

18.7 MPEs/RLs for Magnetic (*B*) Fields

18.7.1 *B*-Field MPEs – The IEEE Approach

IEEE employs simple oblate spheroid (ellipsoid) models of the head, body, and leg to compute the maximum induced E-field E_{int} for a given time rate of change of magnetic field dB/dt (for a sphere, these are very simply related as $E_{\text{int}} = -1/2 \cdot dB/dt \cdot r$). For a sinusoidal field, $dB/dt = 2\pi f B_{\text{RMS}}$, thus for example, treating the head as a sphere of radius 10 cm (0.1 m), dB/dt would need to be limited to 8.86 T/s for the controlled environment BR of $E_{\text{int}} = 44.3$ mV/m at 50 Hz. Dividing by $2\pi f$ gives B_{RMS} to be 2.7 mT, which is the MPE for these conditions. MPE values at other frequencies are derived by consideration of the E_{int} value at a particular frequency (see Figure 18.1) combined with the relevant geometry of the part of the body concerned (e.g., at kilohertz frequencies, the torso rather than the head becomes the part of the body most at risk: the actual transition frequency is the inflection point in Figure 18.2). Figure 18.3 shows how the MPEs vary with frequency, but see the caption notes and Table 18.2 for further details. Expressed as a fraction, the 50 Hz power frequency MPE is 61 μT/mV/m.

18.7.2 *B*-Field RLs – The ICNIRP Approach

Being more recent, ICNIRP has taken advantage of improved induction models for the body, based on realistic representations of individual organs within the body, to a resolution of around $2 \times 2 \times 2\,\text{mm}^3$. The electric characteristics of over 30 different tissue types are incorporated, allowing detailed estimation of where the maximum E_{int} values are likely to occur for a given alternating external *B*-field. Following this approach, the 50 Hz RL is 10 μT/mV/m, thus

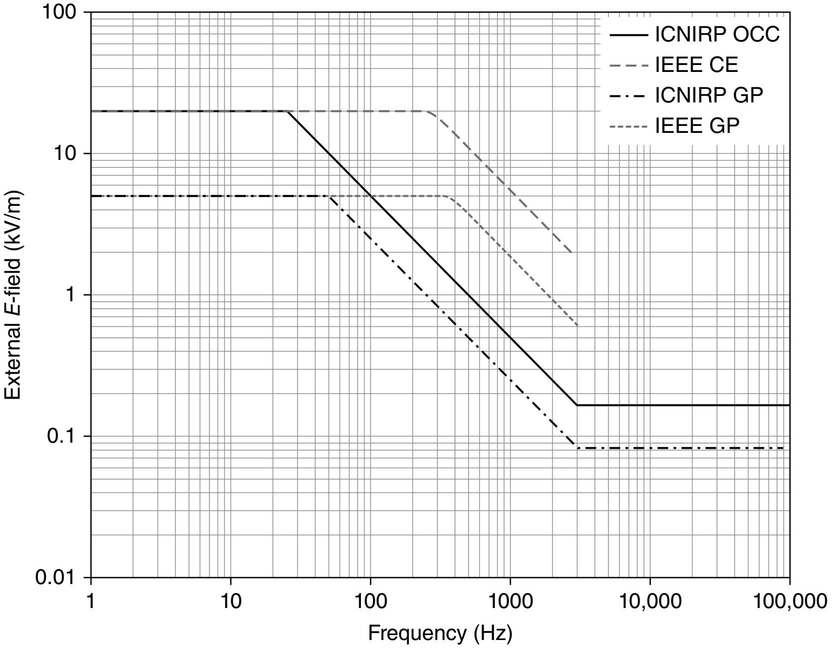


Figure 18.2 Reference levels/maximum permitted exposures for occupational groups (OCC)/controlled environment (CE) or general public (GP) for external electric fields, comparing ICNIRP with IEEE.

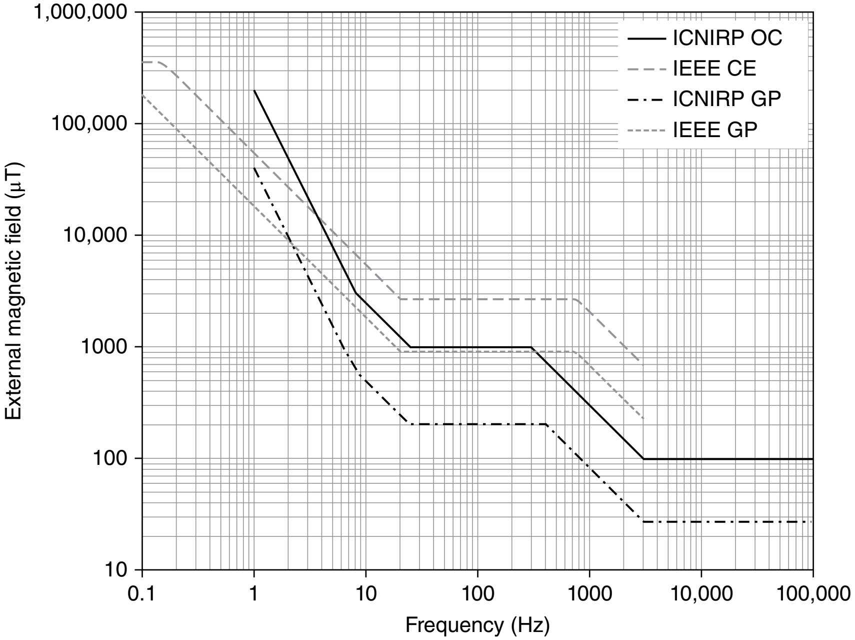


Figure 18.3 Reference levels/maximum permitted exposures for occupational groups (OCC)/controlled environment (CE) or general public (GP) for external magnetic fields, comparing ICNIRP with IEEE.

being six times as conservative. However, the IEEE BRs are significantly higher; thus, the final margin is less (see Table 18.2). Actually, for ICNIRP, there is a reduction factor of 3 to allow for dosimetric uncertainty; thus, the actual estimate of the external field to produce a field of 1 mV/m *anywhere* in the CNS is 30.3 μT (or 33 mV/m/mT). Thus, the introduction of more advanced modeling has led to an understanding of the need to be more conservative.

For PNS stimulation at 50 Hz, modeling has yielded a value of 16.7 μT as needed to produce a field of 1 mV/m anywhere in the PNS (or 60 mV/m/mT). However, because the effects threshold at this frequency are eight times the CNS threshold, the PNS RL is correspondingly much higher. As shown in Table 18.2, the 3-kHz conversion factor is 0.125 and 0.068 μT/mV/m for occupational and general public groups, respectively. This compares with 0.32 μT/mV/m for IEEE, again reflecting the conservatism of advanced modeling.

Power frequency MPEs/RLs are summarized in Table 18.3.

18.8 Extremities

IEEE has relaxed limits for exposure to arms and legs. In the case of IEEE, there is a special relaxation of magnetic field MPEs arms and legs given by

$B = 3.79 \times 10^6/f$ μT, for both general public and controlled environment categories. At 50 and 60 Hz, this amounts to 76 and 63 mT, respectively. This is derived following the methodology outlined above where the leg is treated as an ellipsoid and the external field to induce the PNS BR is then calculated. In the case of general public exposure, this represents an over 70-fold relaxation. This results from consideration of the arms and legs as long, narrow ellipsoids in relation to the PNS BR. In the case of ICNIRP, there is no special relaxation, except for noting that CNS BRs would apply.

18.9 Contact Currents

As mentioned above, current can flow through the body because of contact with charge build-up on objects due to environmental fields. Both IEEE and ICNIRP provide limits on the amount of current that can flow under these situations (IEEE is flat between 0 and 3 kHz, whereas ICNIRP rises above 2.5 kHz before becoming flat again at 100 kHz). These limits are designed to prevent painful shocks rather than perception. IEEE allows some relaxation in limit if the area of contact is large.

18.10 Time and Space Averaging

Since the standards are designed to prevent adverse acute effects, in general, the only time averaging is over one cycle, to give an RMS value (instantaneous value). However, IEEE stipulates that for MPEs in general the averaging is 0.2 s for frequencies above 25 Hz and for 5 cycles below that. Spatial averaging of BRs is as follows: for ICNIRP, over a $2 \times 2 \times 2\,\text{mm}^3$ volume within a single tissue (if possible skin and retina are exceptions to this rule) and for IEEE, the values refer to specific location, without any reference to averaging volumes. For MPEs/RLs, the distance from the source becomes important: for ICNIRP, if the distance exceeds 20 cm, the averaging is across the body or part of body exposed. IEEE stipulates that where the B-field exposure varies across the body, the maximum value should be used to verify compliance.

18.11 Multiple Frequencies

Many sources of ELF fields have complex (nonsinusoidal) waveforms. The Fourier method implies that these complex waveforms can be broken down into a number of components, each sinusoidal and each with its own frequency (and phase relationship with the main or fundamental frequency). The amplitude of each of these components can then be expressed as a fraction of the limit at that particular frequency. These fractions are then summed. If this sum is greater than unity, then the BR or RL is exceeded. Where there is exposure to both E- and B-fields, there is a divergence: IEEE considers that these should be tested against RLs separately, but ICNIRP argues that since they both induce E_{int}, they should be considered additively.

18.12 The Place of Epidemiological Results in ELF Standard-Setting

At the time of writing (2015), the epidemiological data concerning, in particular, the association between exposures in the upper percentiles of estimated time-weighted average (TWA) power frequency magnetic field and childhood leukemia risk (discussed in Chapter 20) does not form the basis for setting limit values. However, the more recent advice documents (see, e.g., https://www.gov.uk/government/collections/electromagnetic-fields) acknowledge this association, and ways for reducing personal exposure are suggested.

The possible leukemia link is also acknowledged in ICNIRP (2010), p 824, but then go on to state:

> It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low-frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure.

Similarly, the IEEE Subcommittee takes the view that (IEEE, 2002, p 1):

> The Subcommittee is aware of reported epidemiological associations between long-term exposures to electric and magnetic fields and disease, including childhood leukemia …
>
> The interpretations of these associations is unclear, especially since exposure to magnetic fields does not appear to initiate or advance the development of leukemia … in animals exposed over much of their lifetime.

There is an understandable view that since the main ELF health concern is with childhood leukemia (which is a major and serious disease) and not acute CNS effects (which might mainly cause annoyance and are not directly linked to any form of major disease), the limit values should be related to the former and not the latter. In summary, the arguments against this view are threefold. First, the link between ELF magnetic fields and childhood leukemia has not been demonstrated as being a causative one, so there is no clear evidence that adopting lower limit values would attenuate the excess risk. Second, the epidemiological data do not give thresholds above which excess risk becomes apparent: the cut-points used in epidemiological surveys are chosen with statistical power considerations uppermost. Third, although CNS effects that form the basis of standards are fairly innocuous, they do (in the case of phosphenes) represent inadequate stimuli, whose long-term consequences are difficult to assess and could be severe.

There is speculation that because it may eventually emerge that some aspect of ELF fields has a direct influence on the incidence or progression on childhood leukemia and so some preemptive action needs to be incorporated into standards now. However, given the extent of experimentation on large populations of laboratory animals, largely showing no effect, and the absence of a convincing interaction mechanism for low-level, chronic exposure (discussed in Chapter 21), the possibility of this seems rather low. However, most of these experimental approaches have utilized constant (RMS) values of field or on fields of a constant value intermittently switched on and off. It may yet emerge that the basis of an influence on cancer risk is some rather subtle aspect of ELF field, perhaps in conjunction with other environmental factors. If this were to be established, avoiding these precise conditions would then form the basis of protection. Until then, it would appear that standards bodies really have no alternative but to base restrictions on known hazards (which occur at the instant of overexposure, or soon after) rather than to speculate on whether adding further reductions in limits would protect against childhood leukemia risk in the long term.

18.13 ICNIRP Versus IEEE

Many countries have adopted guidelines or advice based on ICNIRP. As mentioned, the European Union introduced a directive in 2013 based on ICNIRP (2010) and many other countries have followed a similar pattern. Although the IEEE limits have not been formally adopted by any jurisdiction, the rationale behind them has been very influential in formulating guidelines within North America, including Canada.

Because of shortness of space, it is not possible to cover all of the details of both of these documents: readers are encouraged to download them for more specific information. The purpose of this chapter has been to highlight the main features of providing limits-based guidance for ELF exposure.

Tutorial Problems

1 Using an electric field meter, values of up to 9.7 kV/m were obtained immediately below power transmission lines and within an easement (right-of-way).

What advice should be given to members of the public regarding access to this easement?

2 In the cab of an electric locomotive powered by a 16.7-Hz supply, a magnetic field value of 1.3 mT was measured with the locomotive in motion and 0.3 mT with the locomotive stationary. It is intended that the locomotive cab is to be opened to the public for viewing on a railway promotion day. What would be your advice to the organizers of this function?

3 In a smelting plant, magnetic field readings were obtained in the control room. There were a number of harmonic components at different frequencies as follows:

50 Hz: 0.5 mT
700 Hz: 0.2 mT
1400 Hz: 0.2 mT

Would workers in the control room comply with ICNIRP guidelines?

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19

Instrumentation and Measurement of ELF Electric and Magnetic Fields

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19.1 Introduction

The fundamental limits on exposure to extremely low-frequency (ELF) fields in standards, as explained in Chapter 18, are termed "basic restrictions". The physical quantities used to specify the basic restrictions are tissue-induced electric fields $\left(E_{\text{int}}\right)$. Measurement of *in situ* E_{int} is impractical for other than special compliance cases, testing, or scientific research.

With known external field characteristics and tissue electrical properties, the induced tissue electric field E_{int} can be calculated using induction models representing a human body or its parts. Various models, such as simplified loop/ellipsoid representations or more detailed anatomically realistic computer models, have been used. In recent years, a number of modeling studies for various exposure conditions using millimeter-voxel models have been published by a number of authors (Gandhi and Chen, 1992; Gandhi and Kang, 2001, Gandhi et al., 2001; Cech, Leitgeb, and Pediaditis, 2008; Dimbylow, 1998, 2000; Dawson, Caputa, and Stuchly. 1997a,b; Dawson, De Moerloose, and Stuchly, 1997; Dawson and Stuchly, 1998; Dawson, Caputa, and Stuchly, 1999a,b; Dawson et al., 2001; Dawson, Kavet, and Stuchly, 2004; Stuchly, 1996; Stuchly and Gandhi, 2000; Hirata et al., 2010) and standards institutions such as the European Committee for Electrotechnical Standardization (CENELEC), the Institute of Electrical and Electronics Engineers (IEEE), and the International Electrotechnical Commission (IEC) based principally on the work of Dimbylow and Dawson just mentioned. The work in this area is progressing, and it is anticipated that these induction modeling tools will become available to average users for compliance evaluation purposes.

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Edited by Andrew W. Wood and Ken Karipidis.

In short, in such a computational model, a human body including major organs is represented by millions of millimeter-size voxels forming approximated shapes with their respective tissue conductivities. Numerical calculation methods (e.g., impedance method, finite difference, finite difference-time domain, and scalar potential finite difference) of local induced currents or voltages are performed and then different types of averaging methods are applied for organs or larger tissue volumes.

To facilitate a more practical compliance procedure, equivalent limits based on environmental fields termed as “reference levels” (RLs)or “maximum permitted exposures” (MPEs) are also given in standards (for convenience, from here on, both will be referred to as RLs) (IEEE, 2007; ICNIRP, 2010). These have been derived on the basis of maximum coupling and uniform field conditions, such that that compliance with RLs should ensure compliance with the basic restrictions. The physical quantities used to specify the RLs are the environmental unperturbed electric field and magnetic field (or magnetic flux density: MFD). The latter two terms are often used interchangeably, but MFD is more specific.

In dealing with ambient electric and magnetic fields in a typical residential setting, measurement can be done with a simple handheld meter. However, for complex field sources with varying spatial, temporal and spectral characteristics, persons wanting to perform field measurements or exposure assessments should have a good knowledge of the instrumentation to be used and the techniques described in various Standards including those from IEEE and IEC – some of which are listed in the references section of this chapter.

For the ELF range (up to 3 kHz), due to the quasi-static nature of the environmental electric and magnetic fields, they can be measured or assessed separately (at higher frequencies, the fields are linked: see Chapter 14). In addition, assessment of a potential hazard associated with electric discharges and shocks may require measurement/assessment of induced body currents and contact currents.

19.2 ELF Instrumentation – General

In cases where environmental electric and magnetic fields are spatially, temporally and spectrally uniform, measurements can be carried out with basic instrumentation. However, care must be taken when assessing compliance when dealing with sources with atypical or nonuniform characteristics such as multiple-frequency, nonsinusoidal, or high-harmonic contents.

For measurements of environmental electric and magnetic fields, it is unlikely that one instrument will cover the whole ELF range. Separate instrumentation is required for static/DC electric and magnetic fields. In addition, considerations need be given to limitations of probes and sensors and instrument errors.

This chapter provides a brief summary of the physical and electrical characteristics of ELF electric and magnetic field measurement instruments. A list of these instruments, mainly in the two groups of handheld/portable meters and recorders/personal exposure meters, has been given in some publications (Leeper, 2001; WHO, 2007).

The nature of the instruments varies from a simple sensor (e.g., a metallic plate for electric field or a wire loop in case of magnetic field) for spot measurements, to a microcomputer-based device for continuous recording of three-dimensional magnetic field levels at a location or on a person, or for surveying/mapping of field levels in an area.

A variety of different filtering arrangements and different methods of signal processing, conversions, storage, and display are used in the instruments. It is important that their specifications are evaluated for a particular measurement application. Depending on the design, the instrumentation can generally be functionally classified into groups of field survey meters, data recorders, and personal exposure meters.

19.2.1 Field Survey Meters

These meters are designed basically as handheld instruments for point-in-time measurements suitable for a simple survey or spot check of field levels. The basic features include an on/off switch, a range selector, and a display to show the reading. They are generally low cost and easier to operate, compared to the more sophisticated recorders and personal exposure meters. Due to the directional nature of fields, most magnetic field meters would have three orthogonal sensors eliminating the need for searching the maximum field direction. On the other hand due to market demand for low-priced units, available electric field meters are generally equipped with a single sensor; hence, searching for maximum or recording of position of sensor would be required for the measurement process.

19.2.2 Data Recorders

These instruments are designed as computer-based data acquisition systems that can be used for recording the electric and/or magnetic fields over time or distance, for example, monitoring specific locations such as a room, an area in a work place, or along a path near a power line or an electrical installation. The instruments can be operated unattended for a long period of data collection for capturing of temporal variations.

19.2.3 Personal Exposure Recorders

These instruments are designed as small recorders for monitoring of human exposure to environmental electric and/or magnetic fields. The instrument's size and weight are critical as it is continually worn or carried by an adult or a child during the measurement period. Recently, developed microcomputer-based instruments with miniaturized sensors and electronic circuitry have reduced considerably the meter's weight and size.

19.3 Electric Field Instrumentation

Unlike the environmental magnetic fields that show large temporal variations, the environmental electric fields are more temporally stable due to the nature of fixed-voltage electric systems. In addition, surrounding physical objects including metallic and nonmetallic structures, fencing, walls, trees, and vegetation perturb the electric field distribution and can introduce significant reduction/shielding effects to the environmental electric fields in living and working areas.

In standards, RLs of electric fields are given in terms of nonperturbed field in the air (e.g., at 1 m above ground surface) and "free-body" type electric field meters can be used to measure these fields.

In areas near an electric field source, objects/structures at different voltage levels including earthed-objects/structures and the instrumentation casing will influence the charge distribution hence creating distortion of the measured field. Since electric field meters are calibrated for unperturbed fields, care must be taken in compliance verification where electric fields are distorted due to surrounding objects or structures. Meter operators can also introduce additional distortion. Some measurement procedures recommend a meter-operator distance of 2 m or more. Other influencing factors on measurement accuracy include the following:

- Conductivity of the meter's handle
- Position of the electrical axis of the sensor along the direction of the measured field
- Harmonic contents of the measured field
- Ambient temperature and humidity.

Except for a few ELF meters that can be used for both electric and magnetic field measurements, most of the commercially available meters are principally designed for magnetic field measurements (Leeper, 2001). Some of the recorders/personal exposure meters have a provision to receive a signal from an external electric field sensor for electric field measurement. Common forms of electric field sensors that can be used are the free-body spherical, parallel-plate sensors for area survey, or a parallel-plate vest for personal exposure measurements (Deno and Silva, 1984).

The basic principle of operation of an electric field meter is based on the induced charge on the conductive body of the sensing element by the electric field. The corresponding induced current is detected and processed to give an estimated value of the electric field strength.

The charge, Q, induced on each half-sphere is $3\pi a^2\varepsilon_0 E$, where a is the sphere radius and E is the external field. If the field is varying sinusoidally, then $E = E_0\sin(\omega t)$ where ω is the angular frequency $2\pi f$ (f in Hz). The current passing from one half-sphere to the other is given by dQ/dt or $3\pi a^2\varepsilon_0\omega E_0\cos(\omega t)$. The magnitude of the current therefore gives the magnitude of the electric field (with due recognition of dependency on frequency).

Measurement of DC electric fields will require a different type of meter, which will be briefly discussed in the section "DC Electric Field".

19.3.1 "Free-Body" Sensor Type of Meter

The field sensor is basically a conductive enclosure split into two halves by a small air gap as illustrated in Figure 19.1. The associated hardware of the meter is often housed in the sensor itself. This design, sometimes referred to as self-contained meter, is a conveniently portable design and does not require a ground reference. Thus, measurements can be made anywhere

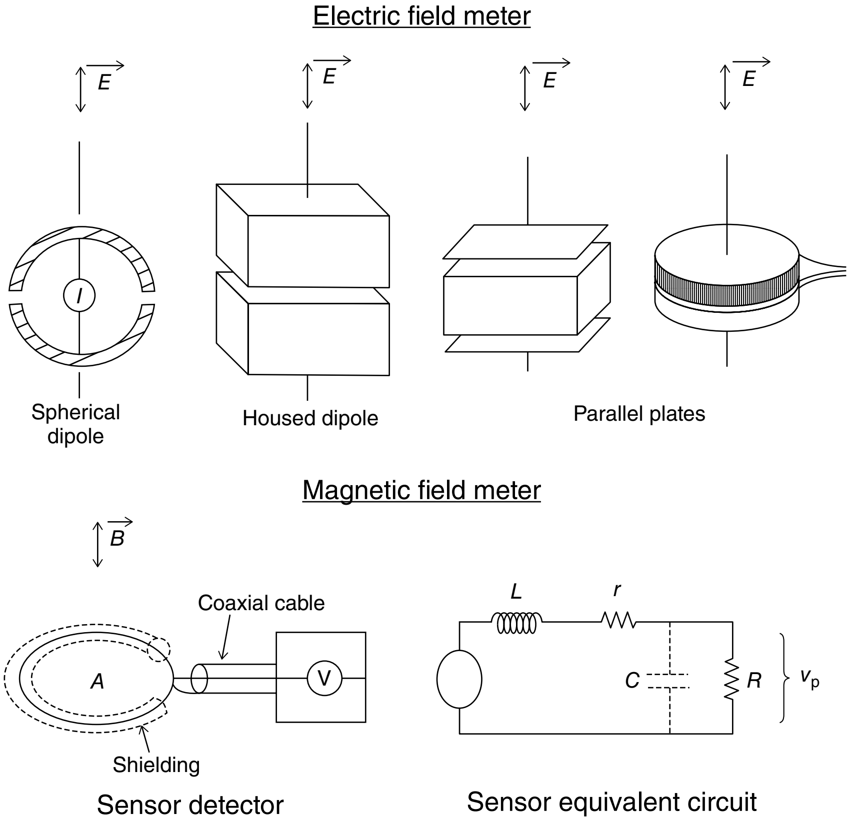


Figure 19.1 Main types of power frequency electric and magnetic field instrumentation.

above the ground plane. These features make it more suitable as a survey type instrument.

Commercial electric field meters are designed and calibrated to measure unperturbed fields generally for measurement applications associated with high-voltage installations. Consequently, large variations in measurement results exist when these meters are used in the environments where electric fields are highly distorted due to complex geometry of field sources and adjacent objects and structures.

19.3.2 Ground Reference Instrument

This design involves the measurement of current to ground from a single-plate sensor when the sensor is placed in an oscillating electric field. An adjacent conducting surface for reference is required in this type of meter and its lack of portability has made it less common.

19.3.3 Equivalent Current Meter

In applications where the electric field is nonuniform over an area equivalent to a human body and the measurement interest is on contact currents, the human body currents can be measured to estimate the average electric field strength.

In an electric field associated with high-voltage transmission lines, for a standing hand-on-side human, a steady-state body current can be estimated using an empirically developed relationship $I = 5.4h^2E(f/60)\mu\text{A}$, where h is the person's height (m), f the frequency (Hz), and E the unperturbed electric field (kV/m) at the location of interest (Deno and Silva, 1984). Under 50/60 Hz HV transmission lines, this body current is amounts to 15–16 μA/kV/m (see Figure 19.2).

19.3.4 DC Electric Field

Several types of sensors are commercially available for measuring DC electric fields. These include the field mill, vibrating plate, and vibrating probe sensors. All are used to measure the field with respect to a reference object (usually electrical ground). The field strengths that are measured by these types of sensors involve the quantification of the AC current between the sensing electrode and the ground, induced by the mechanical vibration of the sensor.

The field mill, graphically shown in Figure 19.3 uses a shutter assembly with a sensing electrode that is periodically exposed and shielded from the electric field by a grounded rotating shutter. The shutter is very close to a ground plane, and in the case of high-voltage DC (HVDC) power lines, the earth itself. The induced charge at any instant, as well as the induced current, is measured between ground and the sensing electrode. The time-varying charge and the current are proportional to the electric field strength (E). Sensitivity of the field

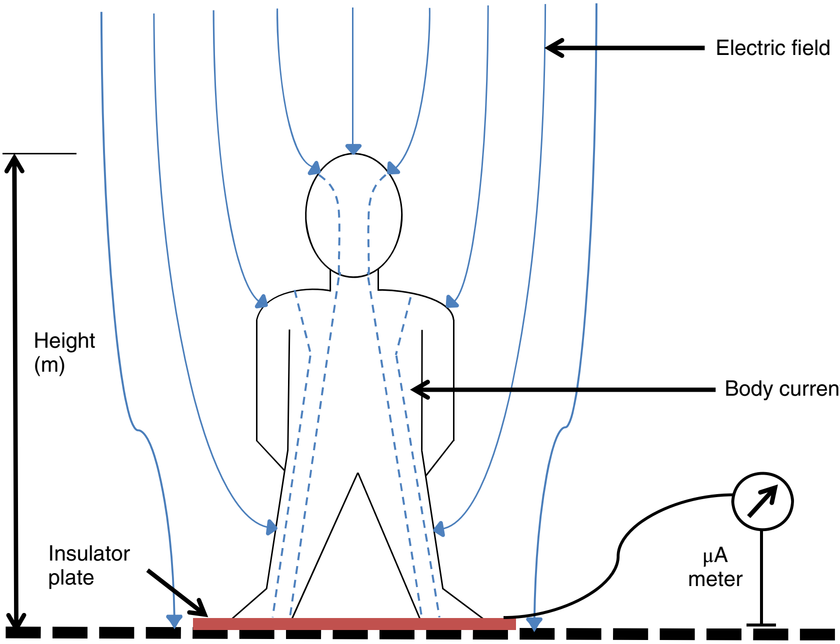


Figure 19.2 Measurement of body current in a person standing in an electric field.

mill sensor is on the order of a few hundred volts per meter with a maximum measurement capability of up to 100 kV/m or more.

The vibrating plate and vibrating probe sensors consist of a faceplate with an aperture and a central vibrating plate or probe. The faceplate is placed in parallel to, and in contact with the ground plane. A mechanical driver moves the vibrating plate or probe in the direction normal to the faceplate. The position

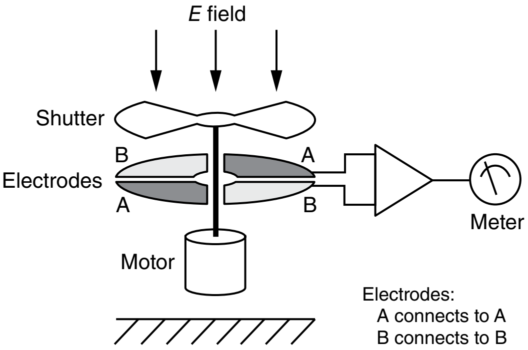


Figure 19.3 Diagrammatic representation of the field mill principle for measuring DC electric fields.

of the vibrating electrode oscillates from one extreme position that is flush with the faceplate aperture to the other extreme position where it is separated a fixed distance below the ground plane (usually, the ground plane is the earth beneath an HVDC line). Sensitivity of the vibrating plate sensor is on the order of a few hundred volts per meter.

19.3.5 Calibration of Electric Field Meters

The calibration of electric field meters requires generation of a known spatially uniform electric field. The volume of the uniform field must be larger than the volume of the meter.

Parallel plates: Considered as the most preferred arrangement, two large parallel conductive plates (1–4 m^2) are used to produce sufficient uniform electric field for calibration purposes. The plate's voltage and their separation distance will determine the electric field strength at the central point between the plates. This arrangement is practically preferable and has been commonly used in practice due to the highly uniform field produced and the relative simplicity in the set up. To a good approximation, the field is given simply as $E = V / d$, where V is the voltage between the plates and d the separation of the two plates (Figure 19.4a).

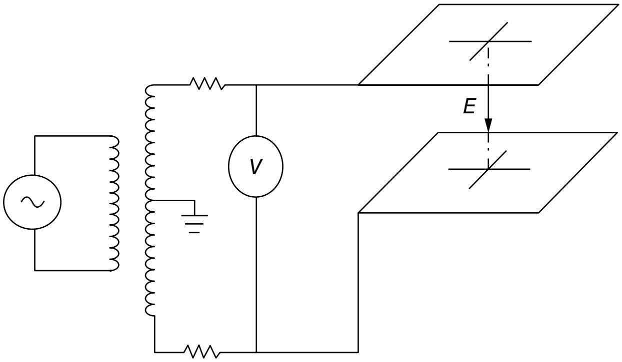
Sphere above a plane: A large sphere (e.g., a sphere in a high-voltage laboratory of 1 m diameter) is placed several meters or more above the ground plane. The electric field strength at a given height from the ground plane is determined by the sphere voltage and diameter and distance from the sphere center to ground plane (Grandolfo, Michaelson, and Rindy, 1983). The electric field directly under the sphere is considered to be uniform for practical purposes. For a 1 m-diameter sphere at $d = 10\text{m}$ above ground energized with $V = 100\text{kV}$, the electric field at 1 m can be approximated as $E = V / d = 100 / 10 = 1\text{kV} / \text{m}$.

In the absence of a laboratory, the electric field under a high-voltage transmission line at a suitable location with known physical parameters can be calculated using validated algorithms with sufficient accuracy and can be used for an alternate electric field source for electric field meter calibration (Figure 19.4b). Alternatively, injection of a known current into the electric field meter's sensor can also be used to calibrate an electric field meter. This procedure assumes known accuracy and characteristics of the sensor used in the meter.

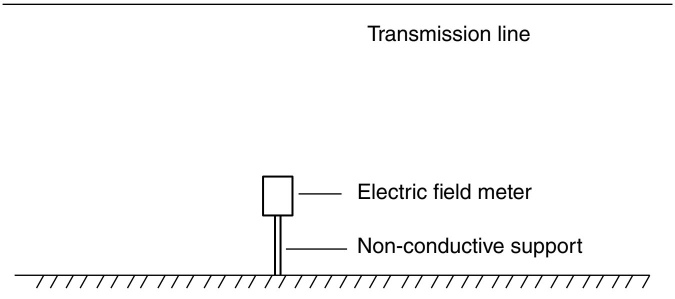
19.4 Magnetic Field Instrumentation

19.4.1 AC Magnetic Field Meters

The fundamental principle of time-varying magnetic field instrumentation is based on Faraday's law predicting that an electromotive force (a voltage) is produced in a loop of wire placed in a changing magnetic field (associated with alternating current sources). The output voltages from the loops (or loops in a



(a) Parallel plates in laboratory



(b) Transmission line known

Figure 19.4 Example of electric field sources for calibration of electric field meters.

single or multiple-axis sensor) are processed and calibrated to indicate the measured MFD. For a three-axis sensor, the resultant field, B_r, given by the root of the sum of the squared output of the three orthogonal coils is usually the quantity displayed.

$$B_\mathrm{r} = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{19.1}$$

19.4.2 AC/DC/Static Magnetic Field Meters

Hall effect magnetic field sensors can measure DC/static magnetic fields as well as low-frequency AC fields. Hall effect instruments are somewhat limited in sensitivity and can generally measure MFD from 100 μT up to 100 T. Some meters measure only DC fields while others are capable of both DC and AC measurements up to approximately 20 kHz. When a conductor, or more practically a semiconductor, is placed in a magnetic field and a current passes in a direction at right angles to the field, a voltage is induced in the orthogonal direction across the conductor that is proportional to the field.

Another type, Fluxgate magnetometer is a sensitive device based on the magnetic saturation effect in ferromagnetic materials. It is constructed of two parallel cores of a ferromagnetic material placed closely together. An alternating current that is induced in a secondary coil wrapped around the cores is measured. The secondary coil signal is proportional to the strength of any external magnetic field that is aligned in the proper orientation with respect to the cores. Fluxgate magnetometers are capable of measuring the strength of the magnetic field from 1.0 nT to 0.01 T with frequencies of 0 Hz to over 100 Hz. These magnetometers show no appreciable instrument drift with time. With fluxgate sensors, it is possible to subtract the constant value of the terrestrial (earth's) static field so that other static fields weaker that the terrestrial field can be measured without this source of error. Fluxgate magnetometers are most commonly used in low-intensity magnetic field measurements and are not as common in everyday applications. Both single and three-axis fluxgate magnetometers are also available for DC/static magnetic field measurements.

19.4.3 Calibration of Magnetic Field Meters

Helmholtz coils (twin-loop configuration) are commonly used to produce uniform magnetic fields along the coil's axial direction in sufficient volume for the calibration of magnetic field meters (Reitz, Milford, and Christy, 1989) (see Figure 19.5).

In this configuration, the coil separation is equal to half of the coil radius and the MFD at the center is:

$$B_z = \left(k\mu_o NI\right)/a \tag{19.2}$$

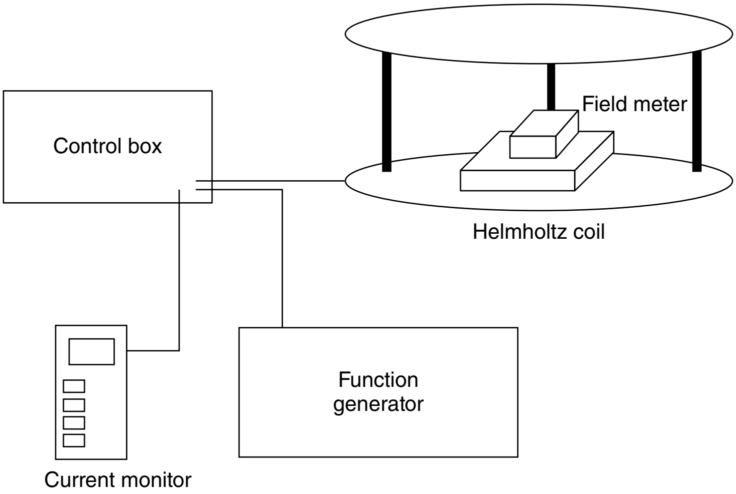


Figure 19.5 Calibration of magnetic field meter using Helmholtz coils.

where

$$k = (4/5)^{1.5} = 0.716$$

μ_o = permeability of air $(4\pi \times 10^{-7})$

N = number of turns in each coil
I = current in coil (A)
a = coil radius (m)

19.5 Measurement and Exposure Assessment Considerations

In certain applications, the selection and use of a magnetic field instrument is simple and straightforward. However, in applications where the measured fields are highly localized and distorted, care must be exercised to reduce measurement errors (Misakian, Silva, and Baishiki, 1991; Olsen et al., 1991). Some of the main relevant measurement issues are discussed as follows:

- *Source harmonic contents and meter frequency response*: Among many commercially available instruments, there are considerable variations in the frequency response of the instruments depending on the design of each meter. This will strongly influence the measurement results in environments where harmonic content of the field source is high. Care must be taken in selecting the appropriate instrument and in interpretation of measurement results. Filters for meters have been developed to weight the harmonic components according to the relative exposure limits at that particular frequency (ICNIRP, 2003; De Santis et al., 2013). The use of such a filter ensures that in making a broadband measurement, the harmonics where the relevant limit values are higher are not over-represented in the overall measurement.
- *Residential field sources*: In the ELF region, the residential ambient fields differ from those fields produced near transmission lines and power system installations in several respects. This requires additional consideration in measurement procedures when conducting residential MFD measurements. Depending on the instrument and operator, it can be difficult to obtain consistent measurement results due to the nonuniformity and harmonic content of fields near appliances.
- The background MFD levels are often much lower than those produced in the vicinity of electrical appliances/equipment and power system installations. Differences can reach a few orders of magnitude; therefore, instrument errors, limitation in operating ranges, and the inherent random variations of the field sources can produce large uncertainty.
- Residential field sources produced by appliances and ground currents can contain large percentages of harmonics.

- MFDs produced by three-phase balanced systems (such as power transmission systems) will produce elliptically polarized fields while single-phase sources (in residential settings) will produce linearly polarized fields.
- Wiring geometry in residences is more complex than straight-conductor powerlines, so field sources are more localized and linearly polarized.
- *Low-field applications*: It was experienced in the past that in a low-field environments such as the background field levels in some residences, there were significant differences in the performance of various instruments (Olsen et al., 1991). Some improved performance in instrument design has been achieved so, careful selection and calibration of the instrument can provide more accurate measurement in the low-field environments. It is often required to calibrate the meter for MFD levels of less than $0.1\,\mu\mathrm{T}$. This requirement poses a practical problem as the ambient field level in the laboratory where the calibration takes place can be higher than this level. If a very low field environment is not available, a small ferromagnetic box larger than the meter sensor can be used to check the performance of the meter for very low or practically zero-field operation.
- *Nonuniform magnetic field*: RLs refer to uniform ambient magnetic fields over the relevant parts of body (e.g., head/torso). In performing spot measurements of nonuniform magnetic fields (e.g., next to cables/equipment) for a compliant comparison with RL limits, considerations should be given to the spatial averaging aspect to avoid overestimation. Future measurement standards or application guides may be required to formally develop appropriate compliant evaluation methodologies. Some literature is available on ongoing work by a number of bodies (IEEE, 2007; IEC, 2007–08; CIGRE, 2007).

In most of these cases, the ambient magnetic fields would not be uniform, but would vary significantly over the human body and the orientation may not be such as to maximize field-human body coupling. It would introduce a further conservative margin by simply comparing a maximum measured field near such a source to the RL value. A more detailed compliant assessment can be pursued. A number of publications on induction models of a human body and several IEC standards on the topic are available for this purpose.

For numerical computational of electric and magnetic fields, there are a wide range of tools available. References to these tools and related discussion on some of these topics are presented in Chapter 31, under the section on mitigation strategies for ELF electric and magnetic fields.

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20

Epidemiological Studies of Low-Intensity ELF Fields and Diseases in Humans

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20.1 Leukemia in Children

Concerns about an association between cancer and fields related to electric power distribution were first raised in 1979 by a study from Denver, Colorado, which found that children who died from cancer in 1953–1973 were more likely to live in a home with a wiring configuration suggestive of high current flow, as compared to healthy comparison children; this was based simply on the external appearance of the electrical power distribution system (Wertheimer and Leeper, 1979).

More than 30 years on, the most thoroughly studied, but still the most controversial, topic remains of whether cancer, in particular leukemia in children, is increased by long-term exposure to extremely low frequency (ELF), specifically, 50–60 Hz, magnetic fields (MFs) with average fields of above 0.3 or 0.4 μT compared to levels below 0.1 μT, produced by domestic electrical power systems, the use of electrical appliances, or proximity to high-voltage power lines. While the exposure assessment in the original study was very crude, dependent only on the configuration of the wiring distribution (wire codes), more recent studies have assessed exposure by historical calculations or measurements from 24 hours up to a week in the child's home, supplemented by measurements in other places such as schools, or by getting the child to wear a recording instrument for at least 24 hours.

The association is complex to study. Leukemia is uncommon affecting about one child in 1500 before the age of 15, so mounting large studies is logistically challenging. All the major studies have been case–control studies (see Chapter 3) in which children who have been diagnosed with leukemia (cases)

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are compared to healthy comparison children of the same age and sex (controls). Leukemia is a complex disease with many different subtypes that may have different etiologies; a large range of other factors including genetic, nutritional, and environmental exposures have been linked to leukemia and therefore have to be taken into account when studying MFs; and there is the fundamental challenge of measuring the relevant exposure.

The relevant biological exposures must have happened months or more likely years before diagnosis, perhaps as early as the antenatal period. As no clear testable hypothesis has been raised by animal or cellular studies, the most relevant exposure parameter is unknown. Following general experience with other hazards, most studies have assessed long-term average exposures before the time of diagnosis. There have been two main types of exposure assessment. In one, detailed measurements are made of field strengths in the child's home, and if possible in previous homes, or else restricting the studies to children who have lived in the same home for all those years; and personal exposure meters may also be used. It has to be assumed that exposures measured in current time will be closely related to exposures in earlier years; or more precisely, that the relationship between the two is not different for case and for control children. In the second method, the exposures during the relevant years are calculated from the position of the residence in relationship to high-voltage power lines and historical data on electricity loads carried by these lines. Both are clearly only approximate methods; the second method takes no account of individual behavior, but it has the major advantage that these estimates of exposure can be calculated for all subjects, whereas the personal measurement methods require the cooperation of case and comparison children and their families, and therefore, inevitably these studies have a proportion of nonparticipants.

There have been a substantial number of studies, carried out in different countries with various methods, which individually give varied results. However, two separate but overlapping pooled analyses, in which the original data from several studies was reanalyzed in a combined manner, showed an association with an increase in leukemia risk with exposures to average MFs of 0.3 μT or higher in one analysis, and 0.4 μT or higher in the other. Such fields are experienced in only a few percent of residences in different countries (Ahlbom et al., 2000; Greenland et al., 2000). Table 20.1 summarizes the two important pooled analyses published in 2000.

The two pooled analyses included over 3800 children with leukemia, but the key results applying to the highest exposure category depend on 44 cases in one analysis and on 99 in the other; all the other children had lower exposures. Both pooled analyses show an increased risk. The 95% confidence limits are quite wide because of the small numbers in the highest categories. These associations have been seen both in studies which use personal measurements and in studies that use historical calculation methods to assess exposure.

Table 20.1 Pooled analyses of studies of residential magnetic fields and childhood leukemia.

Two pooled studies have given the main evidence on this association
Ahlbom et al. (2000) used data from 9 case–control studies and found an odds ratio of 2.00 with 95% confidence limits of 1.27–3.13, for exposures of 0.4 μT or higher, with 44 children with leukemia in this highest exposure group: that is, the risk of leukemia was doubled, and the increase was statistically significant
Greenland et al. (2000) used data from 12 studies, 7 of which were also included in the Ahlbom analysis, and found an odds ratio of 1.68 with 95% confidence limits of 1.23–2.31 for exposures of above 0.3 μT, with 99 children with leukemia in this highest exposure group: that is, the risk of leukemia was increased by 68%, and the increase was statistically significant
The two analyses vary in many ways relating to the choice of exposures, time periods, comparison groups, and other details, but the results are generally consistent

The association clearly does exist in several studies, and the key point of controversy is whether it is causal – is leukemia *caused* by these levels of MF exposure, so that reducing the fields will prevent some cases? The main alternative explanations are that the association is due to other factors that may be related to the type of housing which has high fields, which is generally lower value housing (related to socioeconomic status), or that it is due to biases produced by nonparticipants in the personal measurement studies; in either situation, reducing the fields would have no effect in preventing leukemia.

There are results which detract from the overall consistency of the evidence. It is striking that what can be regarded as the best of the individual measurement studies, the large studies carried out in the United States, the United Kingdom, and Canada specifically to test the MF hypothesis (Linet et al., 1997; McBride et al., 1999; UK Childhood Cancer Study Investigators, 1999), have not confirmed the association overall; moreover, the ways in which the results were used in the pooled analyses differ somewhat from how they were used in the major studies themselves, and these influences could affect the results (Elwood, 2006). Table 20.2 shows details from the large US study.

Much attention has also been given to proximity to electric power transmission lines; this factor is brought into the studies of MF exposures in either the calculation of likely exposures or the effect on measured exposures. It has also been looked at directly, for example, in the large British study, showing no association (UK Childhood Cancer Study Investigators, 2000). Another British study did show increases in risk near powerlines (Draper et al., 2005), although the authors pointed out that the pattern of risk did not match the pattern of electric or MF intensities. A further study again found a nonsignificant increase; the authors state that the estimated attributable risk is below one case per year (for the whole of England and Wales) and that "magnetic-field exposure during the year of birth is unlikely to be the whole cause of the association with distance from overhead power lines that we previously reported" (Kroll et al.,

Table 20.2 Case–control study of childhood leukemia and magnetic fields Linet et al. (1997).

This study was conducted by the National Cancer Institute in the United States The study included 638 children diagnosed with acute lymphoblastic leukemia (ALL, the commonest type) at ages under 15 years in 9 states in the United States, and 620 control children selected by random telephone calls, each matched to a case child by age, sex, and geographical region. Detailed interviews were done with the mothers, and magnetic fields were assessed in the one or two residences that the child had spent at least 70% of their time in the 5 years prior to diagnosis. Wire codes were assessed, and magnetic fields were measured over 24 hours in the child's bedroom, with 30-second measurements in other rooms and outside the front door, with a three-axis induction coil sensor. Time-weighted averages were calculated. Compared to the lowest exposure category of less than 0.065 μT, the relative risk (odds ratio) for fields of 0.2 μT or higher, which was the primary predefined hypothesis in the study, was 1.24, with 95% limits of 0.86–1.79. Thus, the risk of leukemia was increased, by 24%, but this could have easily been due to chance. In higher categories, representing further analysis beyond the main hypothesis, the risks at exposures of 0.2–0.299, 0.3–0.399, 0.4–0499, and 0.5 μT or higher were 0.92, 1.39, 3.28, and 1.41; so there was no regular trend or dose–response pattern. The authors' conclusion was "Our results provide little evidence that living in homes characterized by high measured time-weighted average magnetic-field levels or the highest wire-code category increases the risk of ALL in children". Some others have emphasized the fact that risk was increased (1.24 overall and 3.28 in one category), while ignoring the statistical variability and the lack of a regular trend

2010). Theories relating electric and MFs, corona discharges, and air pollutants around powerlines have also raised concerns but are not supported by consistent evidence (Advisory Group on Non-ionising Radiation (AGNIR) and *Ad hoc* Group on Corona Ions, 2004).

Further meta-analyses have been produced. Kheifets et al. (2010) assessed seven studies published after 2000, which included 10,865 cases and 12,853 controls. The odds ratios for exposure categories of 0.1–0.2, 0.2–0.3 μT, and greater than or equal to 0.3 μT, compared with less than 0.1 μT, were 1.07, 1.16, and 1.44 (95% limits 0.88–2.36), respectively. They concluded that "the association is weaker in the most recently conducted studies, but these studies are small and lack methodological improvements needed to resolve the apparent association." So the situation is little changed by these further studies.

So in summary, there are a number of studies and combined analyses that demonstrate an *association* between increased childhood leukemia and levels of residential MFs higher than what is normally encountered; although some important studies do not show this association. Moreover, there is no consistent laboratory or animal experimental evidence showing carcinogenic effects at these dose levels. The pooled analyses of the studies led the International Agency for Research on Cancer to classify MFs as a "possible human carcinogen", Class 2B (International Agency for Research on Cancer, 2002) – a classification that justifies caution and further research, while not concluding that causation has been confirmed (see Chapter 15 for more about the IARC classifications). The interpretation of most major reputable interdisciplinary groups, as seen in the World Health Organization (WHO) Environment Health Criteria volume 238 published in 2007 (World Health Organization, 2007) is that although an association has been seen, it cannot be interpreted as a cause and effect relationship, as the alternative explanations of selection effects and confounding factors cannot be excluded. There is vigorous debate; for example, the BioInitiative Report, first published in 2007 and updated in 2012 (Carpenter and Sage 2007), presents alternative views of both the epidemiological and laboratory studies by scientists who argue that the evidence is sufficient to show causation and should therefore be acted upon in terms of exposure standards and public policy.

20.2 Other Cancers

Most of the debate has centered on childhood leukemia and MFs, as that is where the scientific evidence of an association is strongest. There are also many studies of other types of cancers in children and of various types of cancers in adults. Of these, studies of leukemia in adults in relationship mainly to occupational exposures, and also studies of brain cancers, have been relatively numerous, but with conflicting results and little overall consensus. There have also been many studies of breast cancer in relationship to both occupational and residential MFs; here, the more recent and highly sophisticated studies using personal MF measurements have clearly shown no evidence of an increased risk, unlike some of the early studies which raised the question (Advisory Group on Non-ionising Radiation, 2006). There has even been a study of cancer in domestic pet dogs related to MFs, finding some increased risks (Reif, Lower, and Ogilvie, 1995).

20.3 Occupational Studies

As well as case–control studies of different types of cancers, there have also been cohort studies of occupational groups with likely exposure to high levels of low-frequency fields, such as electrical utility workers and welders, and in the Scandinavian countries, studies linked to census information on occupations, that would be expected to involve higher levels of electric or MF exposure. A range of results is seen with some studies suggesting associations with cancer, heart disease, or neurological diseases, but many other similar studies show no such association and overall the evidence is not consistent.

20.4 Neurological Diseases

There are a number of case–control and cohort studies which suggest an association between MF exposure and Alzheimer's disease and perhaps other neurodegenerative diseases (World Health Organization, 2007). A large ecological study in Switzerland showed increased risks of Alzheimer's disease in people living close to powerlines (Huss et al., 2009), but a further study in Denmark (Frei et al., 2013), with stronger methods, showed no such relationship. A meta-analysis of 42 publications showed weak associations with motor neuron disease and Alzheimer's disease, but not with Parkinson's disease, multiple sclerosis, or all dementias (Vergara et al., 2013). Due to the limitations of the studies, the question remains open.

20.5 Reproductive Outcomes

There have also been quite a number of studies of reproductive outcomes particularly miscarriage and birth defects. One of these showed an association between miscarriage and short-term high-intensity peaks of exposure, although as this is based on a particular exposure parameter derived from the data of the study rather than being a preset hypothesis, it requires further studies to assess it (Li et al., 2002). More recent studies have not confirmed ELF fields on reproductive outcomes.

There have also been studies of psychological issues including depression and suicide, and neurobehavioral aspects such as cognitive effects, sleep quality, and electroencephalogram (EEG) changes, and again the results of these studies are generally inconsistent (World Health Organization, 2007).

20.6 Major Reviews

A detailed review was published in 2015 by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), set up by the European Commission (Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015). The summary on ELF fields is as follows (p. 7):

> Overall, existing studies do not provide convincing evidence for a causal relationship between ELF MF exposure and self-reported symptoms. The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukemia with estimated daily average exposures above 0.3–0.4 μT. As stated in the previous opinions, no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies, prevent a causal interpretation. Studies investigating possible effects of ELF exposure on

> the power spectra of the waking EEG are too heterogeneous with regard to applied fields, duration of exposure, and number of considered leads and statistical methods to draw a sound conclusion. The same is true for behavioral outcomes and cortical excitability.
>
> Epidemiological studies do not provide convincing evidence of an increased risk of neurodegenerative diseases, including dementia, related to power frequency MF exposure. Furthermore, they show no evidence for adverse pregnancy outcomes in relation to ELF MF. The studies concerning childhood health outcomes in relation to maternal residential ELF MF exposure during pregnancy involve some methodological issues that need to be addressed. They suggest implausible effects and need to be replicated independently before they can be used for risk assessment. Recent results do not show an effect of the ELF fields on the reproductive function in humans.

In summary, reputable international review bodies such as the WHO accept that there are a number of epidemiological studies showing an *association* between childhood leukemia and higher levels of residential MF exposure (World Health Organization, 2007). However, the WHO and most other reputable groups, while accepting this, do not feel that the evidence is strong enough to show that MFs actually *cause* childhood leukemia and therefore conclude that existing standards and social practices in regard to controlling exposures related to electrical distribution systems and so on are adequate. In general, the amount and quality of epidemiological evidence linking MFs to other diseases in children or adults, or linking electric fields to any disease, is considerably less than that relating childhood leukemia to MFs.

However, there is active debate and there are scientists who hold different views. There are many articles and web sites giving one-sided views on these questions, typically only referring to studies suggesting a hazard and ignoring those which have different results. The authority of the IARC and WHO documents and others like them is that all published peer-reviewed studies are considered and documented, and it is often helpful to compare the studies cited in a particular article with these more comprehensive sources, to detect any selection of studies – “cherry picking” – that is, going on.

Sources for Updates

Reliable sources for regular updates include the following:

- World Health Organization (http://www.who.int/peh-emf/en)
- Public Health England (UK) (https://www.gov.uk/government/collections/electromagnetic-fields)
- National Institutes of Health (USA) (http://www.nlm.nih.gov/medlineplus/electromagneticfields.html)

- ARPANSA (Australia) (http://www.arpansa.gov.au/RadiationProtection/index.cfm)
- The Swedish Radiation Safety Authority (SSM) produces regular reports on new research on EMF and health issues (https://www.stralsakerhetsmyndigheten.se/.../SSM-Rapport-2015-19.pdf).

Tutorial Problems

1 What is a pooled analysis? Why are they important?

2 A US case–control study showed an odds ratio for leukemia in children exposed to average fields of 0.2 μT or higher of 1.24, with 95% limits of 0.86–1.79. What does this mean?

3 The IARC classifies radiofrequency in Group 2B. What does this mean?

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21

Possible Low-Level Extremely Low-Frequency (ELF) Electric and Magnetic Field Effects?

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21.1 Exposure to ELF Fields

In Chapter 17, there was some discussion on the levels of electric fields within tissue, induced by external extremely low frequency (ELF) fields, which could be of concern, and which provide the basis for standards setting. The possibility of unnatural stimulation of nerve cells within the retina (and perhaps of nerves within the memory-forming region of the brain) is thought to be reduced or eliminated by keeping internal electric (E) field values below 50–100 mV/m. Using the formulae discussed in that chapter, external electric fields in excess of 10–50 kV/m and magnetic fields of 1–10 mT are required to induce tissue electric fields of this magnitude. Largely because of epidemiological evidence linking time-weighted average magnetic fields below 1 μT to an increased risk of childhood leukemia (reviewed in Chapter 20), there has been continued concern that there could be mechanisms of interaction, other than neurostimulation, which could lead to adverse health outcomes at fields many times below those on which standards are based. In fact, since the early 1980s, there has been a spate of reports (running into the tens of thousands) of bioeffects in laboratory experiments using, in some cases, really low field values. There has also been a focus on low-level magnetic rather than electric field exposure, since the early epidemiological data pointed to an association with power-line currents (hence magnetic fields) rather than voltage (which would correlate with electric fields).

This chapter is not the place to present a comprehensive review because this has been done many times before and by teams of experts representing many

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branches of science. Table 21.1 lists some of the more recent reviews, many of which are in the public domain and can be downloaded. This short chapter attempts to describe some of the overarching themes in the attempts to unambiguously identify and characterize "low-level" effects of ELF. In some ways, this parallels the debate on whether low-level radiofrequency (RF) effects occur (see Chapter 16), although in this case it is not a question of whether nonthermal effects occur, because thermal mechanisms do not form part of the way ELF is understood to interact with tissue. This chapter tries to assess the current "state-of-play" regarding presumed low-level effects.

21.2 Some "Landmark Studies"?

Of the thousands of studies mentioned above, there have been a small number that stand out as representing a series of major themes for many research groups to contribute to. What follows is not an exhaustive list and in more extensive reviews the lists are a lot longer:

21.2.1 The Calcium Effect

This was reported by W Ross Adey's group as early as 1979 and there have been numerous attempts to repeat or fine-tune this effect ever since (Adey, 1981). Essentially, the passage of calcium ions out of brain cells was found to alter if these were exposed to either RF with a low-frequency modulation (16 Hz) or even to the 16 Hz alone. Alteration of calcium levels over time might conceivably lead to diminished ability of the body to ward off disease, although this point is largely conjectural. It is acknowledged that calcium is a very important regulator of many cellular functions however, so changed levels of signaling properties could conceivably lead to long-term harm.

21.2.2 The Denver Childhood Cancer Study

This was the first epidemiological study suggesting a raised risk of cancer in children exposed to "high current capacity" distribution or transmission lines. This has been already discussed in Chapter 20, but coming, as it did, at the same time as interest in the "calcium effect", gave some support to the notion that there was a public health issue and that a mechanism could be identified.

21.2.3 Melatonin

This hormone, which is linked to the phenomenon of jet lag, has been found to be responsive to rapid changes in the earth's magnetic field and perhaps also to power frequency fields (Reiter, 1993). There is evidence that melatonin is protective against cancer, via free radical scavenging (Stevens, 1987), but whether this effect is significant at normal body levels still remains unclear. It was the

Table 21.1 Reviews of studies of ELF-EMFs on biological systems, including those at low levels of exposure.

Year	Body	Title	Quote	Notes
2015	SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks); European Commission (SCENIHR, 2015)	Opinion on potential health effects of exposure to electromagnetic fields (EMF)	Overall, existing studies do not provide convincing evidence for a causal relationship between ELF MF exposure and self-reported symptoms. The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukemia with estimated daily average exposures above 0.3–0.4 μT. As stated in the previous opinions, no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation: (p 7)	Updates earlier opinions (March 2007, January 2009, and July 2009). Covers frequencies from terahertz to static, with approximately 30 pages devoted to ELF *per se*. Recommends further work on biophysical mechanisms and coexposures
2012	Bioinitiative: a report by 29 independent scientists from around the world (Sage, 2012)	A rationale for biologically based exposure standards for low-intensity electromagnetic fields	The most serious health endpoints that have been reported to be associated with extremely low frequency (ELF) and/or radiofrequency radiation (RFR) include childhood and adult leukemia, childhood and adult brain tumors, and increased risk of the neurodegenerative diseases, Alzheimer's and amyotrophic lateral sclerosis (ALS). Recent studies largely reinforce the potential risks to health (rather than reducing our concerns, or providing actual indications of safety): (Summary page)	Updates an earlier report (2007). Considers ELF and RF low-intensity studies together, despite known interaction mechanisms being quite different. One of the authors also acted as an external expert for the SCENIHR Opinion

2010	ICNIRP (ICNIRP, 2010)	Guidelines on limits of exposure to time-varying electric, magnetic, and electromagnetic fields (1 Hz–100 kHz)	Overall, in contrast to the epidemiological evidence of an association between childhood leukemia and prolonged exposure to power frequency magnetic fields, the animal cancer data, particularly those from large-scale lifetime studies, are almost universally negative. The data from cellular studies are generally supportive of the animal studies, though more equivocal: (p 823)	The analysis of low-level effects is quite brief, but evidence for cancer association and hypersensitivity is summarized, largely by reference to previous reviews
2007	WHO (2007)	Extremely Low Frequency Fields, Environmental Health Criteria No. 238	Overall, there is no evidence that ELF exposure alone causes tumors. The evidence that ELF field exposure can enhance tumor development in combination with carcinogens is inadequate: (p 322). In relation to reproduction the conclusion was: "Overall, the evidence for developmental effects and for reproductive effects is inadequate": (p 254)	Final draft overseen by panel of 32 scientists: earlier drafts produced by wider groups of experts. Risk assessment included scenarios in which childhood leukemia causation had been established
2004	NRPB (2004)	Review of the Scientific Evidence for Limiting Exposure to Electromagnetic Fields	In the context of possible adverse health effects from EMFs, the conclusions of published expert scientific reviews have identified only one reasonably consistent epidemiological finding of an adverse health outcome associated with exposure to EMFs at levels lower than exposure guidelines: that is an apparent increased risk of childhood leukemia with time-weighted exposure to power frequency magnetic fields above 0.4 μT. It is the view of NRPB that the epidemiological evidence is currently not strong enough to justify a firm conclusion that such fields cause leukemia in children: (p 7)	Review undertaken by (then) the National Radiation Protection Board (UK) staff to give advice to the UK government on the most appropriate form of protection, particularly examining the issues of uncertainty in the science and aspects of precaution. Advice from an expert group on actions of weak electric fields on neural systems incorporated

(Continued)

Table 21.1 (Continued)

Year	Body	Title	Quote	Notes
2003	ICNIRP (Matthes et al. 2003)	Exposure to Static and Low Frequency Electromagnetic Fields, Biological Effects and Health Consequences (0–100 kHz) – Review of the Scientific Evidence and Health Consequences	No overall conclusions, but areas of uncertainty and/or need for further study for clarification under each of headings listed at right	Includes a report from the ICNIRP (then) standing committee on Biology. Review of around 1000 reports under headings of "biochemical and cell-free models", "cellular models", "animal studies", and "human laboratory studies"
2002	IEEE (2002)	IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz	Because none of the above reviews concluded that any hazard from long-term exposure has been confirmed, this standard does not propose limits on exposures that are lower than those necessary to protect against adverse short-term effects. The Subcommittee will continue to evaluate new research and will revise this standard should the resolution of present uncertainties in the research literature identify a need to limit long-term exposures to values lower than the limits of this standard: (p 2)	This conclusion was based on earlier reviews, including those listed below
2002	IARC (2002)	Nonionizing radiation, Part 1: static and extremely low-frequency (ELF) electric and magnetic fields	There is limited evidence in humans for the carcinogenicity of extremely low-frequency magnetics fields in relation to childhood leukemia. There is inadequate evidence in humans for the carcinogenicity of extremely low-frequency magnetic fields in relation to all other cancers: (p 338)	Monograph followed meeting of an international expert group. Note the Group 2B classification (possibly carcinogenic to humans) applies to ELF *magnetic* fields. ELF *electric* fields (and static fields) are in Group 3 (not classifiable as to their carcinogenicity to humans)

2002	California EMF Program (Neutra, DelPizzo, and Lee, 2002)	An evaluation of the possible risks from electric and magnetic fields (EMFs) from power lines, internal wiring, electrical occupations, and appliances	To one degree or another, all three of the DHS scientists are inclined to believe that EMFs can cause some degree of increased risk of childhood leukemia, adult brain cancer, Lou Gehrig's disease, and miscarriage. They strongly believe that EMFs do not increase the risk of birth defects or low birth weight. They strongly believe that EMFs are not universal carcinogens, since there are a number of cancer types that are not associated with EMF exposure. To one degree or another they are inclined to believe that EMFs do not cause an increased risk of breast cancer, heart disease, Alzheimer's disease, depression, or symptoms attributed by some to a sensitivity to EMFs	Report represents views of three staff members of the California Department of Health Services: Reviewer 1, a physicist and epidemiologist; Reviewer 2, a physician epidemiologist; and Reviewer 3, an epidemiologist with training in genetics
2001	NRPB (AGNIR, 2001)	ELF electromagnetic fields and the risk of cancer	Those results that are claimed to demonstrate a positive effect of exposure to power frequency magnetic fields tend to show only small changes, the biological consequences of which are not clear Overall, no convincing evidence was seen from a review of a large number of animal studies to support the hypothesis that exposure to power frequency electromagnetic fields increases the risk of cancer	Advisory group to UK (former) National Radiation Protection Board, chaired by late Sir Richard Doll. Originally set up in 1990, produced 5 reports prior to this one, which was specifically directed to examining evidence in relation to cancer
1999	NIEHS Olden (1999)	Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields	The NIEHS believes that the probability that ELF-EMF exposure is truly a health hazard is currently small. The weak epidemiological associations and lack of any laboratory support for these associations provide only marginal scientific support that exposure to this agent is causing any degree of harm	Report to US congress by the Director of the National Institute of Environmental Health Sciences on the "EMF-RAPID" program (see below)

(Continued)

Table 21.1 (Continued)

Year	Body	Title	Quote	Notes
1998	NIEHS (Portier and Wolfe, 1998)	Assessment of health effects from exposure to power-line frequency electric and magnetic fields. NIEHS Working Group report	Convincing evidence for causing effects is only available for magnetic flux densities greater than 100 μT or internal electric field strengths greater than approximately 1 mV/m. To date, there is no generally accepted biophysical mechanism by which actions of lower intensity ELF-EMF exposures, including those reported to be of concern in epidemiological studies, might be explained	This report represented the culmination of the US 5-year EMF Research and Public Information Dissemination (RAPID) program. The report distilled a number of "Break-out" meetings on key topics, in addition to feedback from worldwide experts
1997	NRC (1996)	Possible health Effects of Exposure to Residential Electric and Magnetic Fields	Based on a comprehensive evaluation of published studies relating to the effects of power frequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects, or reproductive and developmental effects An association between residential wiring configurations … and childhood leukemia persists in multiple studies, although the causative factor responsible for that statistical association has not been identified	"(US) Congress asked that the National Academy of Sciences (NAS) review the research literature on the effects from exposure to these fields and determine whether the scientific basis was sufficient to assess health risks from such exposures". Committee of 16 eminent scientists and policy analysts

view of the authors of the Environmental Health Criteria (EHC) monograph that, despite a quite extensive body of evidence both from *in vivo* and *in vitro* studies, the link between power frequency magnetic fields and cancer incidence or progression via melatonin effects had not been substantiated (WHO, 2007).

21.2.4 Human Volunteer Studies

In addition to volunteer studies of melatonin levels (in plasma, saliva, and urine), there have been several on a variety of physiological and psychological end points in humans, comparing responses of actual power frequency EMF exposures with sham exposures. The levels chosen have, in general, been below the occupational limits. Studies have included heart rate variability (Graham et al., 2000; Sait, Wood, and Kirsner, 2006), EEG, cognition (Stollery, 1987; Preece, Wesnes, and Iwi, 1998; Keetley et al., 2001), and stress and other hormone levels (WHO, 2007). These types of studies have also included symptom provocations, focusing on individuals who consider themselves as "electrosensitive" (see Chapter 24 for a review of these types of study).

21.2.5 Animal Studies

There have been several landmark studies involving exposure of rodents to environmentally relevant magnetic fields over their lifetimes. Some of these have involved well over 1000 individual animals and some have combined ELF exposure with exposure to chemicals known to induce or promote cancer. Others have employed rodent strains genetically predisposed to specific forms of cancer or rodents in which tumor cells or colonies have been transplanted. Overwhelmingly, these studies show no effects of power frequency ELF on life expectancy or the ability to produce healthy offspring. There is overwhelming evidence from tens of independent studies, including two studies on transgenic mice that develop a disease similar to childhood leukemia, that cancer rates are no different to that of controls. These studies have used a range of intensities, from 1 to 1000 μT (10–10,000 mG). A UK review (AGNIR, 2001) concluded that:

> Overall, no convincing evidence was seen from a review of a large number of animal studies to support the hypothesis that exposure to power frequency electro-magnetic fields increases the risk of cancer.

The one study that seems to show an effect on progression of rat mammary tumors was controversial and has not been independently confirmed to any degree of satisfaction.

21.2.6 Effects on Genetic Code

Some experiments with magnetic fields indicated an increased rate of reading the genetic blueprint molecules DNA and RNA, which might indicate an increase in the rate of cell division. Careful attempts to repeat these experiments by two other groups failed, however. Some related experiments at the University of Washington seem to indicate an increased rate of chromosomal breakage in response to RF exposure (Lai and Singh, 2004). Since this is a rather counterintuitive finding (in view of the energy transfer involved), the scientific community has suspended judgment pending more robust independent confirmation.

In vitro studies using exposures below 100 μT (1000 mG) show no convincing evidence of genotoxicity or cancer progression rates. The induced current patterns in *in vitro* (i.e., in a test tube) exposure setups are quite different to those *in vivo* (i.e., using living animals) for the same magnetic flux density.

21.3 Mechanism Studies

Studies supporting the notion of biological effects of ELF at levels well below those that present-day standards are based on have been regarded with some scepticism because of the lack of a credible mechanism for interaction (as there is in the case of electrostimulation, for example). On the other hand, it is recognized that certain organisms have acute sensitivity to electric fields (around 500 nV/m in certain fish (Kalmijn, 1982)) and magnetic fields (changes of a few hundred microtesla, in the case of some birds (Mora et al., 2004)). It should be remembered, however, that these organisms have specialized receptors specifically to detect these fields. Humans, as far as we are aware, do not possess these receptors, nor do any other receptors in the human body behave in an analogous way. It could be argued that the nervous tissue in the retina behaves like a magnetoreceptor (and indicates when the levels are unacceptably high), but that is not its main function. In the case of epidemiological evidence, the lack of a credible mechanism at levels less than a microtesla is one of the main reasons for regarding causality as not having been established. As part of a contribution to on-going scientific debate, several scientists have put forward possible mechanisms, which if substantiated, could provide a causative link. The following list summarizes some of the proposed mechanisms of interaction purporting to give a mechanistic basis of the putative action of low-level 50/60 Hz magnetic fields with biological materials.

21.3.1 Solitons

21.3.1.1 Features

The protein strands on the cell membrane surface are assumed to act as electric field detectors (Adey, 1981). These disturbances are conducted to the inside of the membrane via solitary-wave (soliton) propagation along protein transmembrane strands. Inside the cell, this ELF signal is assumed to couple to enzymes, altering reaction rates.

21.3.1.2 Drawback

The precise energetics of this scheme have not been investigated, but according to Adey's own estimate, thermal noise can only be overcome by a co-operative molecular system 300 m in extent (the actual cellular distances are 30 million times smaller).

21.3.2 Cyclotron Resonance

21.3.2.1 Features

Classical equations of a charged particle moving in a combined static and alternating magnetic field (Liboff, 1985).

21.3.2.2 Drawback

The model requires values of viscosity (or collision frequency) many orders of magnitude smaller than those expected in membrane channels.

21.3.3 Ion Parametric Resonance

21.3.3.1 Features

Similar to the above, but involves the energy levels produced when a calcium ion binds to a membrane site (Lednev, 1991).

21.3.3.2 Drawback

Adair (1998) has presented four theoretical reasons why such a mechanism cannot operate.

21.3.4 Magnetite Particles

21.3.4.1 Features

The hypothesis is that brain tissue contains microcrystals of the magnetic ore magnetite, which respond to external magnetic forces giving rise to intense volume currents in the surrounding tissue (Kirschvink et al., 1992).

21.3.4.2 Drawback

Suggestion is that "such effects can occur only with large magnetic fields and are not applicable to the normal human environment …" (Olden, 1999).

21.3.5 Free Radical Lifetimes

21.3.5.1 Features

Free radicals are dangerous to cellular processes and are formed due to a variety of causes (Brocklehurst and McLauchlan, 1996). Normally, they recombine without causing damage, but if their lifetimes are extended, the chance of their escaping and causing damage increases. Magnetic fields do extend free radical lifetimes, but only at levels above a few tens of microtesla and in chemical rather than biological systems.

21.3.5.2 Drawback

Adair (1999) has discussed the possibility of this occurring at environmentally relevant magnetic field levels and considers this to be unlikely.

21.3.6 Stochastic Resonance

21.3.6.1 Features

This is a phenomenon whereby a signal in a noisy environment becomes actually easier to detect because of the noise (Kruglikov and Dertinger, 1994). It has been suggested that such phenomena may add to the acute sensitivity of the sense of hearing and smell. However, the amount of enhancement is modest and is inadequate to explain the huge disparity between membrane noise and induced voltage discussed above.

21.3.6.2 Drawback

Adair (1996) has also shown the model to be inadequate to explain EMF effects.

21.3.7 Radon Progeny Plateout

21.3.7.1 Features

This is primarily associated with strong *electric* fields close to transmission line cables and is relevant only to those areas associated with high ground emissions of the radioactive gas radon (Henshaw et al., 1996).

21.3.7.2 Drawback

To be credible, the electric field gradients in the lining of the airways of the lung have to be unrealistically high (around 7×10^9 V/m/m, implying that in the airway the electric field would need to drop from 100 V/m to 0 in a distance one-tenth of the thickness of a cell membrane).

21.3.8 Neural Networks

21.3.8.1 Features

This is a further consideration of the acute electric sensitivity in fish mentioned above and applying the principles of signal detection enhancement to systems of interconnected nerves in general, or at least special networks as occur in the retina (which is known to be particularly sensitive to magnetic fields, as was highlighted in Chapter 17) or in the hippocampus, a region of the brain concerned with memory formation (Saunders and Jefferys, 2002). Although there is no clear evidence of ELF fields at low levels causing changes in cognitive function, there is evidence from *in vitro* studies that nerve firing patterns can be altered by moderate imposed electric fields (Deans, Powell, and Jefferys, 2007).

21.3.8.2 Drawback

The lower bound on discrimination is likely to be 10–100 mV/m in tissue (WHO, 2007), which is in fact the range of values used to determine the basic restrictions in place in the standards currently (see Chapter 18).

As a further note, the "melatonin hypothesis" dealt with possible repercussions of altered melatonin output patterns: it did not consider the fundamental question of how these patterns might be altered by weak magnetic fields. Even if altered melatonin output patterns from the pineal gland in humans or animals following 1.2 μT alternating magnetic field exposures can be substantiated, this provides no clues on what the mode of "magnetic reception" might be.

In his report to Congress, the Director of the US National Institute of Environmental Health Sciences stated:

> All of the theories for biological effects of ELF-EMF suffer from a lack of detailed, quantitative knowledge about the processes to be modelled.
>
> Nevertheless, theoretical models are useful, even in the absence of critical data, because they can indicate what data are needed, suggest previously uncontemplated experiments, suggest bounds on risks under defined situations and provide nonlinear methods of analysis of critical data based upon presumed mechanisms. The current biophysical theories for ELF-EMF would suggest little possibility for biological effects below exposures of 100 μT [1,000 mG]. However, considering the complexity of biological systems and the limitations required by the assumptions used to mathematically model these theories, this finding has to be viewed with caution (Olden, 1999).

The authors of the EHC monograph (WHO, 2007) reached very similar conclusions in considering mechanisms: "None of the three direct mechanisms considered [induced electric fields in neural networks, radical pairs and magnetite] seem plausible causes of increased disease incidence at the exposure levels generally encountered by people. In fact they only become plausible at levels orders of magnitude higher …" (WHO, 2007, p 4).

21.4 Why Is Evidence Regarded as "Inconclusive"?

The 100 or so government and health organization reviews into both EMF and RF safety at levels below the currently accepted guidelines all use very similar language. As an example, for ELF, the EHC monograph (WHO, 2007) states that "… on balance the evidence is not strong enough to be considered causal, but sufficiently strong to remain a concern". The sentences before this quote (on p 12 of this monograph) are as follows:

> Scientific evidence suggesting that every-day, chronic low-intensity (above 0.3–0.4 μT) power frequency magnetic field exposure poses a health risk is based on epidemiological studies demonstrating a consistent pattern of increased risk for childhood leukemia. Uncertainties in

> the hazard assessment include the role that control selection bias and exposure misclassification might have on the observed relationship between magnetic fields and childhood leukemia. In addition, virtually all of the laboratory evidence and the mechanistic evidence fail to support a relationship between low-level ELF magnetic fields and changes in biological function or disease status.

Thus, although the epidemiological evidence exists (and was the basis of the IARC "2B" classification discussed in Chapter 20), this has not been backed up by laboratory evidence or mechanism studies and the epidemiological evidence itself is prone to error due to uncertainties in estimating exposure. However, this does not adequately explain why so many laboratory experiments seemed to indicate significant (and possibly adverse) effects at low levels of exposure. One feature of EMF/EMR research is the number of "effects" that have been reported in pilot experiments (which may have been flawed in design or ability to control for extraneous factors), which have not been confirmed subsequently or have later been shown to be due to artifact. Many of these changes have only just achieved statistical significance and some experimental designs suffer from "multiple comparison" weaknesses. In fact, some effects have been shown in one set of experiments but not in repeat experiments carried out in other laboratories or even the same laboratory. While it may be argued that it is only when the experimental conditions are "just right" that a subtle resonance-like phenomenon can be observed, the simpler view is that however subtle, the effect should be readily repeatable. Moreover, the principle of Ockham's Razor would force us to adopt the view that random variation is what is really being observed.

The advantage of the review approach involving panels of scientists from around the world (which was the case of both the EHC and the IARC processes, both bodies being affiliated with WHO) is that comparisons can be made between several studies examining a similar endpoint to judge consistency and coherence of results. Nevertheless, it would be wrong to imply that all reviews have come to the same conclusions as WHO. Another group, the Bioinitiative Working Group, convened by Cynthia (Cindy) Sage, an environmental consultant, presented an alternative view (Sage, 2012). The two dozen or so scientists in this group have long-held opinions that the major review bodies (particularly WHO/ICNIRP and IEEE) have been overly dismissive of reports suggesting hazards below the levels discussed in Chapter 18. The report has several chapters written by the scientists concerned and in general advocates a substantial lowering of limits. The report covers both ELF and RF EMFs: even though their interactions with the human body are quite distinct, this distinction is often quite blurred in the arguments put forward for more conservative limits. A report from the Californian Health (Neutra, DelPizzo, and Lee, 2002), written by three staff scientists, also represented a view that more conservative limits were required.

Even though these latter two reports would represent a minority view among scientists who have been researching ELF bioeffects, these views cannot be ignored. It highlights the uncertainty that exists in dealing with effects that could be quite subtle. In fact, the risk assessment carried out in the WHO monograph (WHO, 2007) was done *assuming* causality between magnetic fields and childhood leukemia. The percentage of childhood leukemia cases attributable to this cause was estimated to be between 0.2% and 4.9%, a huge range, highlighting the degree of uncertainty. Other estimates have put the risk at around 2% of cases or about 1 case (per year) per million children aged 0–14 in the population (around 20% of the total population). Of course, if there is no causative link then the percentage is zero, but there still exists the possibility that by reducing *fields* the exposure to the *actual* causative agent will also be reduced. There is little doubt that the number of affected children is relatively small and since treatment is now successful in around 80–90% of cases, there are more urgent calls on health spending to effectively lower child mortality. For example, simple access to clean drinking water and improved sanitation can reduce child mortality by 23%, with only modest expenditures per capita (Fink, Gunther, and Hill, 2011).

21.5 Dealing with Scientific Uncertainty in a Prudent Manner

As outlined earlier (in Chapters 2 and 3), the establishment of cause and effect using the scientific method is a long and laborious process, especially if there is conflicting evidence and the reported effect sizes are small.

Where "low-level" effects are unsubstantiated and the putative mechanisms unknown, establishing effective mitigation strategies becomes problematical. Current interpretations of the "Precautionary Principle" and "Prudent Avoidance" are considered in Chapters 25 and 26. These are responses to uncertainties in the state of the science. They are not strategies that emerge directly from a scientific consensus as to what can be done to reduce risk. The NIEHS Final Report (Olden, 1999) recommends, in the case of ELF, a "passive regulatory action" such as "a continued emphasis on educating both the public and the regulated community on means aimed at reducing exposures" rather than "aggressive regulatory concern." Add to this the advice from WHO (2007) that "Provided that the health, social, and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposure is reasonable and warranted." Thus, the presence in the literature of conflicting reports, some suggesting possibly harmful bioeffects below the limits discussed in Chapter 18 is not in itself reason for introducing arbitrary extra safety margins, but neither is the appropriate response to ignore them. Appropriate strategies based on mitigation costs versus possible benefits (assuming that mitigation would in fact lead to reduced leukemia incidence) are discussed in Chapter 27.

Tutorial Problems

1 There is still apparently a divergence of views among scientists on whether the limits referred to in Chapter 18 are adequate. List reasons as to why this should be and suggest ways of resolving this divergence.

2 Your government has just voted to approve a budget of $1,000,000 "to reduce the uncertainties regarding power frequency EMFs and childhood leukemia." Discuss strategies for spending this money, including public information dissemination.

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Part VI

Static Electric and Magnetic Fields

22

Static Electric and Magnetic Field Hazards

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22.1 Sources

People are exposed to electric and magnetic fields from both natural and man-made sources that use electrical energy at various frequencies. When the source is spatially fixed and the source current and/or voltage is constant in time, the resulting field is also constant and is referred to as a static field; hence, the terms *magnetostatic* and *electrostatic.* Electrostatic fields are produced by fixed voltages, whereas magnetostatic fields are established by permanent magnets and by steady currents (IARC, 2002).

22.1.1 Natural Fields

Static electric and magnetic fields occur naturally in the Earth's atmosphere. The natural electric field is directed radially because the Earth is negatively charged with respect to the electrically conducting ionosphere, which is about 50 km above its surface (Barnes, 1986; IARC, 2002). The strength of the electrostatic field depends to some extent on the geographical latitude, being at its lowest toward the poles and the equator and at its highest in the temperate latitudes. Field strength values are typically 1–100 V/m in reasonable weather, although fields may range from 50 to 500 V/m, depending on the temperature, humidity, altitude, time of day, and season. During precipitation and bad weather, field values can change considerably, varying over a range of ±40 kV/m. The typical atmospheric electric field is not very different from the background electric field found in most homes, which is produced by 50/60 Hz electric field sources (Repacholi and Greenebaum, 1999; IARC, 2002; WHO, 2006).

The natural magnetic field originates from electric current flow in the upper layer of the Earth's core and is primarily dipolar in nature. It consists of a static

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component due to the Earth acting as a permanent magnet and several other small components, which differ in spectral characteristics and are related to such influences as solar activity and atmospheric events (WHO, 1987). There are significant differences in the strength of the geomagnetic field, which depend on geographic location and whether magnetic materials are in the vicinity (Repacholi and Greenebaum, 1999). The total field intensity has a maximum level of about 70 μT at the magnetic poles and a minimum of about 30 μT near the equator (ICNIRP, 2009). In temperate latitudes, the geomagnetic field is approximately 45–50 μT at sea level, whereas Hansson Mild (2000) has reported fields as low as 24 μT in regions of southern Brazil. The geomagnetic field is not constant and fluctuates continuously according to diurnal, lunar, and seasonal variations (WHO, 1987; IARC, 2002).

22.1.2 Man-Made Fields

Man-made sources of static electric and magnetic fields are to be found in residences, electricity distribution, research facilities, industrial and medical procedures, and several other technologies related to energy production and transportation (Stuchly, 1986; WHO, 1987). A list of sources and their corresponding magnetic field exposure levels are represented in Table 22.1.

In residential or other every day environments, small artificial sources of static electric and magnetic fields are common. Electrostatic fields of up to 500 kV/m can be generated by friction between appropriate materials (WHO, 2006). Magnetostatic fields are produced by permanent magnets in equipment such as audio speakers, battery-operated motors, microwave ovens and trivial ornaments such as refrigerator magnets. Small magnets that are encountered in domestic situations can produce fields ranging from 0.03 to 0.07 T on the surface to 1–10 mT within a centimeter away from the surface (Stuchly, 1986; Kowalczuk, Sienkiewicz, and Saunders, 1991; Moulder, 2003; WHO, 2006).

In electricity distribution, there are high-voltage direct current (HVDC) transmission lines that generate static electric and magnetic fields. Under an overhead 500 kV DC transmission line, the electrostatic field can exceed 30 kV/m or higher, depending on the distance between the conductors and ground. The magnetic flux densities under these lines can be up to a few tens of microtesla, depending on the current load and the distance from the line. For an underground transmission line buried at 1.4 m and carrying a maximum current of approximately 1 kA, the maximum magnetic field is less than 10 μT at ground level. While HVDC overhead lines and underground cables are fairly commonly used for transmission of electricity over very large distances, relatively few are in use today for the distribution of electricity (Repacholi and Greenebaum, 1999; IARC, 2002; WHO, 2006).

In transport, static electric and magnetic fields may be encountered in electric trains, trams, magnetically levitated trains, and other electrified vehicles that operate with a DC motor. Static electric fields inside the passenger and

Table 22.1 Different sources of static magnetic fields and their corresponding magnetic flux densities.

Source	Magnetic flux density (mT)	
Environment		
Geomagnetic field	0.03–0.07	
Small magnets	1–10	Within a centimeter from the surface
Electricity distribution		
HVDC transmission lines	0.01–0.02	At ground level
Transport		
Electric trains	up to 1	In the passenger compartment
MagLev trains	up to 50	At the passenger floor level
Industry		
Aluminum production	2–100	At worker locations
Electrolytic processes	4–50	At worker locations
Magnet production	0.3–5	At the hands, chest, and head
DC railways	Up to 0.12	At worker locations
DC welding	Up to 5	At the waist of the operator
Medicine		
MRI	150–10,000	For patients
MRI (research)	up to 10,000	
Dental applications	100	1 mm from the surface
Therapeutic devices	90–300	At the surface
High-energy technologies		
Magnetohydrodynamic systems	10	At 50 m
Superconducting magnets	20–80	At worker locations
Thermonuclear fusion reactors	5–10	In areas accessible to workers
Research facilities		
NMR	600	At 0.5 m
Bubble chambers	600–1500	When changing film cassettes
Particle accelerators	0.5–2000	At worker locations
Superconducting spectrometers	1000	Operator accessible positions
Isotope separation units	Up to 50	Usually <1 mT

operator compartments of electric trains are typically highest near windows and do not exceed a few tens of volts per meter (WHO, 2006). Exposure to static magnetic fields in the passenger compartment of electric trains can be as high as 1.0 mT (Moulder, 2003; WHO, 2006). Several countries have magnetically levitated trains or "MagLevs" for fast and efficient transportation. Exposures in a MagLev train can be as high as 50 mT in the floor level of the passenger compartment (Roy and Repacholi, 2003; WHO, 2006).

In medicine, magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) systems used for medical diagnosis and research can produce high static magnetic fields (WHO, 2006). The majority of MRI devices that are used in clinical practice expose patients to fields ranging from 0.15 to 3 T (Repacholi and Greenebaum, 1999; Moulder, 2003, ICNIRP, 2009). MRI systems used for medical research can produce fields up to 10 T (ICNIRP, 2009). Operators of MRI units are occupationally exposed to fields up to about 5 mT (Repacholi and Greenebaum, 1999). Interventional medical procedures under MRI are becoming increasingly common and these can expose medical staff to static fields similar to those experienced by the patient (ICNIRP, 2009).

Artificial sources of static magnetic fields are found in various occupational settings. Exposure to these fields may be encountered by workers that use DC equipment, such as in industries that involve electrolytic processes like in aluminum production. Aluminum manufacturing workers have been reported to be exposed to fields of 5–15 mT for long periods of time, with maximum exposures up to 100 mT. Workers in plants using electrolytic cells (such as in the production of chlorine) have been reported to be exposed to fields of 4–10 mT for long periods of time, with maximum exposures up to 50 mT (WHO, 1987, 2006; IARC, 2002).

Other occupational exposure to static magnetic fields may be encountered by railway workers on train systems operating from DC power supplies, workers in the production of magnets and magnetic materials, and welding machine operators. Maximum levels of 120 μT have been reported in Russian DC powered locomotive engineers (Ptitsyna et al., 2003). In permanent magnet production plants, fields measured at the worker's hands were reported at 2–5 mT and at the chest and head ranging from 0.3 to 0.5 mT (WHO, 1987). Most welding devices operate at 50/60 Hz currents, although static magnetic field levels for DC metal inert gas (MIG) or metal active gas (MAG) welding have been reported up to 5 mT at the distance of 1 cm from the welding cable (Stuchly and Lecuyer, 1989; Skotte and Hjollund, 1997).

High static magnetic field strengths may be encountered around technologies used for energy production and storage, such as magnetohydrodynamic systems, superconducting magnetic energy generators and storage systems, and thermonuclear fusion reactors. The field levels of magnetohydrodynamic systems used in power generation have been estimated to be about 10 mT at a distance of 50 m from the source and fall below 0.1 mT at distances greater than 250 m. For superconducting magnets, typical fields ranging from 20 to 50 mT have been reported with a maximum value of about 80 mT. Although fields as high as 9–12 T are present within the reactor of a thermonuclear fusion process, the levels drop to about 7 mT in the region immediately surrounding the reactor and below 0.1 mT outside the reactor site. Estimated exposure levels for workers in fusion reactors range between 5 and 10 mT under normal conditions (Stuchly, 1986; WHO, 2006).

High-strength static magnetic fields may also be encountered in high-energy physics research facilities that use nuclear magnetic resonance (NMR), bubble chambers, particle accelerators, superconducting spectrometers, or isotope separation units; although these installations are fairly rare. NMR spectroscopy used to obtain physical and chemical properties of molecules can involve the use of large superconducting magnets with static magnetic field levels up to 20 T, which drop to 600 mT at half a meter from the magnet (WHO, 2006). In bubble chambers used for subatomic particle detection, fields of about 0.6–1.5 T have been reported at operator locations (WHO, 1987; Stuchly, 1986). Individuals working with particle accelerators have been reported to be exposed to fields above 0.5 mT for long periods of time, with exposures above 0.3 T for many hours and maximum exposures of up to 2 T (Moulder, 2003). Operators of superconducting spectrometers are usually exposed to fields of 1 T, whereas fields around isotope separation units can be as high as 50 mT although they are usually less than 1 mT (Roy and Repacholi, 2003).

22.2 Interaction Mechanisms

22.2.1 Static Electric Fields

As in the case of an extremely low frequency (ELF) field (Chapter 17), a static electric field is perturbed by conducting objects like the human body. The field does not penetrate the conducting body and is always perpendicular to the body surface, inducing a surface charge. At sufficiently high field strengths, this charge may be perceived through its interaction with body hair, particularly on the head or limbs (Repacholi and Greenebaum, 1999; IARC, 2002).

An electrically grounded person touching a charged insulated metal object will draw current from the object and may experience an electric shock or spark discharge. Similarly, a person walking, across a carpet in a dry atmosphere, becomes charged and discharges on touching a grounded metallic object (Repacholi and Greenebaum, 1999). The actions of direct contact or spark discharge can result in effects ranging from perception, to pain, to burn.

22.2.2 Static Magnetic Fields

Static magnetic fields are almost unperturbed by the human body and interact directly with magnetically anisotropic (polarized) or ferromagnetic materials and with moving charges (currents) (Repacholi and Greenebaum, 1999). There are three classes of physical interactions of static magnetic fields with biological systems: (i) magnetic induction, (ii) magnetomechanical effect, and (iii) electronic effects (ICNIRP, 2009).

22.2.2.1 Magnetic Induction

Magnetic fields exert *Lorentz forces* on moving ions in solution and thereby give rise to induced electric fields and currents. This interaction leads to the induction of electric field and electrical potential and is the basis of magnetically induced potentials observed in blood flow measurement. This is also known as the Hall effect. Flow potentials due to external magnetic fields are generally associated with ventricular contraction and the ejection of blood into the aorta in animals and humans (where blood velocity is highest). The Lorentz interaction also results in a magnetohydrodynamic force opposing the flow of blood (ICNIRP, 1994; IARC, 2002; WHO, 2006). The reduction of aortic blood flow has been estimated to reach about 5% at 10 T and 10% at 15 T (van Rongen et al., 2007). Flow potentials may also affect cardiac function (heart rate and rhythm) at fields higher than 8 T (ICNIRP, 2009).

Movement of the whole or part of the body, for example, eyes and head, in a static magnetic field gradient will also induce an electric field and current during the period of movement. Theoretical calculations suggest that such induced tissue electric fields will be substantial during normal movement around or within fields greater than 2–3 T and may account for the numerous anecdotal reports of vertigo and nausea and occasionally magnetophosphenes experienced by patients, volunteers, and workers moving in the field (van Rongen et al., 2007; ICNIRP, 2009).

22.2.2.2 Magnetomechanical Effect

Uniform static magnetic fields can align magnetically anisotropic structures, for example, the movement of a compass needle in the Earth's natural static magnetic field. Since the amount of magnetically anisotropic material in the human body is minimal, this effect is not considered of importance for human health (WHO, 2006; van Rongen et al., 2007).

Magnetic field gradients can cause movement of paramagnetic and ferromagnetic materials. The forces and torques exerted on metallic objects can be of concern to (i) people with pacemakers and metallic implants and (ii) patients in MRI units (metallic objects being propelled into the bore of the MRI unit) (WHO, 2006; van Rongen et al., 2007).

22.2.2.3 Electron Spin Interactions

The third mechanism relates to the *Zeeman effect*, whereby a static magnetic field changes the energy levels of certain molecules. One consequence of the Zeeman effect is to change the probability of recombination of pairs of radicals formed in certain biochemical processes. This may result in changes in the concentration of free radicals, which can be highly reactive (IARC, 2002).

Although experimental evidence for such effects in biochemical systems has been reported their biological significance is not clear at present. This "radical pair mechanism" has been suggested as a mechanism by which animals, particularly birds, may use the Earth's magnetic field as a source of navigational information during migration, and there is some experimental support for this view (ICNIRP, 2009). There is further mention of this in Chapter 17.

22.3 Health Effects

Several reviews have been published on the biological and health effects of exposure to static electric and magnetic fields. They include Kowalczuk, Sienkiewicz, and Saunders (1991), IARC (2002), ICNIRP (2003), WHO (2006), and ICNIRP (2009). These publications provide more details of the scientific literature, which will be summarized in this chapter.

22.3.1 Static Electric Fields

As discussed earlier, a static electric field will not penetrate the body, but will induce a surface charge on exposed humans, which may be perceived by its interaction with body hair and by other effects such as spark discharges (microshocks) or burns if the discharge is very large (Repacholi and Greenebaum, 1999; IARC, 2002; WHO, 2006). The perception threshold by humans is dependent on various factors and can range between 10 and 45 kV/m. Data on annoying sensation thresholds is scarce but it is likely that they are also quite variable. Microshocks that cause pain can arise when a person who is well insulated from the ground touches a grounded object or when a grounded person touches a conductive object that is well insulated from ground. However, the threshold static electric field values for microshocks will vary depending on the degree of insulation and other factors (WHO, 2006). There is little biological evidence from experimental studies on animals or humans showing any other adverse health effects (WHO, 2006).

22.3.2 Static Magnetic Fields

22.3.2.1 *In Vitro* Studies

A number of different biological effects of static magnetic fields have been explored *in vitro*. Studies of cell-free systems (isolated membranes, enzymes, or biochemical reactions), isolated cells, or tissue samples have investigated cell orientation, cell metabolic activity, cell membrane physiology, gene expression, cell growth, and genotoxicity (WHO, 2006; ICNIRP, 2009).

The *in vitro* studies have reported mixed results for all the endpoints that have been investigated. However, most data have not been replicated. The observed effects are rather diverse and were found after exposure to a wide range of magnetic flux densities of up to 8 T. Thresholds for some of the effects were reported, but other studies indicated nonlinear responses without clear threshold values (WHO, 2006; ICNIRP, 2009).

Overall, there is little convincing evidence from the *in vitro* studies that are indicative of any health effects.

22.3.2.2 Animal Studies

A large number of animal studies have investigated various endpoints including cardiovascular effects, neurobehavior, reproduction and development, and geomagnetic field orientation and navigation (Kowalczuk, Sienkiewicz, and Saunders, 1991; IARC, 2002). Few studies, however, have examined possible chronic effects of exposure, particularly in relation to cancer (WHO, 2006; ICNIRP, 2009).

Several studies with rodents exposed to field levels ranging from milliteslas to 10 T have led to reports of minor changes in cardiovascular parameters such as blood pressure and flow rate (Ichioka et al. 2000; Okano, Masuda, and Ohkubo, 2005; Okano and Ohkubo, 2006). However, these studies were prone to confounding factors (such the effect of anesthesia on the animals), and the reported effects have not been independently replicated (ICNIRP, 2009).

In neurobehavioral studies, the most consistent responses seen suggest that the movement of laboratory rodents in static magnetic fields equal to or greater than 4 T may be unpleasant, inducing aversive responses and conditioned avoidance (Weiss et al., 1992; Nolte et al., 1998; Houpt et al., 2003). Such effects are thought to result from magnetohydrodynamic interactions between the static magnetic field and the vestibular system of the animals (ICNIRP, 2009).

Exposure to static fields of up to 6 T has not been demonstrated to have an effect on fetal growth or postnatal development in mice (Sikov et al., 1979; Konermann and Monig, 1986; Murakami, Torii, and Masuda, 1992; Okazaki et al., 2001).

There is a great deal of evidence that several vertebrate and invertebrate species are able to use static magnetic fields, at levels as low as geomagnetic field strengths, for orientation and navigation. Certain species can detect small changes in the geomagnetic field. These effects could be significant for humans (WHO, 2006).

Several other endpoints that have been studied including the immune, haematopoietic, and endocrine systems have not provided convincing evidence of any adverse effects (WHO, 2006; ICNIRP, 2009).

22.3.2.3 Human Experimental Studies

A number of experimental studies on humans have investigated the effects of static magnetic fields up to 8 T on sensory perception, cognitive function, and physiological parameters (IARC, 2002; ICNIRP, 2009).

Several studies have reported that individuals exposed to static magnetic fields above 2–3 T in or near an MRI system experience transient sensory effects associated with movement in a static field gradient such as vertigo, dizziness, nausea, a metallic taste, and magnetophosphenes when moving the eyes or head (Schenck et al., 1992; de Vocht et al., 2006a, 2006b; Atkinson et al., 2007; Patel et al., 2008). Sensitivity to these effects varied considerably between individuals; however, it has been reported that the incidence and severity of these symptoms can be decreased by slowing the movement of an individual through the magnetic field gradient (Chakeres and de Vocht, 2005). How patients and health personnel move in a static magnetic field gradient is therefore an important issue (Heinrich et al., 2011).

Cognitive effects such as memory, speech, and auditory–motor reaction time have been investigated by several studies including Chakeres and de Vocht (2005), Chakeres, Bornstein, and Kangarlu (2003), Kangarlu et al. (1999), and Sweetland et al. (1987). Generally, no cognitive effects were observed in these studies following stationary exposure to MRI static magnetic fields of up to 8 T. In a series of studies, de Vocht and coworkers have reported negative effects on eye–hand coordination and visual contrast sensitivity associated with head movement in static magnetic fields between 0.5 and 1.6 T (ICNIRP, 2009).

Some human studies have investigated cardiovascular effects and other physiological parameters. Chakeres et al. (2003) and Kangarlu et al. (1999) reported that following exposure to an 8 T static field, volunteers showed no change in heart rate, diastolic or systolic blood pressure, or body temperature compared with values measured before exposure (Repacholi and Greenebaum, 1999; IARC, 2002). These findings were confirmed in the more recent study by Atkinson et al. (2007) where the strength of the static magnetic field was 9.4 T.

Overall, the results from the human studies do not point to any serious health effects resulting from the stationary exposure to static magnetic fields up to 8 T. It should be noted, however, that such high exposures can lead to various sensory effects and in the underperformance of some cognitive tasks during head or body movement; these effects are expected to be temporary (ICNIRP, 2009).

22.3.2.4 Epidemiological Studies

Epidemiological studies have mainly been carried out in occupational groups because general population exposure to static magnetic fields is very small compared to that of workers (Repacholi, 1988).

There have been relatively few studies of cancer incidence in workers exposed to static magnetic fields. Budinger et al. (1984) found no excess cancer in workers exposed to 0.3 T fields from particle accelerators, and Barregard, Jarvholm, and Ungethum (1985) found no excess cancer in workers exposed to 10 mT fields in a chlorine production plant (Moulder, 2003). Two other studies on the chlorine production industry by Barregard, Sallsten, and Jarvholm (1990) and Ellingsen et al. (1993) reported modestly increased risks for lung cancer; however, these studies did not conduct static field measurements and there was no information on smoking histories. Chlorine production workers are also exposed to asbestos, polychlorinated naphthalenes, and dioxins, as well as time-varying magnetic fields (Feychting, Ahlbom, and Kheifets, 2005).

There are also several studies of aluminum reduction plant workers. In general, these studies were not designed to analyze the effects of static fields, but aluminum reduction plant workers are exposed to fields of 5–15 mT (Moulder, 2003). The first study on aluminum plant workers by Andersen et al. (1982) reported an increased incidence of lung cancer; however, interpretation of this result was limited due to incomplete smoking histories. Other studies showing an association with cancer include Rockette and Arena (1983) who reported indications of higher than expected mortality from pancreatic, genitourinary, and lymphohematopoietic cancers and Milham (1985) who reported significantly elevated mortality from leukemia. In another small study, cancer mortality and mortality from all causes in French aluminum workers were not found to differ significantly from that observed for the general male population (Mur et al., 1987). Other studies by Spinelli et al. (1991), Rønneberg and Andersen (1995), and Ronneberg et al. (1999) did not show an increased mortality due to static magnetic fields. In general, control of confounding has been limited in studies of aluminum plant workers who are exposed to various agents including chemical fumes, heat, and time-varying fields (Feychting, Ahlbom, and Kheifets, 2005).

There have been several studies that have investigated cancer risks among welders. However, none of these studies have estimated the exposure to static magnetic fields, and it is impossible to distinguish between effects caused by welding fumes, static fields, or time-varying fields. Studies of welders have been reviewed by Kheifets et al. (1995, 1997).

Some studies have looked at fertility, miscarriages, and birth defects. Kanal et al. (1993) and Evans et al. (1993) found no effect on fertility, miscarriage rates, or birth defects in the offspring of female MRI operators possibly involving exposures of static fields up to 1 T. Mur et al. (1998) found no significant effects on the fertility of men exposed to 4–30 mT static fields in the aluminum industry. Two nonoccupational studies generally found no major defects in offspring to women exposed to MRI during pregnancy (Myers et al., 1998) or developmental effects to children exposed to MRI after birth (Clements et al., 2000).

Looking at other effects, Marsh et al. (1982) found no major health problems in electrolytic plant workers. Davis and Milham (1990) reported effects on the immune system of potroom workers; however, Tuschl et al. (2000) did not find immune system effects on MRI workers. Skyberg, Hansteen, and Vistnes (1993) reported no chromosomal aberrations on laboratory cable splicers who are also exposed to high time-varying fields. Finally, Moen et al. (1995, 1996) found no musculoskeletal disorders in various workers exposed to static magnetic fields.

Overall, the current epidemiological research on static magnetic fields has many methodological limitations including poor or nonexistent exposure assessment, the results are based on small numbers and there is a lack of control for confounding (ICNIRP, 2009). A particular problem is that workers exposed to static magnetic fields are also exposed to a wide variety of other potentially harmful agents, including some established carcinogens. Therefore, the available evidence from epidemiological studies is not sufficient to draw any conclusions about potential health effects of static magnetic field exposure (Feychting, Ahlbom, and Kheifets, 2005).

22.4 Low-Level Effects

Current scientific knowledge does not suggest any detrimental effect on major developmental, behavioral, and physiological parameters for exposure to static magnetic fields up to 2 T. From analysis of the established interactions, long-term exposure to low-level magnetic fields should not have adverse consequences (ICNIRP, 2009). There are various laboratory studies that have reported biological effects at low levels and these have been reviewed elsewhere (WHO, 2006; ICNIRP, 2009). In general, studies reporting biological effects at low levels have not always been consistent and the results have not been adequately confirmed.

22.5 Interference with Implanted Medical Devices

Electrically powered medical devices can be susceptible to interference from static electric and magnetic fields, particularly if the person is moving within the field. Examples of such devices include cardiac pacemakers, defibrillators, drug delivery pumps, neurostimulators, and hearing aids. While several types of medical devices have been designed for immunity to electrical interference (e.g., cardiac pacemakers), many devices in use have not been designed or tested for immunity. Even with reasonable immunity to interference, serious patient consequences may occur if the immunity is exceeded (ICNIRP, 1994; IEEE, 2002).

Current static field guidelines restrict exposures for wearers of cardiac pacemakers and other electronic devices to 0.5 mT (see Chapter 16) (ICNIRP, 2009).

A variety of nonelectronic prosthetic devices implanted in patients could be made of ferromagnetic materials that could change position when the patient moves into an elevated static magnetic field. Such devices include aneurysm clips, pins and orthopedic rods, and plates. Movements or dislodgements, possibly caused by magnetic fields, depend on a number of factors including the strength and gradient of the field, the degree of ferromagnetism of the implant or material, its size, and its orientation with respect to the field. There is no evidence that static magnetic fields of 0.5 mT or lower would exert sufficient forces to change the position of such devices and create a health hazard (ICNIRP, 2009).

Tutorial Problems

1 What sort of static magnetic field strength will you be exposed to when standing within centimeters of an audio speaker (clue: audio speakers contain permanent magnets)?

2 Do static electric fields penetrate the human body?

3 Have static magnetic fields that are normally encountered in the everyday environment been proven to cause cancer or any other health effects?

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23

Static Electric and Magnetic Field Guidelines

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23.1 Introduction

The development of new technologies using static electric and magnetic fields has increased the likelihood of human exposure to these fields and raised some concern as to the possibility of adverse health effects. Guidelines and standards have been issued nationally and internationally by health authorities and radiation protection organizations for the safe exposure of workers and the general public (Grandolfo and Vecchia, 1996; ICNIRP, 2009a).

23.2 Static Electric Fields

There are no good data on which to base limits of human exposure to static electric fields. Theoretically, an exposure limit could be derived from the minimum breakdown voltage for air; however, the field strength experienced by a person within a static electric field will vary according to body orientation and shape, and this would have to be accounted for in deriving an appropriate limit (Grandolfo and Vecchia, 1996).

The former National Radiological Protection Board (NRPB, now Public Health England) in the United Kingdom provided advice on restrictions of human exposure to electromagnetic fields up to 300 GHz in 1993 (NRPB, 1993), and the advice was updated in 2004 (NRPB, 2004). The advice also includes recommendations for static electric and magnetic fields. According to the NRPB guidelines, it is not possible to recommend basic restrictions to avoid direct effects of human exposure to static electric fields. Guidance is given to avoid annoying effects of direct perception of the surface electric charge and

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indirect effects such as electric shock. For most people, the annoying perception of surface electric charge, acting directly on the body, will not occur during exposure to static electric field strengths less than about 25 kV/m.

The Institute of Electrical and Electronic Engineers (IEEE) in the United States developed a standard for human exposure to electromagnetic fields in the frequency range 0–3 kHz in 2002 (IEEE, 2002). The IEEE specifies a general public limit for static electric fields of 5 kV/m noting that at that level induced spark discharges will be painful to approximately 7% of adults (well-insulated individuals touching ground). In a controlled environment (occupational exposure), the IEEE limit is set at 20 kV/m although this may be exceeded when a worker is not within reach of a grounded conducting object (a specific limit is not provided in the standard).

Threshold limit values for static electric fields have been recommended by the American Conference of Governmental Industrial Hygienists (ACGIH, 2008). The threshold limit values refer to the maximum unprotected workplace static electric field strength that represents conditions under which it is believed that nearly all workers may be exposed to repeatedly without adverse health effects. According to ACGIH, occupational exposures should not exceed a static electric field strength of 25 kV/m, that is, the same field strength recommended by the NRPB. The ACGIH points out that this value should be used as a guide in the control of exposure and, due to individual susceptibility, should not be regarded as a fine line between safe and dangerous levels. This limit refers to the field strength present in air, away from the surfaces of conductors, where spark discharges and contact currents may pose significant hazards, and is intended for both partial-body and whole-body exposures. ACGIH also recommends that, lacking specific information from the manufacturer on electromagnetic interference, the exposure of pacemaker and medical electronic device wearers should be maintained at or below 1 kV/m.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP), which has published guidelines for extremely low frequency fields (ICNIRP, 2010) and static magnetic fields (ICNIRP, 2009a), does not extend its guidelines to static electric fields. However, at 1 Hz, ICNIRP specifies limits of 5 and 20 kV/m for general public and occupational exposure, respectively (ICNIRP, 2010).

The different guidelines for limiting human exposure to static electric fields are given in Table 23.1.

23.3 Static Magnetic Fields

Existing guidelines base their static magnetic field limits on several considerations. Electrical currents induced by movement through a static magnetic field must be kept to a level less than those that occur naturally in the body. In addition, the electrical currents induced in large blood vessels by blood flow must

Table 23.1 Different static electric field guidelines.

Guideline	Static electric field (kV/m)	
NRPB, UK (1993)	25	Workers and general public
IEEE, USA (2002)	20	Workers
	5	General public
ACGIH, USA (2008)	25	Workers
	1	Medical electronic device wearers

be kept to a level that will not produce hemodynamic or cardiovascular effects. Lastly, the issue of interference with implanted medical devices must be considered (see Chapter 22) (ICNIRP, 2009a).

ICNIRP published guidelines for exposure to static magnetic fields in 1994 (ICNIRP, 1994) and these were updated in 2009 (ICNIRP, 2009a). In these guidelines, a distinction is made between exposure limits for workers and the general public. For occupational exposure, the exposure limit is 2 T for the head and trunk and 8 T for the limbs. When the environment is controlled and appropriate work practices have been implemented to control for movement-induced effects, a limit of 8 T is also acceptable for the head and trunk. For the general public, a reduction factor of 5 with respect to the occupational limit for the head and trunk is applied; so the ICNIRP general public limit is 400 mT for any part of the body, except for persons with cardiac pacemakers and other implanted electronic devices, where the exposure limit is 0.5 mT.

The IEEE 2002 standard specifies limits for static magnetic field exposure (IEEE, 2002). IEEE noted that a host of adverse effects have been reported at 1.5 T, including vertigo, difficulty with balance, nausea, headaches, numbness and tingling, and unusual taste sensations. The IEEE therefore adopted the 1.5 T level as a median threshold value for adverse effects. A peak value of 1.5 T is associated with a slowly varying sinusoidal field of 1.06 T (RMS). Consequently, the limit of 353 mT was set at a factor of 3 below the median for controlled environments, noting that the affected population of sensitive individuals is estimated to be less than 1% of exposed individuals. For the general public, the IEEE applied an additional safety factor of 3, which leads to the value of 118 mT.

The threshold limit values issued by ACGIH in 2008 refer to static magnetic flux densities to which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects (ACGIH, 2008). The ACGIH time-weighted limit is 60 mT for whole-body exposure and 600 mT for exposure of the extremities (averaged over 8 hours). The ACGIH also specifies maximum ceiling values of 2 T for the whole body and 5 T for the extremities. The static magnetic field limit is 0.5 mT at any time for pacemaker users or others with implanted electronic devices.

The European Union (EU) issued a directive in 2013 on the minimum health and safety requirements regarding the exposure of workers to electromagnetic fields including limit values for static magnetic fields. Based on sensory effects resulting from moving in a static magnetic field, the EU directive specifies a limit of 2 T for the whole-body and 8 T for the limbs under normal working conditions. Under controlled working conditions including controlling movements and providing information to workers, the EU directive specifies a limit of 8 T.

The different guidelines for limiting human exposure to static magnetic fields are given in Table 23.2.

23.4 Magnetic Resonance Imaging Guidelines

Magnetic resonance imaging (MRI) has become an established medical diagnostic tool. MRI together with magnetic resonance spectroscopy (MRS)

Table 23.2 Different static magnetic field guidelines.

Guideline	Static magnetic field (T)	
ICNIRP (2009a)	*General public*	
	0.0005	Persons with implanted electronic devices
	0.4	Any part of the body
	Occupational	
	2	Head and trunk
	5	Limbs
ACGIH, USA (2008)	*Occupational*	
	0.0005	Persons with implanted electronic devices
	0.06	Whole-body (averaged over 8 h)
	2	Whole-body maximum
	0.6	Extremities (time-weighted-average)
	5	Extremities maximum
IEEE, USA (2002)	*General public*	
	0.118	Peak exposure
	Occupational	
	0.353	Peak exposure
EU (2013)	*Occupational*	
	2	Normal working conditions
	8	Localized limbs and controlled conditions

involve exposure of the patient and operator to strong static magnetic fields of up to 7 T or higher (it must also be noted that MRI also involves exposure to time-varying magnetic fields and radiofrequency electromagnetic fields). Since MRI procedures continue to expand with regard to usage and complexity, safety issues and related guidelines are important aspects of this diagnostic modality (ICNIRP, 2004).

ICNIRP issued a statement on MRI procedures for the protection of patients in 2004 and amended the statement in 2009 (ICNIRP, 2004, 2009b). The amended advice recommends a three-tier approach to limiting the static magnetic fields from MRI procedures to patients. For routine examinations, ICNIRP recommends an upper limit for whole-body exposure of 4 T (normal operating mode). This increases to 8 T for specific examinations where discomfort and/or adverse effects for some patients may occur (controlled operating mode); ICNIRP advises that a clinical decision must be made on balancing adverse effects with any diagnostic benefits. Finally, ICNIRP recommends exposures higher than 8 T only in special experimental conditions where ethical approval may be required (experimental operating mode).

For workers involved in the installation, testing, use, development, maintenance, or research related to MRI for patients, the EU 2013 directive has specified conditions where exposure to static magnetic fields may exceed 8 T (EU, 2013). This provision acknowledges the benefits of certain life-saving or life-preserving services to the public, such as the use of MRI.

23.5 Summary

Guidelines and standards have been developed by several health authorities to protect against established effects from static fields. Although all the guidelines use the same effects as their basis there is disparity between their exposure limits. This disparity can be attributed to using different studies that show different thresholds as well as the application of different safety factors in the limits. In general, limits have become less conservative in recent years since the nature of the risks is better understood.

Tutorial Problems

1 What is the basis for setting safety guidelines for static electric fields?

2 What is the basis for setting safety guidelines for static magnetic fields?

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Part VII

Dealing with Hazard Perception

24

Perceived Hypersensitivity: Anecdotal Versus Objective Evidence

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24.1 Introduction

Reports of individuals experiencing a range of unpleasant and debilitating symptoms when in the vicinity of devices or infrastructure emitting electromagnetic fields (EMFs) have been increasing since the 1970s. These individuals suffer from a condition that is commonly referred to as electromagnetic hypersensitivity (EHS). EHS is a condition characterized by a variety of physical and subjective symptoms that the sufferer attributes to EMF exposure. Headaches, burning sensations, tinnitus, nausea, difficulty concentrating, and sleeping problems are among the most frequently reported symptoms. Generally, these symptoms are claimed to be triggered by devices that utilize the radiofrequency (RF) and extremely low frequency (ELF) domain of the nonionizing radiation (NIR) spectrum, including mobile phones and their base stations, Wi-Fi, electricity transmission and distribution systems, and, more recently, Advanced Metering Infrastructure or "smart" meters. The type, frequency, duration, and severity of the symptoms experienced, and the devices claimed to trigger these symptoms, vary widely between EHS sufferers.

The etiology of EHS is extremely controversial. In stark contrast to the growing anecdotal reports of sensitivity to EMF, the majority of the observational and experimental studies conducted to date have not found evidence that exposure to EMF is the cause of EHS symptoms (Röösli et al., 2010; Rubin, Das Munshi, and Wessely, 2005; Rubin, Nieto-Hernandez, and Wessely, 2010). This is consistent with the views of a range of leading international health bodies who, on the

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basis of reviews of the scientific literature, have concluded that there are no established health risks associated with EMF from wireless technologies more generally nor any established mechanism by which this could occur (Health Canada, 2015; Health Council of the Netherlands, 2009; SCENIHR, 2009; World Health Organization, 2014). It is important to note, however, that the International Agency for Research on Cancer (IARC) has classified ELF magnetic fields and RF as 2B "possible carcinogens", but emphasized that the evidence for an increase in glioma and acoustic neuroma among users of mobile phones was limited and that the evidence for an increase in other cancers was inadequate (World Health Organization, 2014).

The current discrepancy between the scientific evidence and the reports of those who experience EHS not only leaves the public feeling uncertain and anxious about the potential adverse health risks associated with EMF exposure but also limits the treatment and support offered to EHS sufferers. For some sufferers, the effects of these symptoms have been kept under control by minimizing the use of certain EMF-emitting devices or by avoiding them altogether. But for others the symptoms have not proven manageable through avoidance, often leading to resignation from employment or domestic relocation. Unfortunately, some of the remedies offered can involve considerable cost without tangible benefit, and medical practitioners who come into contact with people who experience EHS often have only rudimentary knowledge of the condition and how to appropriately support their patient. Simply fostering the patient's belief that it is caused by EMF or dismissing the condition as a "psychological reaction to new technology" are both inadequate responses to a phenomenon that can be debilitating, and careful consideration about the patient's situation is required.

This chapter explores the anecdotal and objective evidence regarding perceived sensitivity to EMF. The first section discusses the history and prevalence of EHS and provides a brief overview of the symptoms that have been anecdotally reported to be caused by EMF exposure. The second section outlines the current scientific view and highlights some of the methodological issues that challenge research in this field. The final section reviews some of the treatments and interventions offered to EHS sufferers.

24.2 Anecdotal Evidence of Sensitivity to Electromagnetic Fields

24.2.1 History and Terminology

Anecdotal reports of sensitivity to devices that utilize EMF are not a new phenomenon. In the late 1970s, reports of facial skin symptoms related to workers using visual display terminals (VDTs) arose throughout Great Britain and Norway and were followed by similar reports in Sweden, the United States, and Japan in the 1980s (Lindén and Rolfsen, 1981; Nilsen, 1982; World Health

Organization, 2004). As technology has progressed,[1] so too has the reported sensitivity to devices that emit EMF, with emitters such as mobile phone and Wi-Fi systems, and more recently Advanced Metering Infrastructure (or "smart" meters), now claimed to adversely affect individuals. The symptoms reported are purportedly triggered by levels of EMF that are well below the thresholds known to cause adverse health effects in humans (ICNIRP, 1998, 2010).

In 2004, the World Health Organization (WHO) proposed that the term "idiopathic environmental intolerance attributed to electromagnetic fields" (IEI-EMF) be used in place of EHS (World Health Organization, 2004), in order to avoid implying a causal role of EMF in producing the reported symptoms. The term IEI was previously introduced as a descriptor for Multiple Chemical Sensitivity (MCS) and is a descriptor that does not make any assumptions of chemical etiology, immunological sensitivity, or EMF sensitivity. Despite the WHO recommendation, a review of experimental and cross-sectional studies published in 2011 revealed that this terminology was only adopted by 1% of studies investigating this condition with the majority instead using the terms "hypersensitivity to EMF", "EHS", "HS", "sensitivity to EMF", or "electrosensitivity" (Baliatsas et al., 2012). Consistent with the WHO recommendation, this chapter uses the term "IEI-EMF" regardless of the terminology employed by the individual studies discussed within.

It is important to note that while the IEI descriptor is defined as being a disorder that cannot be explained by other known psychiatric or somatic illnesses, people who experience IEI have been found to often meet the diagnostic criteria for DSM-IV disorders, or known psychiatric or well-defined somatic conditions that account for the symptoms reported by the IEI individuals (Bornschein et al., 2002). Despite this, a recent review of the literature found that the majority of studies investigating IEI-EMF did not screen participants for these conditions (Baliatsas et al., 2012), making psychiatric illness a potential confounder in the research.

24.2.2 Prevalence

Currently, there is no established diagnostic criterion available to identify individuals who experience IEI-EMF, making it difficult to establish the prevalence of the condition. The most common inclusion criteria for studies investigating this condition are individuals who self-identify as "EHS" or "IEI-EMF" sufferers or self-report attributing health problems to EMF exposure. While there is evidence that not all individuals attributing health complaints to EMF exposure identify themselves as "being EHS" (Kato and Johansson, 2012; Schüz et al., 2006), a number of studies have attempted to estimate the prevalence rate of the condition. As seen in Table 24.1, prevalence estimates differ substantially between regions and studies.

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[1] Note that modern computer designs no longer employ Cathode Ray Tubes, substantially reducing the exposure to NIR and associated concerns.

Table 24.1 Estimated prevalence rates of IEI-EMF.

Country	Prevalence (%)	Sources
Sweden	1.5	Hillert et al. (2002)
California	3.2	Levallois et al. (2002)
Austria	3.5	Schröttner and Leitgeb (2008)
Netherlands	3.5	Baliatsas et al. (2015)
United Kingdom	4.0	Eltiti et al. (2007)
Switzerland	5.0	Schreier, Huss, and Röösli (2006)
Germany	~10	Blettner et al. (2009)
Taiwan	13.3	Tseng, Lin, and Cheng (2011)

It is possible that the differences in IEI-EMF prevalence rates may reflect differences in the questions asked and the time of the survey being administered, rather than an actual difference in prevalence rate. As such, the prevalence of IEI-EMF should be noted with caution, as the figures presented in Table 24.1 may represent an over- or under-estimate of IEI-EMF prevalence.

24.2.3 Characteristics of IEI-EMF

A number of case studies and cross-sectional survey studies have been published documenting the variety of symptoms that people attribute to a wide range of EMF sources. These studies offer valuable insight into the everyday experiences of people who suffer from IEI-EMF.

Cross-sectional survey data reveal that IEI-EMF is characterized by a broad range of dermatological, neurasthenic, vegetative, and mood symptoms. Typically, reported symptoms include headaches, nausea, skin irritations, tinnitus, fatigue, dull pain, and concentration difficulties. IEI-EMF individuals report symptoms in response to a range of EMF sources including mobile and cordless phones, mobile phone base stations, personal computers, ELF (i.e., power lines, electrical appliances, and railroads), MRIs, and UV from sunlight. The EMF sources that IEI-EMF individuals report hypersensitivity to are sometimes specific (e.g., report responding to one source only), while for others, they are general (e.g., report responding to a range of, or "all" EMF sources). IEI-EMF sufferers also sometimes report that the EMF sources responsible for triggering the onset of symptoms differ from those causing symptoms when they are already experiencing symptoms (Hagström, Auranen, and Ekman, 2013; Kato and Johansson, 2012; Röösli et al., 2004; Schüz et al., 2006).

Survey studies also illustrate that IEI-EMF is an extremely heterogeneous condition. The type, number, frequency, and severity of symptoms experienced by IEI-EMF sufferers can differ substantially between individuals. The time taken for symptoms to develop and subside also varies largely between IEI-EMF individuals. For example, some sufferers experience short-lasting, "acute" symptoms in relation to using or being in the vicinity of people using a mobile phone, while others report more prolonged and debilitating symptoms that they claim are the result of a build-up of exposure from a variety of sources over time (Hocking, 1998; Röösli et al., 2004).

It is important to note that many of the symptoms typically reported by IEI-EMF individuals closely overlap with MCS as well as a number of other disorders commonly seen in the general population. For example, sleep, skin, and concentration problems, as well as headaches, nervousness, nausea, and other nonspecific symptoms, are also present in thyroid dysfunction, liver disease, anemia, kidney disease, and chronic inflammation (Dahmen, Ghezel-Ahmadi, and Engel, 2009). Notably, compared to healthy individuals, those identifying themselves as being sensitive to EMFs also report a greater sensitivity to a range of other "nuisance" factors such as furry animals, pollen, dust, mites, mould, food, gluten, amalgam (or other) dental fillings, nickel, and cosmetics and report a higher prevalence of being disturbed (on at least a weekly basis) by noise from neighbors, ventilation systems, and traffic; by car exhaust, street smells, soot, dust, stuffy, or dry air; and by low room temperatures (Hillert et al., 2002).

Apart from the physical impairments experienced by IEI-EMF sufferers, these individuals also report a significant degree of social, mental, functional, and financial strain on their lives. Individuals with IEI-EMF also report increased levels of distress, health service use, moving away from cities to areas perceived as "safer" or "low-EMF", and being either partly or completely unable to work due to their IEI-EMF-related health issues (Hagström, Auranen, and Ekman, 2013; Johansson et al., 2010; Kato and Johansson, 2012; Röösli et al., 2004; Rubin, Nieto-Hernandez, and Wessely, 2010).

24.2.4 Conclusions

The significant impairment suffered by IEI-EMF individuals suggests a clear need to determine whether EMF exposure causes their symptoms. However, the cross-sectional, anecdotal reports of individuals' attribution of symptoms to EMF sources cannot comment on the existence of a causal relationship between EMF and symptomatology (Hocking, 1998). In most of the above-mentioned studies, no measures of EMF exposure were taken, and where they were, such retrospective self-reports are known to suffer from recall bias (Vrijheid et al., 2009). Further, these studies cannot account for the possibility that belief *about* EMF (rather than the EMF itself) may be responsible for the symptoms, which has been demonstrated to occur (Szemerszky et al., 2010). Nevertheless, the characterization of individual cases can generate hypotheses that can then be tested in epidemiological and randomized, double-blind, provocation studies in order to address questions of association and causation, respectively. These types of studies are considered in the following section.

24.3 Objective Evidence of Sensitivity to Electromagnetic Fields

Science has tried to understand IEI-EMF through both observational epidemiological studies and experimental laboratory studies. Many studies of varying quality have been conducted and continue to be undertaken in the hope of resolving the etiological debate.[2] This section provides a brief outline of some of the recent objective evidence regarding IEI-EMF. While sensitivity to a whole range of devices that emit different EMFs has been reported (as seen in the previous section), here we concentrate mainly on studies that have investigated the effect of exposure to RF emitted from mobile phone base stations and handsets, as these have been the cause of the most concern and researched more thoroughly in recent times.

24.3.1 Studies Addressing Association

Epidemiological cross-sectional studies attempt to find an association between symptom reports and exposure, by estimating the amount of exposure individuals (who may or may not believe that they are sensitive to EMF exposure) are receiving in their daily lives in relation to the type, frequency, and severity of the nonspecific symptoms that they experience. These studies have primarily investigated the relation between symptoms and RF emissions from mobile phone base stations. One of the major benefits of these studies (over laboratory studies) is that they allow for the investigation of longer exposure periods and symptom outcomes in large samples under normal living conditions. A number of epidemiological studies have been conducted, with varying methods and results.

Two recent studies have reported significant associations between symptoms and exposure to EMF. Hutter et al. (2006) found a relationship between exposure level and headache score in large a sample of people living near 10 selected mobile phone base stations. Similarly, Abdel-Rassoul et al. (2007) reported a higher prevalence of neuropsychiatric complaints, including symptoms such as headaches, in a sample of people living and working near a base station than matched controls. The majority of studies assessing the association between symptom reports and exposure, however, have failed to show any significant relationship (Röösli et al., 2010).

While epidemiological studies attempt to bridge the gap between the anecdotal reports of IEI-EMF and the controlled laboratory studies investigating the causal role of EMF exposure in producing the reported symptoms, these studies face serious methodological limitations, especially in regards to exposure characterization. Many studies rely on the historical reconstruction of

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[2] The debate of the causes, origin, or the factors that produce or predispose toward a certain disease, disorder, or syndrome.

exposure history or the individuals perceived distance to an exposure source to estimate how much exposure a person has received, but this is prone to recall bias and often does not take into account the variety of near and far field sources to which people are exposed (Baliatsas et al., 2015). In a systematic review of this field, Röösli et al. (2010) found that epidemiological studies with crude exposure assessments show health effects, while studies with more sophisticated exposure measurements rarely indicate an association. The more sophisticated methods of exposure characterization include the use of spot measurements or personal exposure meters. But these again are limited, in that spot measurements can only provide information about exposure at specific locations and at specific times, while personal exposure meters can be influenced by a number of factors, including calibration, body shielding, and bias associated with the alteration of behavior when exposure levels become known to the participant (Baliatsas et al., 2015). Consequently, while epidemiological studies vary substantially in both quality and outcomes, the limitations associated with such studies make it difficult to conclusively determine whether exposure to EMF is associated with nonspecific symptoms or IEI-EMF itself.

24.3.2 Studies Addressing Causation

Experimental provocation studies offer a powerful method for testing whether the presence of electromagnetic energy is sufficient to trigger symptoms in individuals who experience IEI-EMF. Provocation studies involve volunteers being exposed to active and sham EMF under controlled conditions, preferably in a double-blind testing protocol.[3] Typically, these studies test whether people who report suffering from IEI-EMF are better at detecting EMF than people without the condition and whether sufferers of IEI-EMF respond to the presence of EMF with increased symptoms in the exposure condition compared to sham. Provocation studies typically investigate the response to specific types of EMF exposure that people report being sensitive to, such as those used by mobile phones and the infrastructure associated with such technology.

RF EMF provocation studies conducted over the past two decades have generally failed to provide evidence for a relationship between either mobile phone base station exposures or mobile phone handset exposures and a range of measures including symptom development and severity, well being, and a range of physiological and cognitive parameters (for a review see Röösli et al. (2010), Rubin, Das Munshi, and Wessely (2005), Rubin, Nieto-Hernandez, and Wessely (2010)). Some studies have found that sham RF exposure is sufficient to trigger symptoms, leading many researchers to suggest that IEI-EMF may be the result of a *nocebo* effect, where the conscious *expectation* of symptoms following a

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[3] A blinded protocol is where the participant (single blind) or both the participant and researcher (double blind) are not aware of the exposure condition.

perceived exposure to EMF leads to the formation or detection of symptoms (Landgrebe et al., 2008b; Oftedal et al., 2007; Rubin, Nieto-Hernandez, and Wessely, 2010).

Of the few provocation studies that have found significant effects in the IEI-EMF group, methodological problems have often confounded the results, including the failure to account for multiple significance tests, inadequate counterbalancing, and the deblinding of participants or researchers (Rubin, Nieto-Hernandez, and Wessely, 2010). These confounds appear to explain the failure to replicate such results in larger samples. For instance, although Hillert et al. (2008) found that neither the IEI-EMF nor a control group could detect RF exposure better than chance, a significant number of participants reported headache symptoms more commonly after RF exposure than sham. However, the effect was due to a rise in headache reporting in the control group and the statistical analyses were not corrected for multiple tests. In addition, one study reported that two IEI-EMF participants were able to accurately detect an active exposure condition at highly significant rates (Kwon et al., 2008); however, on a subsequent retest 6 months later, the same two participants were unable to replicate their results, suggesting that their initial performance was not related to a bioelectromagnetic phenomenon. Moreover, Nieto-Hernandez et al. (2011) reported increased ratings of headache and difficulty in concentration in IEI-EMF participants and increased levels of headache and fatigue in non-IEI-EMF participants following exposure to a continuous wave signal. Concentration difficulties were again reported for the IEI-EMF participants after exposure to a pulsed signal. However, after appropriate adjustment for multiple comparisons, these results were not significant. Furthermore, McCarty et al. (2011) reported that an IEI-EMF participant's symptoms were caused primarily by the field transitions created when switching from active to sham conditions, but this did not account for chance through statistics, and the results were not replicated (Rubin, Cleare, and Wessely, 2011).

24.3.3 Limitations to Provocation Studies

To date, the results of provocation studies suggest that IEI-EMF is not caused by exposure to EMFs (indeed, they do not provide any evidence that EMF exposure causes the reported symptoms). Yet, like epidemiological studies, provocation studies are challenged by several methodological limitations, some of which could potentially explain the inability of these studies to find an effect of exposure. One of these limitations relates to recruitment. Little is known about whether subsets of IEI-EMF exist and so it is conceivable that the samples tested may have included a combination of both individuals who are sensitive to EMF and others who may suffer from unrelated conditions. This could result in a large amount of noise being added to the data, which would reduce statistical power and mask any real effects.

Another issue is determining whether the environment that provocation studies are conducted in reflects the environment in which IEI-EMF individuals report symptoms. Often, studies are conducted in laboratories with specialized chambers that block out background EMF. While it is generally thought that this should increase the chances of detecting a true effect, it may potentially remove important synergistic elements present in the environment. Anxiety, which may be heightened due to participating in a laboratory experiment, may also mask effects. Participants may have also encountered other EMF exposures on the way to the experimental session that inadvertently triggers symptoms (Rubin et al., 2006; Rubin, Nieto-Hernandez, and Wessely, 2010). This again would mask any potential effects from being discovered.

Criticism has also been raised concerning the relevance of the simulated RF signals used in many of these studies to participants' reported symptoms (Panagopoulos, Johansson, and Carlo, 2015). Yet, the evidence so far suggests that similar symptoms are triggered during provocation studies, regardless of similarity of the exposure (and irrespective of the exposure status), which suggests that this is not an important confound.

24.3.4 Studies Addressing Physiological and Psychological Characteristics of IEI-EMF

Some studies have also attempted to address whether individuals who experience IEI-EMF differ from healthy controls using other measures that do not involve exposure to EMF, but which assess possible physiological, neurobiological, and psychological differences between the two populations. It may be, for example, that IEI-EMF involves a complex interplay of behavioral traits, cognitive strategies, nervous system vulnerability, genetic background, and other environmental factors (which may or may not include EMF exposure itself).

Several measures of central and autonomic nervous system function have been observed to differ between IEI-EMF individuals and healthy controls (Lyskov, Sandström, and Hansson Mild, 2001; Sandström et al., 1997). There is also evidence that a neurobiological predisposition, alongside other intrapersonal and external factors, may contribute to symptom manifestation in IEI-EMF individuals (Landgrebe et al., 2007, 2008b). IEI-EMF individuals have also been shown to exhibit specific dysfunctional cognitions (Landgrebe et al., 2008b) and have been found to have significantly higher rates of comorbidity with many psychiatric conditions such as major depression, generalized anxiety disorder, somatoform disorder, and elevated levels of modern health worries (Johansson et al., 2010; Landgrebe et al., 2008b; Rubin, Cleare, and Wessely, 2008). Further to this, significant alterations in cortical activity in brain regions involved in pain perception and the experience of unpleasantness have been observed following sham exposure to mobile phone radiation (Landgrebe et al., 2008a).

24.3.5 Conclusions

It is evident that IEI-EMF is a complex condition that is not adequately understood by current scientific models. The rising prevalence of the condition potentially conflicts with the notion that exposure to nonionizing electromagnetic radiation does not pose any substantiated health risk to humans. However, once methodological limitations have been taken into account, epidemiological cross-sectional studies have provided no evidence of an association between exposure from base stations and IEI-EMF symptoms, provocation studies have not provided evidence that the symptoms reported by IEI-EMF are caused by exposure to EMF, and there is some evidence that the nocebo response can explain IEI-EMF. Yet, due to several methodological limitations and a lack of understanding about the nocebo effect, it is premature to conclude that exposure to EMF does not play a role in IEI-EMF, and the current state of science could better be summarized as "failing to provide any evidence that IEI-EMF is related to nonionizing radiation". Some interesting differences in regards to the neurobiological, physiological, and psychological profiles of IEI-EMF individuals and the healthy population have also been observed, but require further exploration and replication before they can be treated as "scientifically established".

In regards to future epidemiological cross-sectional studies, the focus on improving methods to better characterize the level of exposure that participants are subjected to and the way in which health complaints are registered should become a priority. In terms of provocation studies, future studies should aim to take into account the heterogeneous nature of the condition and reduce the amount of potential confounds. This can be achieved by taking an individual case study approach, removing potential nonresponders from collated samples using an initial nonblind trial, and reducing the impact of stress and insufficient washout periods on results.

While disagreement exists over the cause of IEI-EMF, it is generally agreed that sufferers are experiencing real symptoms that significantly impact daily functioning and quality of life, emphasizing the importance of identifying appropriate support for these individuals. The following section of this chapter discusses the efficacy of some of the treatment methods recommended in the literature in the hope that this will provide useful advice for clinicians and health care professionals when consulting with IEI-EMF individuals.

24.4 Treatment and Intervention Strategies

Given that there is currently no evidence of an association between exposure to low-level EMF and adverse health effects, the treatment of IEI-EMF remains challenging. There are, however, many approaches that have been recommended in the management of IEI-EMF and its symptoms.

24.4.1 Exposure Reduction Interventions

Despite the lack of evidence for an association between EMF exposure and IEI-EMF, one of the most common treatment strategies employed by IEI-EMF sufferers is exposure reduction. There are many different types of interventions, with the more popular ones detailed below:

Shielding of rooms and buildings: Rooms and buildings can be shielded from EMF through the use of metallic paints and the construction of Faraday cages. Although these methods can be effective in shielding from EMF on a grand scale, they are very costly.

Shielding of personal devices: This often refers to the use of protective covers or stickers that are claimed to reduce or eliminate the exposure emitted by a device. For many devices, however, this is counterproductive. For example, if a protective cover or sticker claiming to eliminate the exposure emitted by a mobile phone is actually effective, then the phone should no longer work as it requires RF communication with a base station, and it may even enhance the exposure as the device attempts to compensate for the interference by increasing its transmit power.

Protective clothing and fabrics: One option that some IEI-EMF sufferers turn to is to wear protective clothing or use protective fabrics to shield the body from EMF. These fabrics are embedded with metal threads, and when worn produce, to a certain degree, a Faraday cage around the body. For this to be effective however, the clothing or fabric would need to be worn over the entire body and face so that the person was completely enclosed by the metal threads. The effectiveness of the use of such materials was challenged by Leitgeb et al. (2008), who tested the efficacy of protective netting, sham netting, and no netting on a range of sleep quality and somatic complaints in IEI-EMF participants who reported experiencing sleep disturbances in association with exposure to a nearby base station. Three participants reported an improvement in sleep quality that appeared to relate to the use of the protective netting; however, it was subsequently found that these participants had unblinded themselves. A further seven participants exhibited significant improvement in sleep quality after using the sham netting, indicating a possible placebo effect. The majority of volunteers, however, did not exhibit any significant change in any sleep parameter, regardless of condition.

Filters against "dirty electricity": Dirty electricity is the name some give to high-frequency voltage fluctuations due to interruptions in or perturbations of the flow of electrical currents in electrical wiring. Filters against such dirty electricity are commonly promoted; however, it has been shown that these products not only fail to meet the filter claims made but that they also lead to greater power usage and higher magnetic fields (Gajda, Thansandote, and Lemay, 2006).

Relocating to a rural area: Relocating to a rural area has become increasingly popular with people who experience IEI-EMF. These areas generally tend to have less infrastructure than major metropolitan cities, and so it is often perceived that these areas would have lower EMF exposure levels. This is not always the case. Furthermore, relocation can encourage additional avoidance behaviors and lead to increased social isolation and significant financial burden.

24.4.2 Government Recommendations for Exposure Reduction

Many government and public health organizations provide recommendations on how to reduce exposure to mobile phones and other wireless devices. For example, in Australia, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is a government organization that lists a number of recommendations to reduce exposure to EMF if a person would like to do so. These recommendations include increasing the distance between the person and the device (such as with the use of hands-free attachments or speaker modes on mobile phones, or placing wireless routers away from areas where the person spends the most time), using wired connections wherever possible, only making mobile phone calls in areas with good reception and simply reducing the usage time on devices (ARPANSA, 2015). All of these methods can reduce one's overall exposure to EMF.

Exposure reduction techniques have been adopted by a large number of those who view themselves as suffering from IEI-EMF, with one recent survey finding that 76% of respondents reported the reduction or avoidance of NIR as an action they had undertaken (Hagström, Auranen, and Ekman, 2013). The most common ways in which respondents achieved this was through the avoidance of computers and mobile phones and by relocating outside of city areas. But while IEI-EMF sufferers believe that exposure reduction or avoidance behaviors are the most effective means of reducing symptoms (Röösli et al., 2004), the evidence for the efficacy of such techniques from controlled trials is lacking. Furthermore, it is also important to consider the consequences associated with one's removal from an NIR environment. For example, as mentioned above, there can be significant financial costs associated with these interventions and it may increase social isolation.

Perhaps most concerning though, is the potential impact that IEI-EMF sufferers have on people in their care, such as children. Indeed, some people have reported removing their children from school as a means to reduce exposure, despite the wealth of evidence for the importance of school and education in a child's development (Lee, 2000; Parcel and Dufur, 2001; Stevens and Slavin, 1995). Therefore, given the potential negative consequences of some exposure reduction techniques and that some studies have shown that symptoms can be triggered when there is no RF EMF present (Oftedal et al., 2007; Rubin et al., 2006), other treatment options would seem to be preferable.

24.4.3 Symptom Treatment

If a thorough medical assessment has been performed and no cause for the symptoms can be identified, then one approach should be to treat the symptoms. There are a number of ways in which this can be achieved, with varying amounts of evidence and research available assessing the efficacy of such treatments.

24.4.3.1 Cognitive Behavior Therapy

Cognitive behavior therapy, or CBT, is a form of structured psychotherapy designed to change unhelpful or unhealthy thoughts and behaviors. It is a problem-focused and individualized approach that focuses on remedying immediate problems, but it also attempts to develop long-term strategies to replace thoughts and behaviors that interfere with a person's happiness and satisfaction with their life. CBT is the treatment of choice for a range of psychological issues, such as depression and anxiety, but it has also been used extensively to reduce somatic symptoms, such as chronic pain and side effects of medications (e.g., nausea associated with chemotherapy for the treatment of cancer). For more on CBT, see Neenan and Dryden (2014).

Our awareness, interpretations, and memory are biased by our beliefs. Witthöft and Rubin (2013) demonstrated that inducing negative beliefs about EMF exposure through media reports increased the likelihood of participants experiencing symptoms and developing an apparent sensitivity following a sham exposure. Several other studies have also suggested that the belief of being exposed to EMF is sufficient to trigger symptoms in IEI-EMF individuals. Given this, and the fact that CBT has been effective in treating other medically unexplained syndromes (Edwards et al., 2010; Escobar et al., 2007; Sharpe et al., 1996; Speckens et al., 1995), it would seem that CBT may be an appropriate approach for treating IEI-EMF.

However, there is limited research assessing the effectiveness of CBT in treating individuals with IEI-EMF. Despite one questionnaire study in Finland that failed to find significant benefits of psychotherapy (Hagström, Auranen, and Ekman, 2013), several clinical trials have shown that CBT can be effective for those suffering from IEI-EMF (Rubin, Das Munshi, and Wessely, 2006). For example, research in which CBT was used to encourage patients to challenge their beliefs that their symptoms were caused by EMF and to test non-EMF-related explanations as a way of dealing with and overcoming symptoms (Rubin, Das Munshi, and Wessely, 2006), reported reductions in self-ratings of hypersensitivity (Hillert et al., 1998), disability (Andersson et al., 1996), symptoms (Andersson et al., 1996; Harlacher, 1998), and overall perception and degree of suffering (Harlacher, 1998). Currently, there is no research assessing the use of CBT for symptom reduction independent of causal belief, but this may also prove to be a useful approach.

24.4.3.2 Medical/Alternative Interventions

Symptom treatment using medications such as SSRIs (typically used in depressive and anxiety disorders) or beta-blockers (typically used for cardiac interventions, as well as anxiety) has been suggested as a potential treatment option; however, there is no evidence related to their use in IEI-EMF (Hocking, 2014). Such treatments that directly target the symptoms reported could theoretically work; however, they are yet to be clinically tested.

Several other approaches to the treatment of IEI-EMF have been tested, namely supplementary antioxidants (popularly used as a health promotion tool when oxidative stress might be implicated in a disease) and acupuncture (a procedure that involves inserting thin needles into the skin at specific parts of the body for many different medical ailments, particularly in regards to pain relief). However, as for many other symptomatic treatment interventions, neither of these alternative approaches was found to be effective in the case of IEI-EMF (Rubin, Das Munshi, and Wessely, 2006).

24.4.4 Conclusions

Despite the many strategies proposed, the treatment of IEI-EMF remains challenging. Most treatments have not been able to show adequate efficacy, with some even demonstrating counterproductive effects. Nevertheless, there is some suggestion that CBT, when used in a way that challenges patients' beliefs, may be a beneficial approach. The current evidence regarding treatment of this condition remains very limited and therefore more research is required in order for more specific clinical advice and recommendations to be developed.

24.5 Important Considerations for Treatment

1) When faced with a patient who presents with symptoms that they attribute to EMF exposure, it should be assumed that EMF is not the cause as there is currently no evidence that such exposures cause the symptoms reported by IEI-EMF individuals. Therefore, as a first line approach, this condition should be treated medically, with a thorough medical and screening assessment to test for other medically diagnosable conditions.
2) Many IEI-EMF sufferers are concerned about not being believed or not having their condition taken seriously. Therefore, despite the cause of this condition being uncertain, it is important to acknowledge that the symptoms experienced are indeed real.
3) It is important to be aware that no benefit of exposure reduction strategies has been demonstrated, and given that they can result in counterproductive consequences, caution should be applied in encouraging exposure reduction. Where exposure reduction is considered, it is important to focus on methods recommended by experts, such as governmental health bodies.

4) Where a medically available cause for IEI-EMF symptoms cannot be identified, then treatment of the specific symptoms would be advised. Although some treatments have not been shown to be effective, CBT has some empirical support for its efficacy and currently represents the best treatment option for IEI-EMF.
5) It is important to be aware though that even CBT has only a limited body of research testing its efficacy, and so there are “no” treatment options for IEI-EMF that have unequivocal support. We hope that we will see more research dedicated to better understanding this complex situation in the near future.

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25

Prudent Avoidance[*]

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25.1 Introduction

The purpose of this chapter is to introduce the concept of Prudent Avoidance as a response to community concern regarding possible health effects associated with power frequency electric and magnetic fields (EMFs).

Although the focus of this chapter is on prudent avoidance, it is no longer possible to discuss it in isolation from the precautionary principle. Accordingly, we will start with a brief discussion of the precautionary principle and how it underpins prudent avoidance, before focusing on prudent avoidance itself – its principles and its practical application.

The precautionary principle is set out in the Rio Declaration, produced at the 1992 Rio Earth Summit. It states that:

> Where there are threats of serious or irreversible damage, the lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Since that time, the principle has been invoked by both governments and advocacy groups and has gained widespread acceptance. It is in that context that we apply it to EMF. In doing so, we will first break the precautionary

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principle down into its three key elements and discuss them in turn. The elements are as follows:

- A risk of serious or irreversible damage
- Lack of full scientific certainty
- Cost-effective measures.

Firstly, any risk of serious or irreversible damage must be real. That is, a risk cannot be said to be real merely because an individual or group of people believes it to be so. At the very least, there needs to be a body of peer-reviewed scientific evidence that supports the existence of the risk. Assuming that a particular risk is, in fact, real, it is also necessary that its consequences are sufficiently serious to warrant the invocation of the precautionary principle.

The second element relates to a state of scientific uncertainty. In other words, if a risk is established and understood, it is assumed that society will react accordingly and the precautionary principle ceases to be of relevance. It will be recalled that, under the first element, we have suggested that the postulated risk needs to be credible. Assuming this to be the case, and also assuming that there is not yet a full understanding of the issue, the question arises as to how much we do know because it is the extent of our knowledge of the issue that will guide the development of any precautionary measures that the society may choose to adopt.

Once the first two elements have been established, the precautionary principle calls for "cost-effective measures". In such circumstances, the key question is "what specific measures should be applied and to what extent or in what circumstances should they be applied"?

Let us now apply the precautionary principle to the potential impact of EMFs on human health.

The risk of serious or irreversible harm: Over the past 35 years, there has been a wealth of scientific research on this subject. While the results of many studies have been reassuring, there remains a body of evidence that is suggestive of adverse health affects, particularly in relation to magnetic fields and the risk of childhood leukemia. In 2000, the International Agency for Research on Cancer (IARC) classified power frequency magnetic fields as a "possible carcinogen", based on epidemiological studies relating to childhood leukemia. While some may view the level of risk as being minor when compared with other risks that society accepts, because of the prevalence of electricity use in society and the seriousness of childhood leukemia, it is reasonable to conclude, based on today's level of scientific knowledge, that a threat of serious harm exists.

Lack of full scientific certainty: Despite more than 35 years of research, starting from 1979, the certainty of adverse health effects associated with exposure to power frequency EMF has not been established, despite the epidemiological evidence just referred to. Moreover, despite a plethora of theories as to how EMF might affect human heath, we have no convincing mechanism.

The abovementioned examination of the first two elements of the precautionary principle suggests that precautionary measures appear to be justified in the case of power frequency magnetic fields. The only question then is what those measures might be.

Undoubtedly, the continuation of high-quality research aimed at reducing the level of uncertainty is an important part of any suite of precautionary measures. However, addressing research needs is not within the scope of this chapter.

Having established the need for precautionary measures, we will now examine an approach to precautionary measures, which has gained widespread acceptance among community groups and has also been viewed favorably by many within the electricity supply industry. For example, in 1991, the Electricity Supply Association of Australia (ESAA), which was then the peak body representing the interests of the Australian electricity supply industry, formally adopted prudent avoidance as its preferred policy response to community concern about EMF in a climate of scientific uncertainty.

While much has been written in the scientific literature about the precautionary principle, a particularly useful document is "A framework for the application of precaution in science-based decision making about risk" (Government of Canada, 2003). In the present context, it is useful to draw on two of the five guiding principles given in that document for the development of precautionary measures:

1) Precautionary measures should be proportional to the potential severity of the risk being addressed and to society's chosen level of protection.
2) Precautionary measures should be cost effective with the goal of generating the following:
   a) an overall net benefit for society at least cost and
   b) efficiency in the choice of measures.

The inference to be drawn from these two principles is the need to retain a sense of proportion in adopting precautionary measures. Without laboring the point, a commonsense, practical approach needs to be brought to bear. The approach should comprehend not only the potential severity of the risk but also considerations of costs and efficiency. It is in this context that we now move on to discuss "prudent avoidance".

The concept of *prudent avoidance* was first suggested in 1989 by Grainger Morgan (1989) as a sensible response to community concern regarding health aspects of EMF in the face of ongoing scientific uncertainty. This uncertainty in relation to exposure to EMFs was also addressed by Sir Harry Gibbs in a wide ranging inquiry into community needs and high-voltage transmission line development in Australia. In his March, 1991 Report (Gibbs, 1991) he said:

> It has not been established that electric fields or magnetic fields of power frequency are harmful to human health but, since there is some evidence that they may do harm, a policy of prudent avoidance is recommended.

Since 1991, a succession of major inquiries including a further two in Australia (3 and 4) have recommended *prudent avoidance* but the term has not been, and by its nature, cannot be defined with precision.

Internationally, the World Health Organization has also addressed the notion of prudence or precaution on several occasions, including in its 2007 publication *Environmental Health Criteria Vol. 238: Extremely low frequency fields* (WHO, 2007), which states:

> … the use of precautionary approaches is warranted. However, it is not recommended that the limit values in exposure guidelines be reduced to some arbitrary level in the name of precaution. Such practice undermines the scientific foundation on which the limits are based and is likely to be an expensive and not necessarily effective way of providing protection.

It also states:

> Provided that the health, social and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposure is reasonable and warranted.

Prudent avoidance involves taking reasonable steps in any particular circumstance, and although a precise definition cannot be given, it is possible to provide general guidance. The aim of this chapter is to outline a range of options that may be applied in the context of *prudent avoidance* for electricity transmission, distribution, and beyond-the-meter situations from the consumer's point of view. In doing so, it is recognized that design practices and other policies of individual electricity utilities vary considerably. Accordingly, it remains the responsibility of the designers to apply the principles appropriately to particular situations.

No attempt has been made to address the application of *prudent avoidance* in an occupational setting, either for electricity industry employees or for others exposed to magnetic fields during the course of their employment.

25.2 Public Policy Considerations

The uncertain state of the science regarding EMFs has presented significant challenges for those responsible for public policy on health and safety matters. The Gibbs Report (Gibbs, 1991) dealt with this aspect of the EMF issue as follows:

> It then becomes a question of policy what action should be taken to avert a possible risk to public health when it cannot be said either that it

> is probable that the risk exists or in what circumstances a risk, if one exists, arises. A suggestion has been made in the United States that a policy of prudent avoidance should be adopted.
>
> It would not be prudent, but foolish, to make radical or expensive changes to existing lines until further scientific studies have resolved the doubts. On the other hand, when new lines are being constructed, it may be prudent to do whatever can be done without undue inconvenience and at modest expense to avert the possible risk, remembering that if that is not done and future research establishes the existence of a real risk to health, serious problems may arise which can be remedied only at great cost.

The recommendations contained in the Gibbs Report formed the basis of the policy subsequently adopted by many Australian electricity supply businesses.

As mentioned earlier, in 1991, ESAA adopted a formal policy in relation to EMFs. The policy recommends to ESAA members that they operate their electrical power systems *prudently* within Australian health guidelines, and closely monitor, and, where appropriate, sponsor high-quality scientific research.

In an accompanying advice to its members, the ESAA clarified what it meant by acting prudently in this context. In ESAA's view, acting prudently means embracing a range of sensible actions having regard to the uncertain state of the science and which take into account scientific research and community concerns. These actions include informing employees and the public about the issue and practicing prudent avoidance (as described in the Gibbs Report) when designing and building new transmission and distribution facilities. Such actions can include considering the design of the new facilities with respect to the EMFs that may be produced, sharing information on EMFs with the community, and taking community views into account when siting new facilities.

Since 1991, recommendations regarding prudent avoidance have been made in other jurisdictions. In Australia, there have been two major public inquiries since Gibbs. In 1992, in the Australian State of Victoria, the Peach Panel (Panel on Electromagnetic Fields and Health, 1992) recommended that:

> Planning for all new transmission and distribution facilities take prudent avoidance into account. When designing these facilities regard should be given to their capacity to produce magnetic fields, and in siting them, regard should be given to their proximity to houses, schools and the like.

In 1995, following an inquiry into the interconnection of the States of New South Wales and Queensland electricity grids with a high-voltage powerline, the Australian Senate Economics References Committee (Senate Economics References Committee, 1995) found that:

> In acknowledging (these) community concerns, the Committee agrees that, as a minimum policy or until evidence suggests otherwise, the concept of 'prudent avoidance' should continue to be practised by Government and power authorities.

The following sections provide practical guidance to the application and implementation of *prudent avoidance* for electricity transmission and distribution businesses in Australia and elsewhere.

25.3 Prudent Avoidance Principles

Although there is no precise definition of prudent avoidance, there is considerable discussion in the literature that provides guidance as to how it might be applied in practice. In particular, as we saw earlier, Sir Harry Gibbs described prudent avoidance as:

> … doing whatever can be done at modest cost and without undue inconvenience to avoid the possible risk (to health) …

Although useful, this description is open to interpretation, especially in respect of the question as to what might constitute "modest cost". In this regard, in 1993, the California Public Utilities Commission in the United States of America published an order defining *prudent avoidance* as undertaking suitable activities up to 4% of the cost of a new electricity company installation project. While 4% should not be seen as a binding standard, it is certainly a useful benchmark of "modest cost".

The application of *prudent avoidance* in the design and construction of new electrical facilities is a process of assessing the extent to which people may be exposed to fields produced by them and considering what "low-cost" and "no-cost" measures might be taken to reduce such exposure within acceptable constraints. It was considered that the 4% limit adopted by the California Public Utilities Commission was appropriate and, accordingly, it was suggested that, also in the Australian context, "modest-cost" or "low-cost" measures should be interpreted as involving up to 4% of the total project cost. This figure is considered reasonable and should be acceptable to many utilities.

Apart from the quantum aspect of cost considerations, it is important to consider whether the available funds should be directed toward the mitigation of electric fields, magnetic fields, or both. Because the vast majority of concerns expressed over the past 15 years have been directed toward magnetic fields, in the authors' view, all prudent avoidance measures should be directed primarily toward magnetic fields, recognizing that, in many instances, these measures will also lead to reduced electric field exposure.

In broad terms, the range of measures that may be available to reduce exposure to the fields generated by electricity utility facilities come under two broad generic headings:

1) siting measures
2) design measures.

These measures are generally the same as those that were applied to mitigate against magnetic interference to visual display units (VDUs), when these were in general use (and are listed in publication (Melik, 1996).

25.3.1 Siting Measures

- The first aspect to be recognized in the siting of electricity utility facilities is that the process of site selection is a complex one, involving a multitude of considerations of which the possible adverse effects of EMFs is but one.

In this context, the issue of EMFs is rarely an overriding consideration but, rather, should be considered as one of several important factors.

Furthermore, because many of the factors that influence the siting of electricity utility infrastructure have a major sociological dimension, an essential part of the siting process should be the engagement of the affected community in the process. This requires the community to be informed of the proposed project at an early stage, acquainted with the range of factors that may be relevant to the siting decisions and their genuine input sought. In respect of EMFs, the community involvement process could include measures such as

- informing the community about the need for the line and the various site selection constraints;
- providing educational material (preferably including material from independent sources on the issue of EMFs);
- providing factual information on the magnitude and extent of fields likely to be associated with the proposed facility;
- providing information regarding the magnitude and extent of EMFs in the general area and in typical everyday situations, for example, in the home and the street;
- seeking community input/feedback regarding siting issues; and
- reporting back on how the community input/feedback has been addressed and in particular changes incorporated in the light of these.

25.3.2 Design Measures

The following design measures for reducing magnetic fields may be applied to overhead lines of all voltages:

- Increasing conductor height above ground

- Compacting the line by reducing its phase-to-phase distances
- Configuring the conductors/arranging the phases to minimize the magnetic field
- Using more than one conductor per phase (split phase) and arranging them to minimize the magnetic field
- Using aerial bundled conductors (ABCs) (up to 22,000 V)
- Reducing the current
- Shielding or cancellation of fields (passive and active)
- Locating the lines underground (in some cases, this can increase the ground-level magnetic field but the field strength will normally diminish more rapidly with distance).

In frequented areas, the selection of a particular pole top configuration for a new line or a rebuild should favor the configuration, which results in the lowest magnetic fields, subject to cost and technical constraints. In addition, existing conditions and future system requirements must also be considered.

The option selected should neither jeopardize the reliability nor downgrade the operating characteristics of the electricity system. Nor should it create a hazard to maintenance personnel or the public in general.

25.4 Prudent Avoidance – Transmission

The following sections describe a number of specific options for prudent avoidance, which are consistent with the principles outlined in Section 25.3 and which may be applied to transmission facilities.

25.4.1 Transmission Lines

25.4.1.1 Distance

The most common method of reducing peoples' exposure to EMFs is by selecting line routes (i.e., siting) to avoid population centers or areas where people gather. Particular attention should be paid to schools, childcare centers, and other areas where children congregate.

Although a matter for developers/planning authorities, increased separation needs also to be considered when new residential development is proposed adjacent to existing transmission lines. This could involve either the sacrificing of land within the development site or the relocation of some parts of the line.

Figure 25.1 illustrates how magnetic field strength reduces with distance from the line. Raising the height of the supporting structures or towers, and thus the height of the conductors, can also reduce the magnetic field strength below the line. However, the cost and visual impact associated with the increased structure height may limit this technique to selected portions of a line. Structure raising may be more practical for wood pole lines than for steel tower lines, due to the cost factor.

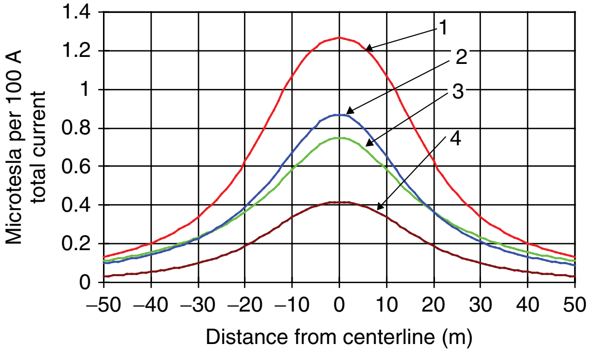

Figure 25.1 Magnetic field profile at 1 m above ground for a typical 500-kV overhead transmission line for various conductor configurations. 1. Single circuit with horizontal flat configuration of phases. 2. Single circuit with triangular configuration of phases. 3. Single circuit with vertical configuration of phases. 4. Double circuit with vertical configuration of phases and with favorable phase sequence (acting to reduce field strength). *Source:* Reproduced from Melik (1996).

25.4.1.2 Conductor Configuration

Different arrangements of phasing can produce different magnetic field strengths for the same line current. In general, triangular arrangements tend to provide more field cancellation than horizontal arrangements, with lower resultant field strengths. The effect of line geometry on magnetic field profile for a typical 500 kV line is shown in Figure 25.1.

Line compaction can also reduce the resultant EMFs by enhancing the field cancellation effect between the phases. Although the ability to achieve compaction is limited by factors relating to the electrical performance of the line, it can be an attractive option as compact lines offer some other advantages. These include reduced visual impact and reduced easement width.

25.4.1.3 Phase Arrangement

For double-circuit lines, it is possible to arrange each three-phase circuit with a different vertical phase arrangement in space, such that some cancellation of magnetic fields occurs. Figure 25.2 illustrates this effect for a typical 500 kV transmission line, with Option 3 being the most favorable phase arrangement from the viewpoint of field reduction. This is usually a relatively low-cost option in the case of an existing line and often a no-cost option for a new line.

Selection of the proper phasing arrangement is usually the most effective way to reduce magnetic fields for two circuits on the same structure or two or more circuits on the same easement for minimal cost, if rerouting is not possible.

25.4.1.4 Split Phasing

A single-circuit line can be constructed as two parallel circuits with a phase arrangement designed to achieve maximum field cancellation. This is known as

Figure 25.2 Magnetic field profile at 1 m above ground for a typical 500-kV double-circuit transmission line with vertical conductor configuration (below), where R W B indicate "red, white, and blue," the common phase labeling used in the industry. *Source:* Reproduced from Melik (1996).

1:	B	B	2:	B	B	3:	B	R
	W	W		W	R		W	W
	R	R		R	W		R	B

the split-phase technique and may be considered if only one circuit exists on a route. Although this form of construction is significantly more expensive than conventional single-circuit construction, it could be used for short sections of a line where it is desired to reduce fields within the suggested 4% cost limitation.

25.4.1.5 Current Reduction

A reduction in current will generally reduce magnetic field strengths. The reduction in field strength is approximately proportional to the reduction in current. For a given load transfer requirement, the only way to reduce the current is to increase the voltage. However, because line voltage is generally fixed by system stability considerations, increasing line voltage will seldom be feasible within the 4% cost constraint, and other design options are likely to be preferable.

25.4.1.6 Shielding and Cancellation Loops

Shielding is the erection of a barrier between an EMF source and a subject to reduce the field strength at the subject. A simple metallic or nonmetallic shielding barrier can substantially reduce *electric fields* from transmission lines but has little effect on magnetic fields. Any object between the source (line) and the point of interest will provide shielding or distortion of the electric field. Common examples are buildings, trees, or any other structure.

For all practical purposes, there are no means to significantly reduce or screen *magnetic fields* from overhead lines. In special applications, screening of individual pieces of equipment is possible, using structures or enclosures made from special metals.

"Cancellation" or "Degaussing" loops are conducting wires suspended between adjacent structures, above or below the phase conductors to provide both shielding and cancellation effects. They may be either "active" (energized) or "passive" (nonenergized) and rely on a current flow in the opposite direction to cancel or reduce the overall field produced by the line. The use of shielding or cancellation loops while technically possible is often regarded as complex, unsightly, and of little practical significance.

25.4.1.7 Undergrounding

Because undergrounding is usually far more expensive than overhead construction, it does not often fall into the category of prudent avoidance, with its "minimum cost/minimum inconvenience" criteria. There will be occasions, however, when partial undergrounding may be consistent with prudent avoidance on a total cost basis, and accordingly, this option is discussed briefly in the following paragraphs.

In underground cables, phase conductors are insulated from earth and each other by a relatively thin layer of solid insulation, as compared to a much larger dimension of air insulation in the case of overhead lines. Accordingly, underground phase conductors can be placed much closer together, providing a more effective field cancellation effect.

On the other hand, underground cables are normally buried 1 m or less below ground and can be closer to people than an equivalent overhead line. Nevertheless, due to the cancellation effect, the use of underground cables usually reduces the effective level of the magnetic field at the point of interest. An exception to this might be the situation of cables in a street area where the point of interest is the footpath or roadway immediately above the buried cable where the field strength is still significant.

When considering undergrounding, it should be noted that, contrary to popular belief, the ground has no magnetic field shielding property and plays no part in further field reduction.

Figure 25.3 illustrates the difference among the magnetic field profiles of overhead transmission, distribution lines, and the underground cable assuming perfect symmetry of the phase currents in all three systems.

A three-phase underground cable in one sheath will produce a lower magnetic field than the same capacity line constructed from three single-core cables because the conductors are closer together and provide more effective field cancellation than three single-core cables, especially if the latter are in flat formation.

25.4.2 Transmission Substations

The magnetic fields produced by transmission substations result largely from the outgoing and incoming overhead transmission lines, especially where they

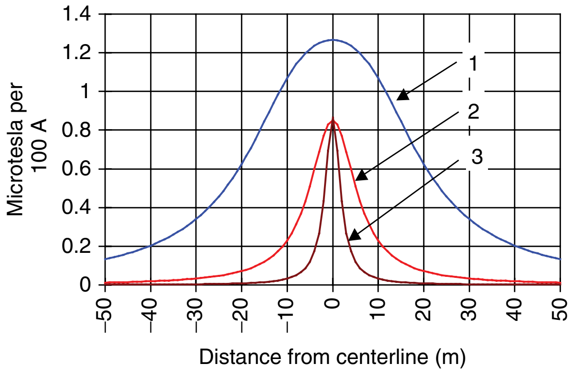

Figure 25.3 Magnetic field profiles at 1 m above ground for typical overhead and underground lines. 1. Under a 500-kV transmission line with horizontal phase configuration, typically carries 500 A or larger. 2. Under an 11-kV distribution line with horizontal phase configuration, typically carries 200 A or larger. 3. Above an underground three-phase, single-core cable circuit with horizontal phase configuration and 100-mm phase separation, typically carries 200–500 A or larger. *Source:* Reproduced from Melik (1996).

come together at entries to busbar arrangements. Consequently, most of the prudent avoidance options available for transmission substations are those detailed in Section 25.4.1.

25.4.3 Land Development

Land development adjacent to transmission lines often occurs after the transmission line has been built. It has been suggested in some quarters that the prospect of future land subdivision and development may create an argument for utilities adopting wider easements in the first place. This suggestion was considered by Sir Harry Gibbs in his 1991 Report. He found no support for such a move, which would alienate additional land and increase costs to the community. He said:

> … it would be particularly undesirable at the present time to prescribe standards or guidelines with regard to exposure to the fields created by transmission lines or the width of easements acquired or used for such lines.

All transmission line easements would be affected while any potential benefit would be restricted to a few isolated developments. Furthermore, because of the variation in magnetic field strength profiles for the various design options as noted in Section 25.4.1, it would be impractical to attempt to prescribe easement widths that result in a consistent magnetic field outcome. It is suggested that the application of prudent avoidance to land development should follow similar principles to those outlined for transmission line development. In other words, it is suggested that up to 4% of the total cost of the development should be allocated to options to reduce people's exposure to magnetic fields. In deciding what particular prudent option to adopt, the developer may consult with the relevant utility in order to identify the most cost-effective measures available for the particular circumstance.

25.5. Prudent Avoidance – Distribution

25.5.1 Distribution Lines

25.5.1.1 Siting

Due to the need to provide supply to customers, the options available to designers in siting distribution infrastructure are limited. Distribution lines, by their very nature and function, are normally located in road reserves to provide supply to customers on both sides of the road, although in some instances, they are located at the rear boundary of residential properties.

Where practicable:

- Distribution lines should be located on the opposite side of the road from areas such as schools, kindergartens, childcare centers, and the like.
- Distribution lines should be sited away from the walls of multistory buildings or areas where children congregate.
- Distribution lines should be located on the side of the road bordered by open spaces where applicable.
- Substations should be located at the electrical center of their low-voltage network, that is, current flows in all directions should be balanced.
- As with transmission lines, the benefits of community consultation and the sharing of information should not be overlooked in the siting of distribution lines. This is particularly relevant when high-voltage overbuilds are being considered.

25.5.1.2 Design

Prudent design options that may be considered subject to their economic viability could include the following:

- Use of ABC for low-voltage and high-voltage (11,000–22,000 V) reticulation to provide more effective field cancellation.
- Use of offset construction (i.e., with all phases constructed on the same side of the pole) to increase horizontal separation from the point of interest.
- Use of underground cable in place of overhead conductors where economically justified.
- Use of three-phase cable instead of three single-phase cables (refer Section 25.4.1.7).
- Balancing of load across all phases to reduce neutral currents.

- Use of insulated twisted service cable instead of open wire services to provide more effective field cancellation.

For new double-circuit lines, adoption of low reactance (RWB/BWR) phasing when current flow in both circuits is in the same direction (refer Section 25.4.1.3).

When installing electrical facilities that involve both low voltage and high voltage, the following options apply:

- When overbuilding (or underbuilding) existing facilities, the phasing on the existing circuits should be determined and the new circuit or circuits phased to minimize the combined magnetic field strength.
- Where new subtransmission facilities are being considered for installation on structures carrying distribution circuits, or where existing installations are to be modified, the most effective field reduction measures may involve changes to the distribution circuits.

25.5.2 Distribution Substations

25.5.2.1 General Principles

Distribution and consumer substations are typically 22,000/415 V or 11,000/415 V and are generally either pole mounted or ground mounted. Ground-mounted substations may be installed in the open or enclosed in a pit or building.

The main sources of magnetic fields from distribution substations are the transformer windings, the high-voltage and low-voltage cables and line connections, the associated switchgear, and also the earth straps and neutrals when forming alternative paths to earth for unbalanced currents.

In recent years, a trend in distribution substation design is toward the use of "dry-type" transformers in preference to the "oil-filled" type. The absence of steel tanks in dry-type transformers and increased thickness of coil insulation results in stronger external magnetic fields. This should be taken into consideration when installing such transformers in new substations or when replacing old oil-filled transformers with new dry types in existing substations.

Underground metallic pipes and telecommunication cables with metallic screens or even structural steel can also be significant sources of magnetic fields if they constitute a return path for a portion of the substation earth or neutral currents (Melik, 1996).

The compact design of gas-insulated switchgear (GIS), as compared to open or enclosed air-insulated switchgear substations, offers significantly lower magnetic fields due to a substantial reduction of the phase separation distances. A degree of magnetic shielding is also afforded by the gas-filled enclosures.

Due to the higher associated current levels, the low-voltage side of a distribution substation has higher levels of magnetic field than the high-voltage side.

Figure 25.4 shows the profiles of the magnetic field at 1 m above the substation floor from horizontally arranged busbars at 2.1 m height and 0.3 m sepa-

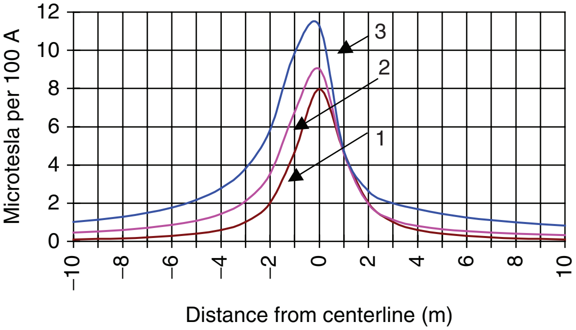

Figure 25.4 Variation of magnetic field with distance under three-phase open type low-voltage busbars, typically carrying 200–1000 A. 1. Balanced current condition. 2. Unbalanced current condition with the net current returning via its neutral busbar. 3. Unbalanced current condition, but the net current returning via an alternative route. *Source:* Reproduced from Melik (1996).

ration. The neutral conductor is at 0.15 m horizontal separation from the leftmost busbar.

Metal-clad substations, where mild steel is usually used for fabrication of enclosures, are afforded a modest level of shielding by the enclosure. Also, reinforced concrete slabs, walls and floor panels can provide some magnetic field shielding. However, it should be noted that, unless cables, busbars and the like are fully surrounded, any shielding afforded by metallic enclosures becomes less effective with increased distance from the source. Building materials such as brick, stone, plaster, wallboards, and wood have no shielding properties for magnetic fields.

The following basic magnetic field management techniques can be applied in the design of substations:

- Increasing the distance of magnetic field sources from the receptor area.
- Reducing the conductor or busbar spacing.
- Selecting an appropriate phase configuration.
- Balancing load between phases to reduce the neutral current.

Power frequency magnetic fields of small magnitude may cause interference with some equipment that use electron beams in their operation, such as in CRT tubes and in electron microscopes. Small magnetic fields can also interfere with the operation of some biomedical equipment that measure small electrophysiological currents, such as in electroencephalography, magnetoencephalography, and electromyography. Mitigation measures, which are discussed here and in detail in Melik (1996), are equally suitable for *prudent avoidance* and to mitigate interference.

25.5.2.2 Specific Measures

In designing distribution substations in situations where prudent avoidance is required, the following design measures may be considered. Some measures are more appropriate for high-rise situations and some for outdoor substations near domestic dwellings.

In the case of high-rise buildings:

- Locating substations away from normally occupied areas such as offices and lunchrooms.
- Planning the substation layout so that the low-voltage side is further away from adjacent dwellings, offices, computer rooms, and so on than the HV side.
- Locating transformers, low-voltage busbars, disconnector switches, and other potentially large sources of magnetic field within the area of the substation as far away as possible from adjacent offices, and so on.
- Avoiding where possible, direct ceiling mounting of heavy current cables, open type busbars or disconnector switches if the floor above the substation is used as residential or office space. The converse applies if the floor below the substation is used as office or residential space.
- Locating all cable trays as far as possible from the substation ceiling and walls that separate it from adjacent dwellings, offices, and so on.
- Designing busbars to minimize separation between phases and between phases and the neutral bus.
- Orienting transformers and other sources that have uneven field patterns so that their highest field strength side is turned away from the field-sensitive area if practicable.
- Using three-phase cables in preference to three single-phase cables where possible.
- Using a trefoil arrangement of cables when using three single-core cables in a three-phase configuration. In such cases, if the neutral conductor is a separate single-core cable, placing it, where practicable, in the center of the trefoil formation of phases.
- Selecting the substation equipment considering, among other important electrical parameters, its low magnetic field design, that is, 11,000/415 V distribution transformers in steel housings, compact metal-clad busbars.
- Avoiding phase by phase grouping of single-core cables connected in parallel. For example, if three single-core cables are used per phase, then all three red phase cables should not be bundled together or placed in one conduit. This also applies to white and blue phases and to the neutrals.
- Distributing all large single-phase loads and all constant current load such as lighting and office equipment equally between three phases of the low-voltage supply.

In the case of outdoor substations:

- Positioning the low-voltage side of the transformer so that barriers such as landscaping, fencing, or block walls inhibit normal access to that side of the substation.
- Locating substations away from normally occupied areas such as bedrooms, offices, and playgrounds.

25.6 Miscellaneous

While the primary focus of this chapter is on utility installations, sources within customers' installations can also make a significant contribution to the overall magnetic field environment. Accordingly, a brief selection of considerations relevant to customer installations are provided in the following sections. Supply conditions may vary from utility to utility and, if inconsistencies are evident, these conditions should take precedence.

25.6.1 Commercial/Industrial Installations

In the case of large commercial/industrial switchboards, the busbars inside the switchboard can have an effect on field levels outside the switchboard. The following prudent avoidance measures may be available:

- Keeping the incoming line and associated meter panel and/or busbars away from frequented areas. This will also help avoid computer interference problems.
- Avoiding the use of separate conductor trays for the energized and neutral wires. If separate trays are necessary, it is best to place them adjacent to low/no use areas.
- Avoiding situations where the active and neutral currents are not sharing the same route, that is, in three-phase circuits where transfer switches are of the three-pole rather than the four-pole type.
- Locating switchboards away from high-use office areas if possible.
- Locating workstations away from switchboards when laying out new or reorganized office areas. A distance of 4–5 m is suggested to provide the additional benefit of avoiding interference to older (cathode ray tube based) computers.
- Using energy efficient lights, lift motors, air conditioning equipment, industrial motors, and manufacturing equipment, which draws less current than nonenergy efficient equipment.

25.6.2 Domestic Meters and Wiring

Generally, the principal source of magnetic fields associated with domestic meter boxes is the wires leading to the meter box. Accordingly, *prudent avoidance* measures associated with meter boxes generally focus on the wiring rather than on the box itself. The following *prudent avoidance* options may be available:

- In general, for new constructions, the layout of meters, switchboard, and wiring may be planned in advance, giving consideration to the magnetic fields that they would produce.
- Locating the meter box in an area that is not adjacent to high-use areas. Good locations would be at the garage, a closet, storage room, or at the back

of a wardrobe (refer Figure 25.5). Bedroom and living room walls are better avoided to reduce fields in active use areas. Many authorities recommend the placement of meters and switchboard in a back-to-back arrangement, with meters outside and switchboard inside the home for security of home and occupants. This arrangement usually places the switchboard in low-use areas (for the sake of appearance) and is consistent with prudent avoidance.

- Locating the main connecting wiring away from high-use areas in cases where meter location and switchboard location are separated by a significant distance, for example, where meters are installed at the fence and the switchboard is located at (or in) the house. The connecting wiring should be run with phases and neutral grouped together, and in a ceiling space rather than a wall space, for example.
- Using service wires of insulated twisted construction, as they produce significantly less fields than open wire (bare conductor) construction (refer Figure 25.5).
- Minimizing or avoiding situations where heavy current wiring, especially that of stoves and air conditioning, is placed in wall cavities within the house. This type of wiring is best located and grouped together in the ceiling. Close proximity of the phase wires and neutral helps to cancel the magnetic fields.
- Running the neutral wire along the same path as the twin active wire connecting two-way switches to provide a cancelling effect on the magnetic fields.
- Use of *smart meters* (electronic energy meters) lowers fields due to the absence of the synchronous monitoring motors used in conventional electromechanical meters.

Using energy-efficient equipment that will use less electricity and save money, and reducing the electrical load on the switchboard, thereby reducing

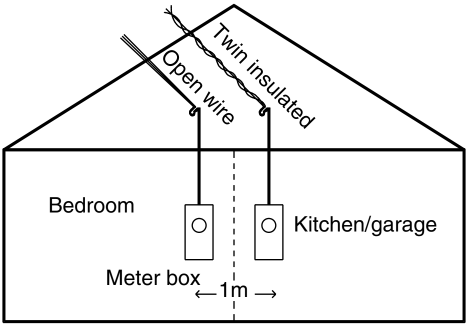

Figure 25.5 Methods of reducing magnetic fields in the home. Note: 1. Insulated twisted service produces 10% of the open wire service fields. 2. Moving the meter box 1 m (as shown above) can reduce fields in the bedroom by 80%.

magnetic fields. Large white goods such as refrigerators, dishwashers, washing machines, and dryers are often sold with energy efficient model alternatives.

25.6.3 Earth Connections

The multiple earthed neutral (MEN) system is commonly used to connect a utility's neutral to earth at a customer's switchboard in Australia and New Zealand. In this system, the power utility neutral is earthed at the supply end (at the distribution transformer) and also at each consumer service connection point (the consumer switchboard).

At the consumer switchboard, the supply authority neutral is connected to the neutral bar, the neutral bar is connected by the MEN link to the earth bar, and the earth bar is connected to a metallic earth stake. In addition, the metallic water pipe entering the consumer premises (building) is also connected to the earth bar of the consumer switchboard by a separate conductor called *equipotential bonding conductor.*

Depending on the condition of these connections and the impedance of the utility neutral, some fraction, or indeed, a large portion of the neutral current may flow through a path other than via the utility's neutral. If this happens, then an equipotential bonding conductor and a metallic water pipe can become substantial sources of magnetic field. In these situations, the supply wiring also becomes a source of significant magnetic field, as the magnitudes of the active and neutral currents are not equal.

If metallic water pipes are a source of magnetic fields, consideration could be given to installing a plastic joint in the water pipe to prevent the neutral current traveling along the pipe.

For electrical safety of plumbers either the plastic joint should be 2 m long or two short plastic joints should be installed 2 m apart. In this case, the plastic joint should be installed on the external to the building part of the metallic water pipe such as to maintain equipotential bonding of the pipe to the electricity earth inside the building.

The standard of the power supply for most residential and industrial electric systems in many European countries is somewhat different. It includes a protective earth (PE) conductor and a separate neutral (N) conductor. The two conductors are connected together only near the power source. This arrangement eliminates diversion of the neutral current or a part thereof from returning to the transformer neutral via any other conductive and earthed services, including metallic water pipes.

This is one of the reasons why the EMF on the streets of many European cities is either zero or very small as compared to the EMF in Australian cities. Here, we are comparing residential and commercial areas in Australian cities with similar areas in the continental Europe where the LV power supply is provided by underground cables.

25.7 Conclusions

The concept of *prudent avoidance* has been recommended as an appropriate public policy response to health concerns associated with magnetic fields. Historically, it has been difficult to scope because by its very nature it cannot be defined in precise terms. Nevertheless, it is possible to adopt many specific measures that are consistent with the notion of doing what can be done at modest cost and without undue inconvenience to reduce people's exposure to magnetic fields. This chapter has sought to clarify the concept of modest cost and to suggest a range of practical options or measures for transmission and distribution applications. Also addressed are a number of options that may be adopted by other stakeholders in this issue such as developers, builders, electricians, and home and building owners.

Prudent avoidance has served the electricity supply industry and others who seek to install electricity assets in a manner that is responsible and consistent with where research is currently positioned. It has been successful in reducing people's exposure where appropriate and in reducing concern and alarm where the public feel that they might be, by the nature of scientific uncertainty, at some risk, however small. By adopting this policy, the electricity industry and other stakeholders have been able to continue to provide network growth for the benefit of all customers.

In Australia, the Energy Networks Association has now taken over the role of ESAA, which was instrumental in adopting this approach many years ago. It is now producing an industry-wide guide to prudent avoidance principles to encourage and facilitate consistency throughout the Australian electricity supply industry. The policy of prudent avoidance also remains consistent with WHO (2007) and current Australian ELF information produced by ARPANSA (2015).

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26

Radiofrequency Fields and the Precautionary Principle

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26.1 Introduction

A recurring theme in public debates about possible risks of exposure to radiofrequency (RF) energy is the call to invoke the precautionary principle (PP), typically in opposition to plans to install electrical transmission lines or cellular phone towers or in recommending that children not use cell phones.

The PP is both politically contentious and flexible in meaning. For example, Vanderzwaag (2002) described "seven slippery aspects" of the PP: confusion in terminology, definitional variations, definitional generalities, the spectrum of precautionary measures available, ongoing philosophical tensions and competing socioeconomic interests, debate over who should be responsible for making precautionary decisions, and limited interpretation by international tribunals.

In this chapter, I first review the various meanings of the PP in the different contexts in which it is invoked and then review its suggested uses in regulating human exposures to RF energy. This chapter can be read as an extension of two other chapters in this volume (Chapters 25 and 27), which deal with precautionary policies related to extremely low frequency (ELF) fields. My main point is that the PP means many different things to different people and consequently simplistic arguments about "invoking" the PP make little sense. The central question should be what policies (precautionary or not) are most sensible for a given situation. The PP relates to risk management, as opposed to risk assessment, and ultimately involves value decisions, the political process, and the legal context in which risk management is done. These vary greatly in different countries and, in any country, vary with time and situation.

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

26.2 What Is the Precautionary Principle?

The Oxford English Dictionary[1] defines "principle" as "…a general statement or tenet forming the (or a) basis of a system of belief, etc.; a primary assumption forming the basis of a chain of reasoning". There is, however, no general statement of the PP, but rather a variety of statements that can be taken as definitions of the PP. Their only common element is their call for a risk-adverse approach to managing risk, which is embodied by the adage "better safe than sorry". The devil, as another adage says, is in the details.

While one can find "precautionary" statements, if loosely enough defined, far back in history, the PP as it is currently discussed has a more recent origin in the 1970s when "precautionary" statements appeared in a variety of international treaties. Starting in the early 2000s, a large academic enterprise developed, with 80–100 papers in academic journals appearing every year over the past decade, written from a variety of viewpoints (Figure 26.1). This flood of papers appears to have reduced somewhat in recent years, but surely not because of declining interest in the PP or in the larger topic of precautionary approaches (PAs) to risk regulation.

Several major threads emerge.

26.2.1 Precautionary Principle in International Treaties

By now, more than a dozen "precautionary" statements can be found in international treaties and declarations (Vanderzwaag, 1999), which can be taken as different statements of the PP, frequently without explicit use of that term.

For example, the 1984 Bremen Ministerial Declaration of the International Conference on the Protection of the North Sea declared that "States must not wait for proof of harmful effects before taking action…." While it might be difficult to measure precisely the damage created by dumping chemical wastes

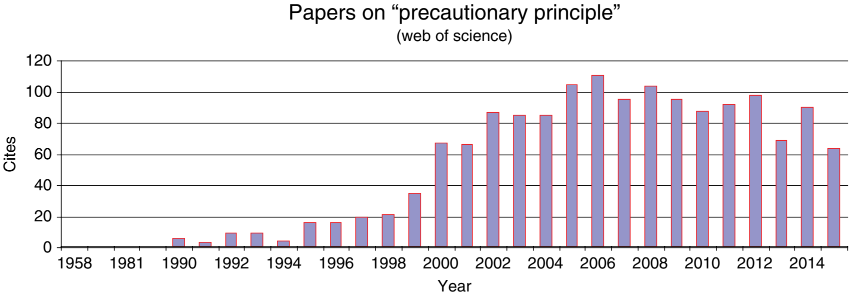

Figure 26.1 Number of papers on precautionary principle per year, from a search on Web of Science.

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[1] OED Third Edition. 2007. Online version, accessed 9 February 2016.

into ocean waters, no genius is required to imagine that such practices are environmentally damaging.

In the same vein, the 1992 Rio Declaration says "Where there are threats of serious or irreversible damage, lack of *full scientific certainty* shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". In this case, "scientific certainty" can be interpreted as either certain knowledge of the risk or certain knowledge that the proposed remedies will be effective.

A much stronger statement of the PP is found in the World Charter for Nature, which says "where potential adverse effects are *not fully understood*, the activities should not proceed". Since there is no action about which one can say future consequences are "fully understood", on face value this would seem to prohibit any new technology.

Faced with this diversity of approaches, Wiener and Rodgers (2002) and Wiener (2011) identified three "flavors" of the PP:

- *A weak formulation*: Uncertainty does not justify inaction. Thus, the Bergen Declaration (1990) says "[L]ack of full scientific certainty shall not be used as a reason for postponing measures to prevent environmental degradation". The Rio Declaration, another weak formulation, raises the issue of cost effectiveness, and thus opens the door to cost-benefit analysis.
- *A stronger formulation*: Uncertainty justifies or requires action. Thus, the preamble to the Declaration of the Third International Conference on the Protection of the North Sea (Preamble) (1990) says to take action even if there is "no scientific evidence to prove a causal link between emissions [of wastes onto ocean waters] and effects".
- *The strongest formulation*: Uncertainty requires shifting the burden and standard of proof. Thus, Wingspread Statement (1998) says "...the applicant or proponent of an activity or process or chemical needs to demonstrate that the environment and public health will be safe. The proof must shift to the party or entity that will benefit from the activity and that is most likely to have the information" (in Raffensperger and Tickner, 1999).

These three different formulations differ significantly in their implications. Indeed, the weakest formulation seems mild and hardly controversial. The strongest versions can be taken to mean that the proponent of a product must show that there is no (or acceptable) risk. Given the impossibility of proving the absence of risk, the standard of proof that would be demanded then becomes a major issue; too high a standard of proof would be tantamount to banning a new technology and drive up costs, which also has negative consequences for users of a technology.

26.2.2 Precaution As a Regulatory Strategy

Fundamentally, two different strategies are available to manage risk from technology (Klinke and Renn, 2001). *Ex ante* policies attempt to manage risk before the consequences of some action are well established. Examples include premarket approval in the regulation of drugs and medical devices in the United States or environmental assessments before a project is begun (many jurisdictions). *Ex post* measures are taken after the harms of a technology have been uncovered, typically by sad experience: "sue the bastards". Because *ex ante* regulation is inherently implemented before the outcome of an action is known, it is inherently precautionary, whether or not explicitly justified by invoking the PP.

Policies to regulate technological risk can be divided along a different axis as well: risk-based and PAs. Risk-based approaches established limits based on known hazards, for example, speed limits on a highway. RF exposure guidelines such as those of ICNIRP (1998) and IEEE C95.1-2005 (2005) are examples of risk-based policies, since they were set to exclude known hazards of RF energy (chiefly, from excessive heating of tissue) with appropriate safety margins. Setting performance standards for equipment is another example (e.g., limits on leakage of microwave energy from microwave ovens). In contrast to risk-based strategies, one can speak of PAs that do not explicitly attempt to avoid a clearly identified risk. These can include reduction measures such as ALARA (as low as reasonable achievable) and BACT (best available control technology). Precautionary measures are typically proposed when there is a perceived lack of sufficient information to allow formulation of risk-based policies, often considered as temporary measures that will reduce the likelihood of irreversible harm from newly identified but poorly understood health risks. (A third approach, termed discursive by Klinke and Renn, includes rulemaking based on citizens' panels, community meetings, roundtables, mediation, and can include elements of risk-based and PAs.)

In practice, governments use a mix of both *ex ante* and *ex post* regulations, and science-based and PAs, depending on the issue at hand and the political and legal constraints. (The United States, with its strong tort system, has been said to rely more on *ex post* regulation of risk than European countries) (Kolstad, Ulen, and Johnson, 1990).

Risk-based approaches are more appropriate where the risks are well identified and predictable (i.e., excessive heating of tissue from RF energy or traffic hazards from excessive speeding). PAs are more suitable when there is a reasonable concern about adverse effects but insufficient evidence to allow reliable risk-based regulation.

An example of a PA in the United States is the regulation of new drugs and medical devices by US Food and Drug Administration (FDA). Despite the requirement that manufacturers prove the "safety and efficacy" of new drugs and devices before being granted permission to market the products, the relatively small studies that are done to obtain regulatory approval cannot reliably identify rare adverse events. Commonly, the FDA will approve a drug or device but require the manufacturer to conduct postmarket surveillance studies to identify safety issues that eventually come to light after the product is introduced to market and large numbers of people have used it. FDA will also terminate clinical studies on a drug if an unfavorable risk profile begins to appear midcourse in a study, before enough evidence has accumulated to provide definitive evidence for the hazard – an application of the PP for sure. In its drug and medical device laws, the "nonprecautionary" United States is more "precautionary" than European countries.

26.2.3 Precautionary Principle in a European Context

The Treaty on European Union (1992), otherwise known as the Maastricht treaty, is the founding document of the European Union. It simply states

> Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay. Environmental protection requirements must be integrated into the definition and implementation of other Community policies.
>
> In this context, harmonization measures answering these requirements shall include, where appropriate, a safeguard clause allowing Member States to take provisional measures, for non-economic environmental reasons, subject to a Community inspection procedure.

Thus, the PP is written into the founding document of the EU and has been codified into legal doctrine that underlies all environmental (and increasingly other risk-related) regulations in the European Union. In the European context, there is no escaping it, even though many risk regulations (e.g., traffic speed limits) may not be explicitly framed in terms of the PP. The second quoted passage above allows member states to take "provisional measures, for noneconomic environmental reasons", another invitation for precautionary policies.

One authority has called the greater emphasis on *ex ante* regulation of risk implied in the Maastricht Treaty as "postmodern in many respects" (Rogers, 2011). But "postmodern" does not necessarily mean arbitrary. In an effort to avoid arbitrary decisions on precautionary grounds, in February 2000, the European Commission (EC, the governing body of the European Union) issued an important communication that laid out criteria for applying the PP by EU countries (and in fact shaped the development of European law on the issue in the subsequent years). The communication applied to EU nations, but it deserves wider attention as an important attempt by an authoritative source to rationalize the application of the principle.

In its communication, the EC acknowledged the central role that the PP plays in European environmental policy, and the need for precaution when managing risk under conditions of scientific uncertainty. But it also cautioned against arbitrary use of the PP and pointed to the need to use it in as politically transparent a way as possible.

Two major points emerge in the Opinion about the use of the PP:

1) *"Precautionary" measures must be applied to address identified risks*: For example, the Communication says "one factor logically and chronologically precedes the decision to act, namely identification of the potentially negative effects of a phenomenon".
2) *"Precautionary" measures must be based on "as best as possible" a review of the scientific evidence*: The Communication says "A scientific evaluation of the potential adverse effects should be undertaken based on the available data … [t]his requires reliable scientific data and logical reasoning, leading to a conclusion which expresses the possibility of occurrence and the severity of a hazard's impact on the environment, or health of a given population …"

Perhaps equally important, the Commission outlined a series of requirements for use of the PP (Table 26.1) (Commentary, p 3, italics in original):

> Where action is deemed necessary, measures based on the precautionary principle should be, inter alia:

- *proportional* to the chosen level of protection,
- *nondiscriminatory* in their application,
- *consistent* with similar measures already taken,

Table 26.1 Guidelines for application of the precautionary principle.[a]

Proportionality	"Measures … must not be disproportionate to the desired level of protection and must not aim at zero risk"
Nondiscrimination	"Comparable situations should not be treated differently and that different situations should not be treated in the same way, unless there are objective grounds for doing so"
Consistency	"Measures … should be comparable in nature and scope with measures already taken in equivalent areas in which all the scientific data are available"
Examination of the benefits and costs of action or lack of action	"This examination should include an economic cost/benefit analysis when this is appropriate and feasible. However, other analysis methods … may also be relevant"
Examination of scientific developments	"The measures must be of a provisional nature pending the availability of more reliable scientific data"… "scientific research shall be continued with a view to obtaining more complete data"

a) Reproduced with permission of EC Commentary, February 2, 2000.

- *based on an examination of the potential benefits and costs* of action or lack of action (including, where appropriate and feasible, an economic cost/benefit analysis),
- *subject to review*, in the light of new scientific data, and
- *capable of assigning responsibility for producing the scientific evidence* necessary for a more comprehensive risk assessment.

The EC communication emphasized that many different "precautionary" responses were possible to a potential risk, ranging from doing simply "watchful waiting" for further scientific developments, to sponsoring studies to gather more information, to voluntary measures, and to outright bans on technologies.

Requiring that precautionary measures be based on "as best as possible" a review of the scientific evidence and be based on "an examination of the potential benefits and costs of action or lack of action" is not all that different from Executive Order 12866 of September 30, 1993, issued by the US President Bill Clinton, which required federal agencies to carry out a careful review of the scientific evidence and a cost-benefit analysis promulgating new regulations.

In the subsequent years, roughly 150 legal cases have worked their way through European courts, resulting in a large body of case law that gives practical meaning to the PP in the European context. The litigated issues have included whether member states can ban import of British beef on account of the "mad cow" disease, whether the EU can ban the import of beef containing artificial hormones, and whether Norway can ban Kellogg's corn flakes (due to safety concerns about nutritional enrichment of the product).

One issue debated in these cases is how strong the scientific evidence for a risk must be to "trigger" precautionary responses by regulators; purely hypothetical risks are not sufficient. For example, in landmark case involving antibiotics in animal feed, the Court of First Instance ruled.

> It is necessary, first, to define the 'risk' which must be assessed when the precautionary principle is applied … A preventive measure cannot properly be based on a purely hypothetical approach to the risk, founded on mere conjecture which has not been scientifically verified … Rather, it follows from the Community Courts' interpretation of the precautionary principle that a preventive measure may be taken only if the risk, although the reality and extent thereof have not been 'fully' demonstrated by conclusive scientific evidence, appears nevertheless to be adequately backed up by the scientific data available at the time when the measure was taken (Alpharma v Council, 2002).

(The Court dismissed a suit brought by Alpharma, which makes antibiotics for use in animal feed, and in its judgment reaffirmed the use of the PP while clarifying the conditions for its application.) What it means to "adequately back up" a risk with scientific data is left as a take-home assignment for the reader.

26.2.4 The PP in Commonwealth Law

Canada and other Commonwealth countries have incorporated a weak form of the PP into their environmental laws. The Canadian Environmental Protection Act (Revised 1999) echoes the 1992 Rio Declaration:

> where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Similar provisions have been adopted by other Commonwealth countries, for example, Australia, where a number of judicial decisions cite the PP (Bell, 2010). Canadian regulations on RF exposure are similar to those in effect in the United States, where the PP has scant legal recognition.

26.2.5 The PP in US Law

While the United States has not formally adopted the PP at the federal level, some US laws have distinctly "precautionary" provisions. The most conspicuous example is the requirement for premarket approval and postmarket surveillance for new drugs and medical devices by the FDA. The Pollution Prevention Act of 1990 set prevention as the highest priority in environmental programs in the country, which is precautionary in spirit if not explicitly based on the PP.

26.2.6 Is Europe More Precautionary than the United States?

While one might be tempted to consider Europe as more "precautionary" in its risk management policies than the United States, a careful examination shows that this is not the case in general; rather the level of precaution in different issues varies greatly depending on variations in culture, history, law, and local politics.

In *The Reality of Precaution*, Hammit et al. (2013) examined more than a dozen case studies involving risk issues such as food safety, regulation of genetically modified organisms, climate change, and medical safety. They found a "rough parity" in levels of precaution in the United States and European Union across these cases, with the United States being more precautionary in some areas (tobacco) and less precautionary in others (e.g., genetically modified crops) than Europe.

For example, Europe has for many years been much less "precautionary" than the United States in its regulation of new drugs and medical devices, with much lower regulatory barriers to approval. This led to a tragic episode in the early 1960s when thalidomide, a drug that had been approved in Canada and 20 European and African countries to combat morning sickness in pregnant women, was brought before the FDA for US approval. The FDA officer who reviewed the new drug application for the drug in 1960 suspected that there might be a problem and delayed the application. Thalidomide was soon shown to cause catastrophic birth defects in the children of women who took it. The officer, Frances Kathleen Oldham Kelsey (1914–2015), became a national hero in the United States for her precautionary actions, and the tragic episode led to still-more precautionary changes in US drug laws.

Due to wide conceptual variability, it can be fruitless to argue whether a strategy for risk management is "precautionary" or "nonprecautionary" or somewhere in between or what the "precautionary principle" would demand in a given situation (assuming that it is applied at all in a particular legal context).

Two paradigm cases related to EMF regulation may be helpful to consider on which many people would undoubtedly agree. It is well known that a tall construction crane near an active AM radio tower can be dangerous if it is not properly grounded because strong RF currents can be coupled into it and passed through the body of a worker who touches it. Work rules require grounding of cranes when operated near AM broadcast transmitters to avoid this hazard, and few people would argue that such rules are motivated by the PP as opposed to avoidance of a well-identified hazard.

The opposite, clearly precautionary, paradigm case is the call to apply the PP to MRI imaging of patients because of recent reports that MRI imaging causes a small increase in DNA strand breaks in lymphocytes from patients after imaging, possibly increasing the risk of cancer later in life (Kaufmann, 2015). In this case, the gap between the presently available scientific evidence (evidence for DNA damage in lymphocytes from patients undergoing MRI imaging from small and rather preliminary studies) and any eventual health impacts is very great. Moreover, other apparently well done studies find no such effects and the effect itself is hardly well established. At best, one can say that some evidence points to possible genotoxic effects of MRI imaging and, if the effect is real, there might be future health impacts to patients – in contrast to the immediate and obvious hazards to construction workers using cranes near broadcast transmitters.

But the dividing line is not clear. In a risk-based context, one can argue that setting exposure limits with very high safety margins against known hazards is an application of the PP, to protect against harmful effects from unforeseen exposure conditions. That approach is taken by Health Canada on its website which states that its RF exposure limits (which are similar in their basic assumptions to ICNIRP and IEEE C95.1-2005 but differ in a number of details) are based on the "precautionary principle",[2] and this characterization has been upheld by courts in other Commonwealth countries with respect to generally similar RF exposure limits in those countries (*Telstra*, 2006). One might argue

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[2] http://www.hc-sc.gc.ca/ewh-semt/consult/_2014/safety_code_6-code_securite_6/feedback_commentaires-eng.php.

whether this is a "true" application of the PP, but since this characterization has been supported by Commonwealth legal precedent and no Papal edict or imam's fatwa provides a more authoritative definition of the "true" PP – who is to prove Health Canada wrong?

Another example is the SAGE program in the United Kingdom (2007–2011) that consisted of stakeholder meetings with citizens on possible risks of powerline fields. The recommendations of that program, arrived at within the "precautionary" framework of the EU, are similar to those adopted in the "nonprecautionary" United States.

Given these ambiguities, one can hardly fault advocacy groups for trying to define the PP in terms favorable to their causes and insisting that the PP "demands" a certain course of action that promotes their agendas. In fact, it demands nothing in particular or even nothing at all apart from more study of a suspected problem. In most jurisdictions outside of Europe, the PP is a counsel of caution, a rule of thumb rather than a defined principle with a long precedent of decisions to guide its application, which is the case of several principles of bioethics. For that reason, one can argue that the PP is not a "principle" at all (Weed, 2002).

Calls to apply the PP can, in fact, be a surrogate argument for policies that might be questionable if considered directly. In its report "Late Lessons From Early Warnings" (Harremoës et al., 2001), a group with the European Environmental Commission reviewed 12 case studies (e.g., ionizing radiation, asbestos, PCBs, and benzene) where technological advances led to serious health and environmental damage, to argue for more strenuous application of precautionary *ex ante* policies. Other examples come readily to mind. If the US Soil Conservation Service had not promoted planting kudzu in the south in the 1930s to control erosion, the kudzu would not have become established as "the plant that ate the south." A similar mistake was made in the 1850s when the English sparrow was imported into the United States and quickly became a major pest.

It is easy to find, in retrospect, examples where different policies should have been implemented. But the real need is different: to make wise policy as events are developing, considering possible risks and costs versus benefits of alternative courses of action. Not all "precautionary" measures are wise, seen in hindsight. One precautionary policy that went badly awry was the 2003 invasion of Iraq, which was presented to the American public as a precautionary response to (false) claims that Saddam Hussein had weapons of mass destruction.

A single-minded focus on risk aversion to the exclusion of other considerations can lead to ludicrous advice. "The president of Liberty University urged students, staff, and faculty at the Christian school to carry concealed weapons on campus to counter any possible armed attack like the mass shooting in San Bernardino, California" the N. Y. Times reported on December 5, 2015. But encouraging students to walk around campus with hidden weapons creates risks of a different sort. Professors at the University of Houston recently attended a presentation about the effects of a 2016 Texas law that allows professors and students to carry concealed weapons on Texas campuses. The presentation urged the professors to avoid getting into heated conversations and not raise sensitive issues with students (Wermind, 2016) – an excellent and sensible application of the PP. (The concealed-carry law was lauded by gun rights groups as promoting their constitutional rights to own guns, and they argued that this would make campuses safer by allowing people to fight back in case a terrorist started shooting up the place.) Trading risks of being killed in a terrorist attack with risks of being killed by an irate or inebriated student is an example of what risk analysts call a risk–risk trade-off (and a very unfavorable one at that). Most citizens outside the United States would consider the proposition of carrying concealed weapons on campus as a legitimate "precautionary" measure to be completely insane.

Risk–risk trade-offs inevitably arise with any attempt to regulate risk. A "precautionary" policy that dissuades patients from MRI imaging due to a (presently unsubstantiated) fear of an increase in cancer risk late in life might result in less effective treatment for the patients, many of whose remaining lifespans might be too short for cancer to develop even if the risks were real.

Ultimately, a single-minded focus on risk aversion might appear to be a workable strategy only if one ignores risk–risk trade-offs that are inherent in any proposed action. As Cass Sunstein put it (2002):

> The precautionary principle [referring to one of the stronger forms discussed above] can provide guidance only if we blinker ourselves and look at a subset of the harms involved. In real-world controversies, a failure to regulate [against a prospective risk] will run afoul of the precautionary principle because potential risks are involved. But regulation itself will cause potential risks, and hence run afoul of the precautionary principle too; and the same is true for every step in between. Hence the precautionary principle, taken for all that it is worth, is literally paralyzing. It bans every imaginable step, including inaction itself.

Or, as one wag put it, to be consistent we should apply the precautionary principle to the application of the precautionary principle itself. The resulting stasis would be good or bad depending on one's point of view.

26.3 Precautionary Approaches to Regulating Human Exposure to Radiofrequency Fields

The issues related to application of the PP are different for powerline (ELF) and RF fields; this discussion considers only RF fields. Precautionary policies related to powerline fields are discussed in Chapters 25 and 27 in this volume.

The question of whether health risks might result from exposure to RF energy below current exposure limits has been controversial for many years concerning many different RF-emitting technologies. However, at present, most public (and to a much lesser extent scientific) controversy relates to the safety of use of cellular telephones. The many scientific studies on the possible biological effects of RF energy, now including several thousand studies that vary in quality and endpoint, have been repeatedly reviewed by health agencies with generally similar findings (lack of convincing evidence for health hazards of RF energy below ICNIRP and other major international exposure limits, but "more research is needed").

While they fail to find clear evidence of health problems at RF exposures below international limits, these reviews also fall short of proclaiming that mobile phone emissions are "safe". For example, in mid-2000, a blue ribbon committee in the United Kingdom (the Stewart committee) issued a report that concluded "the balance of evidence to date suggests that exposures to RF radiation below [recommended limits] do not cause adverse health effects to the general population" (IEGM, 2000). But it added rhetorically, "it is not possible at present to say that exposure to RF radiation, even at levels below national guidelines, is totally without potential adverse health effects". (It is, of course, not possible to say that anything is "totally without potential adverse health effects").

There are, in fact, two distinct issues that differ greatly in terms of exposure characteristics and risk perception. One is possible risks to individual users of cell phones (voluntary exposures, sometimes by children); the other is exposure to an individual by environmental sources of RF energy such as cellular base stations, Wi-Fi networks, and wireless-enabled utility meters. This involves involuntary exposures to people, including children and other "vulnerable" individuals in the population, to RF energy at comparatively much lower levels than an individual would receive from use of a cellular handset. Outside of specialized occupational settings, typical environmental exposures from a host of common sources are inevitably a tiny fraction of international exposure guidelines (IEEE C95.1-2005 and ICNIRP) as well as US (FCC) and Canadian limits (Safety Code 6). These limits were designed to be protective to any member of the population.

The major recent development regarding RF safety that has affected political discourse is the classification of RF energy as "a possible carcinogen" (Class 2B) by the International Agency for Research on Cancer (IARC, 2013). While IARC applied this classification to RF energy without specifying the source, the evidence that chiefly prompted IARC's classification consisted of epidemiology studies linking long-term use of cellular telephones to development of brain tumors. In the context of the IARC decision-making process, the 2B classification indicates a level of suspicion, but without sufficient evidence for IARC to determine that RF energy "is" or "probably is" a cause of cancer.

The IARC 2B classification has been widely cited in recent years in public opposition to other uses of RF energy including Wi-Fi in schools, cellular base stations, or smartmeters (wireless-enabled utility meters that are mounted on customers' houses) and other technologies that use RF energy. RF exposures to citizens from such devices are far lower than from the use of a cell phone.

Responding to public concerns, governments have considered or adopted a variety of precautionary measures, which may or may not have been explicitly framed in terms of the PP. There is a substantial literature on this, much of it from an advocacy perspective. From a more neutral policy perspective, Zander (2010) has written a comparative review of policies in the United States, United Kingdom, and Sweden on siting cellular base stations. Dhungel, Zmirou-Navier, and Van Deventer (2015), Vijayalaxmi and Scarfi (2014), and Stam (2011) have reviewed RF exposure policies, including precautionary policies, in different countries based on a database maintained by the EMF Project at the World Health Organization. Redmayne (2016) has reviewed policies in effect in various countries regarding use of cell phones by children, while Rowley and Dolan and Rowley (2009) discuss the PP as applied to the siting of wireless base stations from an industry perspective.

Some of the many "precautionary" approaches have included:

26.3.1 Gather Information/Sponsor Research but Take No Regulatory Action

Moat governments follow the issue carefully, and more than 35 expert reviews on the topic by health agencies or other official bodies have appeared since 2010 (Verschaeve, 2012). A number of countries (chiefly in Europe) and the European Union have set up major research programs on possible health effects of RF energy. These are perfectly legitimate "precautionary" measures.

26.3.2 Prudent Avoidance

This approach was first put forward 1989 by a group led by Morgan at Carnegie Mellon University (Nair, Morgan, and Florig, 1989) to address public concerns about possible risks of electric or magnetic fields associated with powerlines. This group recommended that measures be taken at moderate cost to reduce exposure to the population to power frequency fields. If the costs are low, the cost/benefit trade-off may be tolerable even though the benefits may be low also.

Prudent avoidance has received limited acceptance in the regulation of siting of high-voltage power lines in a few US states. For example, California asks for an investment of up to 4% of the total costs of a project for EMF mitigation. Typical measures under this policy would involve siting and design of power lines, resulting in modest reductions in population exposures to ELF fields. Very costly measures that would result in large reductions in exposure, for example, burying high-voltage power lines, would not be required by the prudent avoidance policy. Given the high costs of delays for a powerline project due to litigation, utilities consider such costs to be tolerable (and in any event, the costs would be recoverable from ratepayers). It is much harder to minimize population exposures to RF energy when installing cell base stations due to the complex nature of RF propagation, but, nevertheless, some jurisdictions have implemented "prudent avoidance" policies, if not specifically under that name.

Thus, for example, in May 2002, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) adopted a new set of exposure limits for RF energy (RPS3). The standard generally follows international (ICNIRP) limits, but contains the requirement for "minimizing, as appropriate, RF exposure which is unnecessary or incidental to achievement of service objectives or process requirements, provided this can be readily achieved at reasonable expense…. The incorporation of arbitrary additional safety factors beyond the exposure limits of this Standard is not supported".

The ARPANSA RPS3 standard does not explicitly mention "prudent avoidance" as proposed by Nair et al. Indeed, in the words of Vitas Anderson (a member of the committee that drafted the limits), the committee considered and rejected prudent avoidance "due to a perception of waning general support for this concept" (Anderson, personal communication 2 July 2002). Instead, the committee forged an

> uneasy compromise between the perceived political need to incorporate some form of precautionary measures (though the standard's review of the bioeffects literature provides no support for this) and the desire to minimize the community harm that would be caused by unnecessarily denying or delaying public access to RF services that provide social, economic and public safety benefits.

ALARA is a stronger approach that has, seemingly rather gingerly, been suggested in some countries to apply to RF exposures. According to Vitas Anderson (personal communication March 28, 2016), the ALARA principle was incorporated in the 1985 and 1990 editions of the Australian RF safety standard (AS 2772 – 1985 and AS 2772 – 1990) but was dropped from the later (2002) standard. According to him, several earlier attempts to update the 1990 standard failed because of disagreements in the drafting committee about "precautionary" provisions.

More recently, a 2013 report to The Health Council of Netherlands (among other groups) suggested:

> the Committee would like to suggest that there is no reason not to apply the ALARA principle to exposure to RF EMF, meaning that exposures should be As Low As Reasonably Achievable. (Health Council of the Netherlands, 2013)

It does not appear that this ALARA policy has resulted in specific regulations.

Indeed, unless it is very carefully defined, it is difficult to see how ALARA could be applied in a consistent way given the many uses of the RF spectrum and the complexities of RF exposure assessment. Even for the limited problem of siting cellular base stations, the problem becomes very complex. Does ALARA refer to the RF exposure to the most exposed person living near a base station or to some kind of population-averaged exposure? In the latter case, is it relevant that RF exposures to an average citizen from cellular base stations are generally smaller than from other sources of RF exposure (including ones own use of a mobile handset)? Does ALARA mean that cell telephone companies should not offer data services (which consume a lot of bandwidth, increasing the RF power transmitted from a station)? Does ALARA imply that cellular providers should install a great many low-powered base stations throughout coverage area (thereby reducing peak exposures to residents near any one of them) or should they install base stations only in lightly populated areas of a city, thereby requiring subscribers' phones to transmit more power to be able to communicate with these generally more distant stations? ALARA does not translate into any simple algorithm for its implementation.

26.3.3 Other Low-Cost "Precautionary" Measures

One precautionary measure has achieved widespread acceptance: the use of hands-free kits to physically remove a cell phone handset from the proximity of the user's head. The kits reduce the exposure of the head to RF energy (by removing the handset from the head), but if the user places the handset in his pocket or her bra, other parts of the body could receive higher exposure as a result. Hands-free kits are inexpensive and often distributed with new handsets. There is, in addition, an after-market in various shields and devices purported to reduce the exposure to a handset user. These devices are generally ineffective and, in some cases, appear to be outright frauds.

Another low-cost precautionary measure is publicizing SAR (RF absorption) data for cell phones as recommended by the Stewart report (IEGMP, 2000) and implemented in many jurisdictions. This has led to confusion for consumers who, faced with SAR data for mobile handsets, have no clear way to decide which model is safer. Is a GSM digital handset with low SAR but a pulse modulated signal safer than a CDMA model with a somewhat higher SAR but no pulse modulation? In the absence of any substantial evidence that RF energy from either handset is hazardous, and the basic irrelevance of SAR measurements done under precisely controlled laboratory conditions to real-world exposures, not even scientists can decide which kind of handset will actually result in lower exposure to the user.

26.3.4 Reduction in RF Exposure Limits on Precautionary Grounds

Most countries around the world have adopted limits that closely follow ICNIRP. However, the international regulatory situation is complex and constantly evolving (Stam, 2011; Zmirou-Naview, Dhungel, and Varret, 2013; Joas et al. 2008). Presently, 35 countries have instituted some form of precautionary policies regulating exposure to RF fields, either to replace or to supplement science-based exposure limits such as ICNIRP. These limits variously apply to RF exposures to individuals or to emissions from antennas or siting of communications facilities near "sensitive" areas such as schools and hospitals.

The regulatory situation is complex and changing as public opinions on the issue change. As described by Stam (2011), different regulatory measures have included the following:

- Exposure limit from mobile devices based on a PA
- Limitations on use of mobile for children based on PA
- Exposure limits from fixed installations based on PA
- Emission limits from fixed installations based on PA
- Occupational exposure limits based on PA
- Occupational provisions for specific groups based on PA
- Management of occupational exposure to RF fields based on PA.

For example, Liechtenstein[3] reduced its RF exposure limits from communications facilities to 6 V/m, a factor of about 10 in field strength, or 100 in power density, downward from international (ICNIRP) limits. Later (2008) its Parliament further revised the limits downward to 0.6 V/m (an additional 100-fold decrease in the power density, which would have significant impacted wireless communications in the Principality). In response to a campaign by the communications industry and after a general election, Parliament rejected its 2008 limits in 2009, keeping limits for RF exposures from communications towers at roughly 1% of ICNIRP guidelines (measured in terms of power density).

As another example, in 1999, Switzerland passed an ordinance based on the Environmental law that specifies emission limits for limited number of (selected) ELF and RF sources, in effect reducing exposure at sensitive areas such as schools and hospitals.[4] (The ordinance however is complex and a number of special cases apply.) The Swiss communications industry reacted with dismay at these changes. For example, in December 1999 (just before the new Swiss regulations came into effect), Swisscom issued a press release complaining that the new regulation "weakens the attractiveness of Switzerland as an economic location and makes additional transmitters necessary" and will increase the cost of service to its subscribers. Needless to say, the Swiss and Liechtensteiners still have their mobile telephones, but the cost of the measures (both in terms of increased costs of service and in terms of degraded network performance) is difficult to gage.

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[3] http://emfhealth.info/docs/eng/2012_MMF_vp_Liechtenstein.pdf.

[4] Swiss Federal Council, Ordinance relating to Protection from Non-Ionising Radiation (ONIR) 814.710 1 February 2000. German version available online at https://www.admin.ch/opc/de/classified-compilation/19996141/index.html

26.3.5 Advisories to Refrain from Use of Mobile Phones or to Use "Hands-Free" Kits to Reduce Exposure

A number of countries have issued advisories that children should be discouraged from using mobile phones. For example, the Stewart report in the United Kingdom recommended in 2000 (IEGMP, 2000):

> In line with our PA, we believe that the widespread use of mobile phones by children for non-essential calls should be discouraged. We also recommend that the mobile phone industry should refrain from promoting the use of mobile phones by children.

We all know how (un)successful recommendations of this sort have been. In fact, children have greatly reduced their use of mobile phones for voice calls (essential or not) in favor of text messaging – but not for precautionary reasons. A different health concern is emerging, cognitive effects in children from excessive use of smartphones (Radesky, Schumacher, and Zuckerman, 2015), not to mention accidents involving people taking "selfies" near cliffs who absent-mindedly step backwards toward the precipice (Izadi, 2014).

26.4 Difficulties with Precautionary Approaches to Radiofrequency Field Regulation

Attempts to develop precautionary policies to regulate unproven risks of RF energy can be problematic for many reasons. The impression is that precautionary policies have been introduced in many countries on an *ad hoc* basis as a political accommodation to citizens fearful of the safety of wireless base stations, without the extensive analysis and scientific review requested by the EC commentary and without describing the measures as provisional. Precautionary policies that are developed to address public fears about the comparatively low-powered base stations can trip over the presence of transmitters operating at much higher power levels in the same environment, resulting in significant political and legal controversies that were unforeseen when the policies were implemented.

For example, Italy inadvertently fell into a major controversy with it adopted an "attention level" that was a factor of 10 (in field strength) or 100 (in power density) below international (ICNIRP) limits. The public, misinterpreting these "attention levels" as a threshold for hazard, then demanded still stricter limits. As a result, Tuscany and other regions soon found themselves with exposure limits below field strengths produced by many common transmitters in the society (Vecchia and Foster, 2002). A major political and legal dispute arose in 2001–2002 in Italy related to a radio station owned by the Vatican, located outside of Rome, when it was discovered that the RF signals from the transmitter exceeded local exposure guidelines (although they complied with former "nonprecautionary" Italian limits (ICNIRP limits) by a large margin). To respond to public concerns, the government sponsored a study of childhood leukemia in residents near the facility and found a few "excess" cases near the transmitter – an unreliable finding because of the small population in the study. Lawsuits were filed, and in 2011, the Vatican was forced to pay damages for claims that children in a nearby town suffered from increase cancer risk due to exposure to RF energy from the transmitter.[5] Ultimately, the antennas were moved to a different location, not based on any measured attempt to reduce population exposures to RF energy or as a result of the scientific analysis requested by the 2001 EU commentary but simply as a political accommodation to an irate public.

In 1999, Toronto, faced with citizens' protests about the installation of cellular base stations, adopted what it called a "prudent avoidance" policy. Because it was infeasible to locate cell base stations to minimize exposure, the city's "prudent avoidance" policy set exposure limits to RF energy from mobile phones that are a factor of 100 below (then current) national Canadian limits (Health Canada's Safety Code 6):

> In 1999, the Board of Health recommended a policy of Prudent Avoidance due to the degree of uncertainty about health impacts of long-term, low level exposure to RFs. To address this uncertainty, the policy proposed reducing the potential exposure to RFs by using an added factor of protection, an approach that is consistent with the standard setting practices for chemical substances. This approach recommended that the RF emissions from any proposed cell phone tower installations be kept 100 times below Safety Code 6 in areas accessible to the public.[6]

This limit was not justified by a scientific analysis based on avoiding any identified health hazard (or even to avoid identified biological effects of such exposure, regardless of health consequence), but rather in response to statements in an earlier report by Health Canada that outlined areas of uncertainty about "nonthermal" effects of RF exposure. As a practical matter, the levels were set somewhat above exposure levels from typical cellular base stations. The city could then offer "prudent avoidance" to the citizens without substantially affecting the operation of cellular telephone systems.

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[5] Day M. Vatican Radio is told to pay out over cancer risk scare, The Independent (UK) March 1, 2011 (http://www.independent.co.uk/news/world/europe/vatican-radio-is-told-to-pay-out-over-cancer-risk-scare-2228541.html).

[6] Medical Officer of Health (Toronto), Prudent Avoidance Policy on Siting Telecommunication Towers and Antennas, Toronto, November 20, 2007. Available on the Internet at http://www.toronto.ca/legdocs/mmis/2007/hl/bgrd/backgroundfile-8919.pdf.

But there may be unintended consequences and hidden costs to such a PA. First, such policies are likely to increase public concerns. The public perceives exposure limits (of any sort) as "red lines" that separate safe from unsafe exposure. A significant reduction in exposure limits brings exposures closer to the limit. "Precautionary measures may trigger concerns, amplify EMF-related risk perceptions, and lower trust in public health protection" Wiedemann and Schütz (2005) remarked in their study of risk perception and the PP. (If Toronto reduces its limits for RF exposure from cell base stations by a 100-fold, is not there a reason for concern?)

Second, there is the problem of consistency. RF exposure from many common sources of RF energy can easily exceed Toronto's "prudent avoidance" limits. RF exposures to someone standing close (within a meter) to the user of a mobile phone may well exceed 1% of SC6 limits and thus exceed Toronto's precautionary limits. Should use of mobile phones be banned from public spaces? What about transmitters on police cruisers in the city?

Commercial broadcast transmitters in the city operate at far higher power levels than cellular base stations and citizens might reasonably ask that the "prudent avoidance" limits apply to them as well. Atop the CN Tower, a major landmark in the center of the city, is a set of broadcast antennas that transmit a total of more than 1 million watts of RF power, and produce RF exposure levels at publicly accessible locations in the city that are up to a few percent of Safety Code 6 limits, that is, compliant with national RF exposure limits but a few times higher than the city's "prudent avoidance" limits adopted for cellular base stations.

One might ask: why are such "high" exposures from the CN tower (as well as several other broadcast transmitters in the city) tolerated but not comparatively much lower exposures from neighborhood base stations?

The answer, in brief, is that Canadian activists have complained about the tower (as well as about other broadcast transmitters in the city, according to city officials I have corresponded with), but the regulatory constraints are different. The CN tower opened in 1976 and was effectively "grandfathered" by city ordinances under the prudent avoidance policy; City bylaws and ordinances would not apply in the case of the CN tower siting as they would to siting of cellular base stations. Cellular base stations began to appear on the urban scene in large numbers much more recently and have been the cause of many local battles in part because of health concerns. The "prudent avoidance" policy was in effect a political accommodation taken in response to this more recent controversy about cellular base stations, and it was never intended to apply to the much higher powered transmitters already in the city (or to other sources of RF exposure in the environment). But the question of consistency inevitably arises and it can create politically difficult questions for the city to answer.

Third, what was intended to be a low/no cost approach to RF protection may end up costing the city and cellular carriers more than originally anticipated. As time has gone on, the power output of typical cellular base stations has edged upward as carriers add new services and expand capacity to accommodate increased demand for cell services. At the same time, the limits of Safety Code 6 have edged downward, as Health Canada has responded with its own increasingly cautious limits (last revised in 2015) (though the city is still enforcing its "prudent avoidance" limits with reference to the older version of SC6). Also, concerned citizens are now buying inexpensive RF exposure meters and can measure RF levels in the environment, albeit crudely, and complain to the city when their measurements indicate exposure levels above the city's "prudent avoidance" limits, necessitating follow-up investigations by the city or Industry Canada.

So far, this has not caused the city undue hardship, and in any event, its ability to regulate cellular base stations is limited by regulations of Industry Canada (at the federal level). But compliance costs to the cellular carriers and burdens to city officials are both rising, resulting, for example, in the health department preparing reports and conducting surveys of RF exposure levels on an *ad hoc* basis.

Finally, despite the concept (at least in the European Union) that precautionary measures are intended to be temporary pending the development of adequate evidence to develop science-based limits, it is politically unfeasible for Toronto to remove its "prudent avoidance" limits and return to SC6 – as the city discovered in 2013 when its Medical Officer of Health recommended dropping its prudent avoidance policy on the grounds that it was not needed to protect health, thereby unleashing a loud protest by a Canadian activist group (http://www.c4st.org/TorontoPA) causing the Toronto Board of Heath to reject the proposal.

These issues are nowhere near the scale of the controversy surrounding the Vatican radio station; the political and legal environments are different. However what was originally intended as a no-cost/low-cost measure to reassure the public may wind up costing the city more than originally anticipated, both in terms of economic cost and in time spent by its public officials in dealing with the controversy. Of course, if a significant hazard were eventually proven at exposure levels far below SC6, these officials would be commended for their foresight.

26.4.1 Should the Precautionary Principle Be Applied to RF Exposures?

Given the varying concepts of the PP and PAs to regulation and how they are to be used, the question hardly makes any sense. But that call is often made by citizens protesting electrical facilities. Depending on one's view of the PP, one can argue that it *is* being widely applied by governments around the world in their many health reviews and (arguably) in generous safety margins for national RF safety limits.

One authoritative source, the European Commission Commentary on the PP (2000) gave two criteria for "triggering" the PP:

1) [I]dentification of the potentially negative effects of a phenomenon.
2) A scientific evaluation of the potential adverse effects should be undertaken … when deciding whether or not to invoke the precautionary principle … leading

> to a conclusion which expresses the possibility of occurrence and the severity of a hazard's impact …

The scientific literature has been evaluated many times by health agencies and other expert groups. The WHO has not completed its long-promised risk assessment of RF fields (its Environmental Health Criteria, a major review, is scheduled to be completed in 2018 at the earliest). However, *none* of the expert reviews undertaken by health agencies or other official groups have decided that there are proven hazards from exposure to RF fields at levels below international (ICNIRP) limits even as they point to open questions and call for more research. Open scientific questions and suggested but unproven hazards are not, by the EU's criteria, sufficient to "trigger" the PP. Rather, one needs an identified health risk and the PP is triggered by the inadequate nature of the data which would not permit the formulation of conventional science-based limits.

In 2011, the International Agency for Research on Cancer (IARC) classified RF fields as a "possible" carcinogen. The classification was for RF energy without specifying its source, but the evidence that the IARC Working Group considered most useful in its deliberations came from epidemiology studies on long-term use of mobile phones. IARC's "possible carcinogen", designation was, by IARC's formal decision rules, a statement that the Working Group concluded that evidence supports a level of suspicion but is insufficient to conclude that RF energy actually, or probably does causes cancer.

So one might argue that this designation might satisfy the first of the above mentioned EU criteria and trigger PAs to use of cell phones. Interestingly, the IARC itself does not make any precautionary recommendations for RF fields. In its European Code against Cancer (2014), IARC listed "12 ways to reduce your cancer risk" (McColl et al., 2015). Reducing exposure to nonionizing radiation (neither RF nor ELF fields) was not included in the list. As the authors explained in the abstract, "nonionizing types of radiation (those with insufficient energy to ionize molecules) – including extremely low-frequency electric and magnetic fields as well as RF electromagnetic fields – are not an established cause of cancer and are therefore not addressed in the recommendations to reduce cancer risk".

But clearly, the public (or at least vocal elements of it) is concerned about possible health effects of RF fields in the environment, and risk management takes place in the political, as opposed to strictly scientific, arena.

In my view, the most sensible approach is to rely on science-based limits for mandatory exposure standards to avoid identified hazards and rely on softer measures to address public fears (taking into the account the potential of such measures to increase public concerns). In particular, there is the need for better risk communication both by industry and government – publishing technical data about SAR levels from cell phones is not helpful to consumers when not even scientists can explain clearly what the levels mean and how a person might use the data to improve his/her health. It would not be unreasonable to have more stakeholder programs such as the SAGE Program in the United Kingdom (which concerned powerline fields) or to require cellular telephone carriers to have consultative meetings with the public to help to decide where to site cellular base stations.

Ultimately, all technologies have unintended consequences, good or bad, and some degree of caution is always needed. But risk aversion is only one consideration, albeit an important one. Considerations should not be focused solely on avoiding risks (possible or proven) but rather on what is the best choice of action moving forward, given the range of actions that are possible.

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27

How to Handle Precaution

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27.1 Introduction

In modern societies, people are ubiquitously exposed to electromagnetic fields (EMFs) from various man-made sources including power lines, mobile phones, and associated base stations, as well as other wireless communications sources and electrical equipment. At the same time, concern has been expressed that exposure to EMF could cause adverse effects to human health. Consequently, national governments and health authorities have developed measures to prevent, or to minimize, risks associated with exposure to EMF. These measures are underpinned by standards and guidelines that are based on current scientific understanding and aim to protect against all adverse effects that have been demonstrated in qualified research. In recent years, the concept of precaution has emerged, where there is a high degree of scientific uncertainty and a need to take action for a potential risk without awaiting the results of more scientific research. For example, there could be a need to take action to protect against EMF hazards that have been suggested or even mildly correlated but not established by scientific research (Vecchia, 2007).

27.2 A Precautionary Approach to EMF

The World Health Organization (WHO) advises that science-based evaluations of the potential hazards from EMF exposure should form the basis of risk assessment and these are also an essential part of an appropriate public policy response (WHO, 2002). However, the assessment of potential health risks of

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EMF includes a degree of scientific uncertainty around the limited scientific evidence for health effects.

Throughout the world, there has been a growing movement to adopt a precautionary approach for the management of health risks in areas of scientific uncertainty. A wide variety of definitions and interpretations of a precautionary approach have been proposed. The WHO defines the Precautionary Principle as a risk management concept that provides a flexible approach to identifying and managing possible adverse consequences to human health even when it has not been established that the activity or exposure constitutes harm to health (WHO, 2000).

Precautionary approaches such as the Precautionary Principle are risk-oriented, requiring an evaluation of the risk and considering the costs and benefits of any exposure reduction measures. A precautionary approach to EMF is supplementary to recognized scientific evidence-based exposure guidelines and standards. The WHO advises that scientific assessments of risk and science-based exposure limits should not be undermined by the adoption of arbitrary precautionary approaches and particularly arbitrary precautionary limits (WHO, 2000).

In 2000, the European Commission (EU) approved a communication on the Precautionary Principle providing guidance for the application of the Principle. This guidance recommends that measures based on the Precautionary Principle should be as follows:

- proportional to the chosen level of protection
- nondiscriminatory in their application
- consistent with similar measures already taken in equivalent areas in which all scientific data are available
- based on examination of potential benefits and costs of action or lack of action (not just economic costs)
- subject to review in the light of new scientific evidence
- capable of assigning responsibility for producing scientific evidence for a more comprehensive risk assessment.

In this guidance, the Precautionary Principle is "risk oriented," in that it requires an evaluation of risk research including cost-benefit considerations (EU, 2000).

The use of a precautionary approach to EMF does not necessarily mean just taking measures to reduce exposure. A precautionary approach can cover a multitude of measures, including monitoring and participating in scientific research, provision of information, stakeholder engagement, and minimizing exposure.

While a precautionary approach is useful for dealing with uncertainty in scientific knowledge, care is required in its application. A major issue is the lack of evidence that any additional measures will offer any more protection against unknown risks than that provided by just keeping within the science-based exposure levels. It is also important that the introduction of a particular measure does not inadvertently introduce an additional untoward effect in a different area. The consumer and society will ultimately meet costs, both direct and indirect. A precautionary approach could be detrimental were it to encourage high cost actions that provided little benefit to health (ARPANSA, 2002).

A precautionary assessment should be based on avoidable exposures and net benefit (taking costs and other risks into account) with the overall aim to reduce exposure without increasing other risks or reducing the benefits of technological advances. The EU guidance describes the general criteria for a precautionary assessment as considering proportionality, nondiscrimination, consistency, examination of the benefits and costs of action or lack of action, and examination of scientific developments (EU, 2000).

The following hypothetical example illustrates the application of precautionary measures in the case of extremely low frequency (ELF) electric and magnetic fields; similar examples may be considered for other nonionizing radiation types. This example illustrates the general principles but is not intended to be definitive or prescriptive.

27.3 Test Case: Extremely Low Frequency Magnetic Fields

ELF electric and magnetic fields are found wherever electricity is produced, transported, or used. Power lines, electrical wiring, and common appliances (electric blankets, televisions, hair-dryers, computers, etc.) all produce ELF electric and magnetic fields. The widespread use of electricity means that exposure to ELF fields is ubiquitous in modern life and people are constantly exposed in the home, the environment, and the workplace (ARPANSA, 2014).

It is known that acute exposure to ELF EMF causes effects on the function of the central and peripheral nervous systems (WHO 2007, and see Chapter 17). However, these will only occur as a result of intense exposure and are extremely rare. They will not occur in people during their day-to-day living and should not be allowed to occur in the workplace. While such exposure situations are not common, exposure limits need to be applied to minimize direct or indirect acute harmful effects. Guidelines on limits of exposure based on the established health effects related to short, high-level exposure have been developed (ICNIRP, 2010; IEEE, 2002). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends an ELF magnetic field limit of 200 μT for the general public and 1000 μT for trained workers (Chapter 18).

While the adverse effects on health of acute exposure at levels well above current exposure limits to ELF EMF are well established, there is some scientific uncertainty surrounding the potential effects of long-term exposure. There is some epidemiological research indicating an association between prolonged exposure to higher than normal ELF magnetic fields that can occur with close proximity to transmission lines or other electrical supply infrastructure, or by unusual domestic electrical wiring, and an increase in the rate of childhood leukemia. However, the epidemiological evidence is weakened by various methodological problems such as potential selection bias and confounding. Furthermore, this association is not supported by laboratory or animal studies and no credible theoretical mechanism has been proposed (WHO, 2007, Chapters 20 and 21).

The scientific evidence supporting an association between ELF magnetic fields and various other diseases including other cancers, cardiovascular disorders, reproductive and developmental effects, immunological modifications, neurobehavioral effects, and neurodegenerative disease is inconsistent. Although fewer studies have investigated ELF electric fields, there is no substantiated evidence that exposure to electric fields is associated with long-term health effects.

In 2002, the International Agency for Research on Cancer (IARC) classified ELF magnetic fields as "possibly carcinogenic to humans" based primarily on the combined results of epidemiological studies. More recently, the WHO reviewed the evidence for a number of health effects and concluded that new human, animal, and cell studies, published since the IARC review, do not change the overall classification of ELF magnetic fields as a possible human carcinogen (WHO, 2007).

Overall, there is some evidence of an association between prolonged ELF magnetic field exposure and childhood leukemia, but very poor evidence of causality and few clues as to the mechanism or the relevant exposure metric. Given that causality between ELF fields and cancer has not been established, the epidemiological results cannot be used as a basis for the derivation of quantitative risk based limits at the present time. Although the childhood leukemia results do not lend themselves to setting quantitative limits of exposure, a precautionary approach to deal with the possibility of long-term effects may be considered.

27.3.1 Applying Precaution to ELF Magnetic Fields

Although a causal relationship between ELF magnetic fields and childhood leukemia has not been established, estimates of the possible public health impact, if causality is assumed, can be made in order to provide a potentially useful input into the derivation of appropriate precautionary measures. It is important to note that, even assuming causality, there is little information on what the appropriate exposure metric should be as mentioned earlier. There is some evidence pointing to time-weighted average (TWA) exposure as a possible metric and the TWA could be a surrogate for other features of magnetic fields produced by electrical systems, for example, transients. It remains possible that measures to reduce the TWA exposure may not decrease the risk of childhood leukemia and may, in fact, increase other childhood risks (e.g., risks associated with car travel to avoid higher TWA ELF magnetic fields at the closest school).

Precautionary measures include an initial assessment of the exposure together with appropriate mitigation strategies for the sources of exposure within the control of the person undertaking the assessment. For many existing situations, unless an activity or arrangement involving ELF magnetic fields is particularly unusual (e.g., industrial equipment installed within a residence), it is unlikely that even an initial assessment would be warranted. In other cases, a simple screening assessment is expected to be adequate as the potential for low-cost measures to reduce exposures is likely to be very limited. This would apply, for example, to existing facilities or exposure situations where the cost of redesign or reconfigurations would probably be prohibitive. In these circumstances, a simple screening assessment, able to be quickly carried out by personnel without specialist training, may identify exposures that could be reduced at low cost or those that might justify a more comprehensive investigation.

In applying precaution to ELF magnetic fields, care should be taken not to over-state the risk and unnecessarily raise concern. Precautionary measures “should not compromise the essential health, social, and economic benefits of electric power” (WHO, 2007).

27.3.2 Assessment of Potential for Exposure Reduction

Consideration of the “exposure” is not the mere presence of ELF magnetic fields but is the likely presence of people within the fields for periods of time. Factors that may be considered in the assessment of an exposure situation include the magnetic field strength, the number and categories of people exposed, and the length of time spent within the field.

$$\mathit{Exposure} = M \times N \times D \tag{27.1}$$

where

M = magnetic field strength
N = mumber of people exposed
D = duration of exposure

Since the aim is cost-effective reduction of exposure, the assessment should focus on situations where reduction of exposure, that is reduction of field strength, number of people, or duration of exposure, lies within the control of the person or organization for which the assessment is being performed. Exposures that are realistically outside control need not be assessed for precautionary purposes.

Assessment for exposure reduction can best be undertaken when a business, building, or facility is in the planning stage. Mitigation at this point is often more effective and less expensive than after construction.

If it is decided that assessments of exposures of people in existing circumstances are required, they may be undertaken at appropriate locations within the area of responsibility. Elements of such assessments may include the following:

- Determination of whether prima facie evidence exists for the presence of sources likely to produce elevated ELF magnetic fields or the likely presence of vulnerable persons. In the absence of both, no further assessment would be warranted.

  Example: *Small office with three to five employees and no high load electrical installations or special equipment – no further action* (*except for other reasons such as addressing concern*).
- Inspection or consideration of all accessible locations and the noting of all potential sources of elevated ELF magnetic fields.
- Measurement, estimate, or calculation of the ELF magnetic fields, where appropriate. If the source is not used or energized continuously, then details of its durations of use may be noted. Because of the nature of precaution, precise estimates of magnetic fields are not generally necessary.
- Recording the time that persons (including children and adults) spend in different areas of likely elevated exposure and calculating their TWA.

  Example: *If a staff member works a 40-hour week and spends 10 hours in a magnetic field of* $1\,\mu T$, *20 hours in a field of* $0.5\,\mu T$, *and 10 hours in a field of* $0.2\,\mu T$, *then the TWA is* $(10\times 1+20\times 0.5+10\times 0.2)/40 = 0.55\,\mu T$ *for the working week.*

27.3.3 What Factors Influence the Degree of Precautionary Mitigation Measures?

All precautionary measures, *even an exposure assessment*, are likely to incur costs. In the absence of any obvious exposure sources, expectations of strong, hidden sources, or particularly numerous or vulnerable persons, there are few grounds for spending any resources on investigation. However, an assessment may be justified in specific circumstances, particularly if planning a new, or refurbishing an existing, facility. Following a full evaluation of the probability and level of exposure and the number and vulnerability of exposed persons, further investigation of possible mitigation strategies may be undertaken. Any such decision-making exercise may take into account the full range of risks associated with both carrying out and not carrying out the mitigation, including other opportunities, financial risks, and other safety measures that may compete for available funds.

Likely relevant factors include (but are not limited to) the following:

a) Presence of magnetic field sources such as:
  - high-power electrical installations (such as elevators or escalators)
  - known presence of substations or switchboards with high currents
  - transmissions lines
  - certain industrial or domestic situations.

b) Exposed population (number of people exposed might also be a consideration):
   - children, particularly very young children
   - women of child-bearing age, particularly if they are known, or considered likely, to be pregnant
   - young people
   - all other people.

c) Duration of exposure.
d) Presence of other risk factors including high-frequency transients.
e) Existence of other risks concomitant with exposure that mitigation strategies might exacerbate or increase the likelihood of.
f) Potential benefits of the activity or technology that is responsible for the source.

27.3.4 Costs of Mitigation or Reduction of Exposure

Following an assessment of potential exposure, consideration may be given to whether mitigation is desirable and, if so, what form mitigation could take noting among other things the cost of such mitigation. If the mitigation, possibly involving more detailed assessment, is justified, it should be designed so as not to increase other risks for the individual. There is limited guidance on appropriate expenditure on mitigation but some approaches are described by WHO (2007).

There are various models that can be used for applying fair value for mitigation (WHO, 2007). With large uncertainty regarding risks from ELF magnetic fields, precise calculations cannot be expected. The following is an example of how to calculate a reasonable detriment cost that can be applied for precautionary measures (including assessment and mitigation).

$$\text{Detriment cost}, Dc = (R/E) \times V \,(\text{dollars per } \mu\text{T-child-years}) \qquad (27.2)$$

where

R = risk of death from leukemia at childhood (children/10^5)
E = total exposure (μT-years)
V = societal "value of life" (dollars)

The meta-analysis of Ahlbom et al. (2000) of epidemiological studies investigating ELF magnetic fields and childhood leukemia reported a doubling of the incidence of leukemia for those children exposed to TWA fields greater than 0.4 μT (which could range up to 1.0 μT or more in rare occasions). The magnetic field exposures in the community are generally heavily skewed toward the lower range of exposures so, in attempting to estimate the relationship between exposures and risk, it might be assumed that the average TWA exposure of these children could be a number from 0.5 to 1.0 μT. It might also be assumed that these children were exposed from 1 to 10 years. Therefore, it can be assumed that their total exposure (E) ranged from 0.5 to 10 μT-years.

The incidence rate of acute lymphoblastic leukemia in Australia and other developed countries of children aged 0–14 years is about 4.5 per 100,000 (AIHW, 2012; WHO, 2012). While 30 years ago this disease was almost invariably fatal, treatment is now successful in around 80–90% of cases. There are, however, some serious side effects of treatments and increased likelihood of other diseases later in life. For the purposes of this discussion, we will consider the mortality rate to be 20% of the incidence rate.

If the link with magnetic fields is assumed to follow a linear-no-threshold model and associated with a doubling of risk (Ahlbom et al., 2000), then the risk of death (R) of $0.2 \times 2 \times 4.5 \times 10^{-5}$ may be assigned to an exposure (E) ranging from 0.5 to 10 μT-years. Hence, a detriment (R/E) ranging from 0.18 to 3.6×10^{-5} per μT-child-year can be calculated if the dose–response were to be considered to be a linear-no-threshold relationship.

This cost analysis is based on value of potential fatal cases of childhood leukemia that could be avoided if precautionary measures are applied. Numerous studies have attempted to measure the value of a human life; however, a consensus approach for measuring the value of human life does not exist. One approach has estimated the value of a "statistical life" to be around $3.5 million for a healthy prime-age individual in 2008 (Abelson, 2008). It can be estimated that the societal "value of life" (V) could be in the range between 1 and 10 million dollars.

The above estimates may be used in the equation for detriment cost. By rounding the detriment to approximately 10^{-5} per μT-child-year, the amounts from 10 dollars to perhaps a hundred dollars per averted microtesla-child-year may be reasonable if a linear-no-threshold relationship is assumed. In a cost-benefit analysis, these figures may be used to assess the possible risk for a particular exposure situation and compared with community expectations of reasonable expenditure to address such levels of risk.

Other models of the exposure-risk relationship could be used. If there was a threshold in the dose-response relationship then that would result in a higher risk per microtesla-year, a nonlinear response could make costs either greater or smaller. To produce a model with a higher level of detail would require much more careful examination of the exposure situations found in the epidemiology. However, the simple approach described here should be sufficient to provide a rational approach to mitigation. Irrespective of what model of the exposure-risk relationship is used the assumptions made and parameters incorporated should be documented and justified in the assessment.

With regard to adults, there are a considerable number of publications investigating possible links between ELF magnetic field exposure and a number of endpoints including leukemia, brain and central nervous system cancers, breast cancer, amyotrophic lateral sclerosis, and Alzheimer's disease. For each of the endpoints, the associations are generally weak and inconsistent, the studies are not always of a high quality and yet the possibility of an effect cannot be ruled out. While the evidence is much weaker, the overall possible impact of the links with adult diseases is much larger than that of childhood leukemia because of the larger population and greater incidence of the diseases of concern. For this reason, adults may be included with children in applying precautionary measures.

The additional value of avoided morbidity associated with nonfatal incidences of childhood leukemia has not been valued. The reason is the difficulty in assessing this impact, since it depends on the age of the person and the nature and extent of the health symptoms.

27.3.5 What Precautionary Measures Can Be Taken

If it is decided that precaution is to be applied, a range of measures can be taken, including the following:

- removal of the source
- reduction in the strength of the source
- shielding measures for localized sources
- other mitigation methods (reducing the amount of current, cancellation of field: see Chapter 31)
- removal of the exposed population or increased separation from the source
- shortening the duration of exposure
- placement of warning signs, if these are warranted
- education and notification to encourage or allow individuals to avoid exposure through changes in behavior.

27.3.6 Case Studies: Precautionary Assessment and Mitigation

The following case studies describe situations where exposure to ELF magnetic fields is assessed and fair value mitigation is applied; the situations are hypothetical but not unrealistic. In all the examples, the likelihood the link with childhood leukemia is assumed to follow a linear-no-threshold relationship. However, as mentioned earlier, other models could be assigned. The amount willing to be spent on mitigation is based on figures ranging from \$10 to \$100 per μT-child/person-year (from above). The purpose of these case studies is to provide examples of reasonable approaches that could be taken. The values and costs used in the case studies have been conceived and are provided without reference or discussion in the interests of readability and for illustration.

27.3.6.1 Scenario 1

A proposed multistory block of flats was originally designed to have the main supply cable passing directly under the living-room floor of one of the ground floor units.

Exposure: The highest magnetic field within the 0.5 m above floor level in this room, for a 1.5 m wide path is 50 μT (the field will be nonuniform in height and width), as this cable is supplying 25 living units. Assuming that there is an average occupancy of this space by one child for 2 hours per day, there is an expected exposure of about 40 μT-child-years over the next 10 years (i.e., (2 h/24 h) × 50 μT × 10 years).

Mitigation: It could therefore be argued that the cable could be rerouted away from the living areas if this could be accomplished for \$400–\$4000.

27.3.6.2 Scenario 2

A woman has children and is suspicious, without any identifiable reason, that her house has high ELF magnetic fields. She confirms that there are no transmission line towers, nearby high-voltage distribution wiring or heavily loaded distribution wiring close to the house.

Exposure: The a priori probability of her house having significantly higher than normal fields is 5% and the mean field in this case would be about 0.6 μT. She has two children and expects them to live there for the next 10 years. The likely exposure is therefore 2 × 10 × 0.05 × 0.6 × 0.5 (for occupancy of house) = 0.3 μT-child-years.

Mitigation: An explanation of the typical levels of magnetic fields can be provided with a recommendation not to undertake any measurements. Measurements could be undertaken to alleviate concern.

27.3.6.3 Scenario 3

A child's bedroom has 24-hour magnetic fields of 0.8 μT. The child is 1 year old and is expected to live in the room for the next 15 years. Other available rooms in the house have fields of only 0.2 μT.

Exposure: Assuming that the child will occupy the room for 12 hours per day averaged over those 15 years, the expected exposure is 6 μT-child-years.

Mitigation: If the cost to relocate the child to another room is \$60–\$600, then this would seem to be a reasonable action to take.

27.3.6.4 Scenario 4

An inner suburban house is built right to the front property line and there are low-voltage distribution lines only 2 m away in the street. All the bedrooms in the house are at the upstairs front. The house has a frontage of 15 m. Three children aged 1, 3, and 5 live in the house. The magnetic field in the bedrooms averages 1.2 μT, and the field throughout the rest of the house is about 0.4 μT. These fields are likely to be due to the distribution wiring outside and could be substantially reduced by aerial bundling of the wires at a likely cost of approximately \$100 m^{-1}.

Exposure: Assuming that the children are in the bedroom for an average 12 hours per day and in other parts of the house for another 8 hours per day, average, the expected exposure to age 15 is about 27 μT-child-years.

Mitigation: If the wiring in the whole street were to be aerially bundled, this family's share of the cost would be \$1500 (assuming that the other side of the road was not asked to contribute anything) or roughly \$50 μT^{-1} year averted.

Requires contributions from all householders, which is probably unrealistic. In addition, most houses in the street would not have so many children of such young ages or living, perhaps, so close to the street. Other issues such as maintenance of wires and visual impact may need to be considered.

27.3.6.5 Scenario 5

A suburban shopping center has a long walkway to the parking lot. Halfway along is a hidden switchboard with a very localized magnetic field of 12.5 μT. About 2000 people would pass the spot per day, but some people would stop and talk.

Exposure: Over a 5-year period, this could amount to more than 10 μT-person-years (based on an average exposure of 10 seconds). The exposure to any individual would be very small.

Mitigation: The substantial cost of moving the switchboard is probably not justified in the circumstances given. However, a sign on the wall warning of higher than normal magnetic fields and recommending that people not linger at the point would be a cost-effective solution.

The scenarios indicate that in many cases, measures other than engineering solutions are probably the most cost effective for an appropriate precautionary approach.

27.4 Conclusion

Comprehensive guidelines protecting humans from the established harmful effects of EMF exposure have been developed at the international level and adopted in a large number of countries. These guidelines are based on solid science and provide a high level of protection against all the known health effects of EMF exposure.

At levels of EMF exposure below the limits, the risk of any health effect is low, but given some uncertainties that still exist in some areas of scientific knowledge, a precautionary approach may be considered. However, the type and extent of the precautionary approach chosen will depend on the strength of the evidence for a health risk and the scale and nature of the potential consequences. The precautionary response should be proportional to the potential risk. A basic requirement is that precautionary measures should not undermine the credibility of scientific assessments of risk and science-based exposure limits.

Tutorial Problems

1 If a child is at school for 35 hours and spends 25 hours per week in a magnetic field of 0.4 μT in the classroom and 10 hours per week in a field of 0.1 μT in the playground, what is the TWA magnetic field exposure for the week?

2 A child care center has 100 children staying for an average of 40 hours per week. There is 5% chance that the ELF magnetic field exposure at the child care center is 0.5 μT over a 10-year period. What precautionary measures could reasonably be taken?

3 An office worker sits next to a distribution panel where the magnetic field exposure is 1.0 μT. The worker is expected to be employed (and situated in that location) for 30 years. What precautionary measures could reasonably be taken?

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Part VIII

NIR Injury Prevention and Medical Assessment

28

Medical Aspects of Overexposures to Nonionizing Radiation

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By definition, an overexposure to a nonionizing radiation (NIR) is an exposure that exceeds the safety limits as per the relevant standards. The following sets out some principles whereby overexposures to NIR may be managed and supplements this with discussion about specific parts of the NIR spectrum. For the purposes of this chapter, the NIR spectrum comprises ultraviolet (UV) 180–400 nm; lasers; infra-red, 780 nm to 1.0 mm; radiofrequencies (RFs) 300 kHz to 300 GHz; extremely low frequencies (ELF, mainly 50 Hz); and static electric and magnetic fields. This chapter is written with a view to giving advice to a medical practitioner in the case of overexposures.

Patients receiving medical care may be intentionally exposed to intense NIR fields for diagnostic or treatment purposes. Generally, for these exposures, it is considered that the benefits are likely to outweigh the harms and are not deemed as overexposures. However, misadventure may arise leading to medicolegal concerns.

28.1 General Principles of Managing Overexposures

28.1.1 Characterize the Overexposure

Overexposures may occur in a wide variety of settings. These may include the workplace where workers using NIR equipment may be overexposed due to faulty work practices, for example, welders' arc eye, but may include workers who in the course of their work are on the site of an installation and are inadvertently exposed, for example, a lift maintenance mechanic to RF from a nearby antenna on a roof top. Members of the public may also be exposed, for

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example, trespassers onto radio transmission sites (Hocking et al., 1994] or persons in an office situated immediately above a high-current electricity substation.

Figure 28.1 indicates the normal steps in management of a patient who presents with overexposure to NIR. The essential first step for a medical practitioner is to define if an overexposure has actually occurred and if so to what

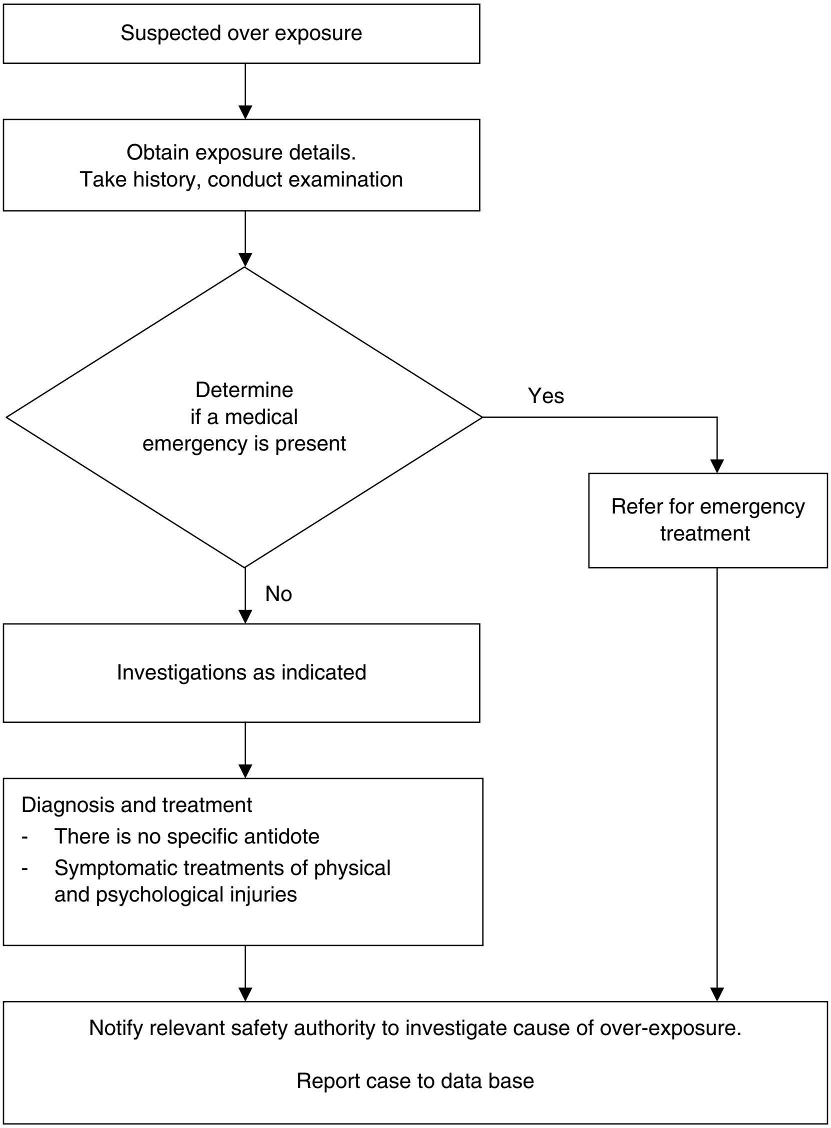

Figure 28.1 Flowchart of Medical Management of NIR Overexposure.

extent. This requires careful history taking from the patient[1] regarding any symptoms, their proximity, and anatomical relationship to the source and the duration of exposure. Photos of the incident site may readily be taken and transmitted on mobile phone to aid assessment of the exposure. Sometimes, details of the source such as wavelength/frequency can be obtained from the patient, but other times, the operator of the source needs to be contacted. Often, detailed measurements of the fields by a competent occupational hygienist will be required, particularly for medicolegal purposes.

The next step is to assess the exposure with regard to the relevant national as well as international standards (these can be downloaded from http://www.icnirp.org/, but see also Chapters 6, 10, 13, 18, and 23 for further details on these). Most standards distinguish between occupational and nonoccupational/public exposures with the standard for the latter being more stringent. Occupational standards should be applied only to workers who are informed and trained regarding their potential NIR exposures and should not be applied to other workers who are inadvertently exposed, and they should be treated as members of the public. Similarly, pregnant RF or ELF workers should be treated as members of the public for protection of the fetus in accordance with the relevant ICNIRP standards (ICNIRP, 1998, 2010). The standards used for common practice are, in the case of RF and ELF, the "reference" levels, but sometimes, the "basic restrictions" will need to be used to determine the true extent of an overexposure (see the chapters identified above). Some ultraviolet standards also distinguish between natural and man-made sources and often only apply to occupational settings.

All NIR standards are set on the basis of established short-term effects as discussed elsewhere in this book. Some NIR standards are set with a safety margin (typically one-fifth or one-tenth of the level at which immediate health effects are likely to occur); therefore, an exposure that only marginally exceeds the standard and is for a short time (minutes or hours) is unlikely to cause health effects. Some NIR exposures are related to cancer (e.g., ultraviolet is a class I (definite) human carcinogen (IARC, 1992; IARC, 2012) and RF and ELF are class 2b (possible) human carcinogens (IARC, 2002, 2013)); therefore, longer term overexposures (months to years) may raise the possibility of carcinogenesis.

28.1.2 Clinical Approach

As with any medical examination, the clinical steps comprise history taking, examination, investigations, and appropriate treatments. History taking begins with characterizing the overexposure as discussed above and is fundamental to considering possible clinical effects. Symptoms immediately arising should be

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[1] A patient is someone who presents to a medical practitioner whether or not there is actual injury.

noted and maybe helpful in diagnosis, for example, the onset of a painful eye a few hours after arc welding, or a sensation of warmth in proximity to an RF transmitter or visual scintilla in an intense ELF field (see Chapters 12 and 17). In addition, a general medical history should be taken including past and family history. A history of medical implants such as orthopedic rods or cardiac pacemakers is important, since exposure to RF or ELF may cause heating in rods or electromagnetic interference in pacemakers or similar devices.

Examination will be directed to the part of the body most exposed. Intense overexposures may be associated with burns. Overexposure to UV is typically associated with erythema of the skin (sunburn). Intense RF overexposure to a limb may cause a compartment syndrome (see the following discussion), and intense ELF may cause cardiac arrhythmias.

Investigations will to some extent be determined by the history and examination. There are no tests to objectively determine the amount of body absorption resulting from an overexposure to NIR. Treatment is symptomatic and appropriate to any pathology detected; there is no “antidote” to NIR overexposure. Patients are often fearful after an overexposure and it is essential to develop confidence and rapport with the patient. This requires the physician to have some knowledge of NIR or to seek expert advice promptly to avoid psychological and sometimes medicolegal complications.

28.1.3 Medicolegal Aspects

Overexposure cases may lead to medicolegal concerns so it is essential to take good notes and seek expert help as required. In addition, cases should be notified to the appropriate occupational or public health authorities so the cause of the overexposure may be investigated and appropriate corrective steps taken.

28.2 Considerations of Components of the NIR Spectrum.

Refer to Table 28.1, which summarizes some of the considerations that are specific to the different forms of NIR.

28.2.1 Ultraviolet, 180–400 nm (UV)

The ultraviolet guidelines (ICNIRP, 2004) distinguish between natural and man-made sources, and this chapter is only concerned with overexposure to man-made sources. The commonest sources associated with overexposures are arc welding (in its many forms), germicidal lights, and solaria.

Arc welding produces UV, visible, and IR radiations with intensity depending on the amperage and the composition of metals and welding rods. Eye protection is dependent on correct use of the welder’s helmet requiring “flicking” the

Table 28.1 Considerations of components of the NIR spectrum.

UV	Laser	RF/MW	ELF
Eyes • keratoconjunctitis (arc eye) • cataract *Skin* • erythema • cancer (SCC, BCC, melanoma) • photodermatitis	*Eyes* • cornea • cataract • retinal burn *Skin* • burns	Warmth (variable) Burns and Compartment syndrome Ocular effects Neurological effects PTSD Reproductive effects – male and female Interaction with metallic implants EMI with medical devices	*Eyes* phosphenes Neurological effects Arrhythmias EMI with medical devices

This table summarizes the clinical effects of overexposure to components of the NIR spectrum.

protective lens into place just prior to striking the arc although this practice is being replaced with instantaneously photoresponsive lenses. “Arc eye” is a type of keratoconjunctivitis that usually has the onset of symptoms, typically a painful eye with photophobia, some hours after ceasing welding. The important differential diagnosis is a foreign body from hammering residual welding slag: the eyes should be examined under magnification (slit lamp if available) to exclude this. Treatment is symptomatic with anesthetic drops. There is little evidence of an increase in skin cancer in welders possibly due to the safety clothing they wear protecting them. There is some evidence of an increased risk of cataract formation (Taylor et al., 1988) and ocular melanoma (Dixon and Dixon, 2004).

Germicidal lights are used as insecticides. They have a substantial UVC component to attract insects onto an electric grill; the UVC can produce marked erythema in humans. Several case reports refer to accidental exposure in diverse settings such as restaurants and pharmacies (Oliver et al., 2005; Zaffina et al., 2012). It is not recorded if there was long-term follow up regarding risk of skin cancer.

Persons who work with certain chemicals that act as photosensitizing agents such as anthraquinone-based dyes and polycyclic hydrocarbons, or who are taking some medications such as chlorpromazine or amiodarone or doxycycline, or who are genetically susceptible, may be prone to develop skin rashes after UV exposure. (For a more complete discussion of photosensitivity, see Morison (2004).)

Solaria or tanning salons have become a cause of concern regarding overexposure to UV and risk of melanoma and skin cancer. Epidemiological studies have shown that exposure to sunbeds increases the risk of both melanoma and nonmelanoma skin cancers: this is covered in Chapter 5.

28.2.2 Lasers

Lasers operate across a wide range of the spectrum including UV, visible, and infra-red wavelengths. The main potential health effects from overexposures are burns to the skin and eye. The risk from an overexposure depends on the class of laser and the wavelength. Lasers that are class 3 and above may have sufficient energy to cause burns to the skin and deeper tissues. Lasers that operate using visible wavelengths (400–700 nm) may enter the eye and cause cataracts and retinal burns. These injuries need to be carefully assessed and managed appropriately, including referral to an ophthalmologist. Laser guidelines are detailed in ICNIRP (2013) and in Chapter 10.

28.2.3 Infra-red, 780 nm to 1.0 mm

The interaction of infra-red (IR) radiation with the body is described in Section 8.4.2 and Chapter 9. This form of radiation is strongly absorbed by the cornea and lens, but does not reach the retina of the eye. Because this radiation is invisible, eye damage could occur without the person being aware of it. Although some types of laser emit radiation in the IR part of the spectrum, the most common source of IR exposure is from furnaces. There is a condition known as "glassblower's cataract", which is thought to be due to long-term eye exposure to IR. Those working in pottery studios or blast furnaces are also at risk of such injury. The use of protective goggles ought to be sufficient to prevent such injury, but occasionally, due to poor compliance, these injuries may ensue. Those presenting with cataract suspected to be linked to IR exposure should be referred to an ophthalmologist familiar with occupational medicine to determine the best form of treatment.

28.2.4 Radiofrequencies (RF) 300 kHz to 300 GHz

Management of overexposure to RF has been discussed in detail elsewhere (Hocking and Gobbo, 2011).

The following health effects may occur:

Sensation of warmth: RF fields act by causing heating. This may cause a sensation of warmth in an affected area, although this is not inevitable with only modest fields and deep penetration.

Shock and burn: RF fields and contact currents may cause painful shock or superficial or deep burns (Hocking et al., 1994). *These should be treated as per other electrical burns (Lee, 1997).*

Compartment syndrome: High doses of RF may penetrate deeply and cause heating of muscle or other tissues without obvious superficial burns. This heating may cause injury and inflammation of muscle tissue and/or thrombosis of blood vessels leading to impaired circulation and ischemia (compartment syndrome). This requires emergency medical attention.

Ocular effects: Radiofrequency may cause keratitis and iritis resulting in pain and a small pupil. Cataracts may be induced in animals exposed to intense RF fields. Cataracts take weeks to months to mature, which gives a window of opportunity to examine the lens immediately after an accident to assess its "preinjury" status and then to examine it again a few months later to observe if injury has occurred.

Nervous system: Effects on the CNS may include headaches and lethargy and cognitive effects such as decreased concentration. These may warrant more detailed assessment by investigations such as MRI or by neuropsychological testing. There is debate in the literature regarding other effects of RF fields on the CNS. Reeves reviewed the case reports of 34 cases of overexposure in the US air force (Reeves, 2000). He found that neuropsychological symptoms were common, and assigned 66% of these cases to "pre-existing psychiatric morbidity". This prevalence of psychological morbidity is improbable for a random event given that the community prevalence is only 15% and the military excludes recruits with psychological conditions. The case reports apparently did not recognize PTSD nor were nerve conduction tests or full neuropsychological assessments conducted on all cases. Comprehensive assessment of these symptoms is warranted before assigning them to "pre-existing morbidity".

Effects on the peripheral nervous system include dysesthesia (pins and needles). Marchiori et al. (1995) reported a case in which a cook put her hand in a microwave oven with a faulty switch and suffered prolonged dysesthesia of the hand and face. The autonomic nervous system may be affected; Foreman reported raised blood pressure in their patients 5 months after an overexposure (Forman et al., 1982). Psychological effects such as PTSD may also occur and be difficult to distinguish from direct effects on the CNS as discussed above.

Reproductive effects: Both male and female reproduction may be affected by overexposure to RF fields. Heating of the testis in animals reduces the sperm count that usually returns to normal after heating ceases; however, the long-term effects on fertility are not known. Male workers (and their partners) may be intensely concerned regarding effects of an overexposure on virility, sterility, and the possibility of malformed babies. This needs to be sympathetically discussed and sperm tests offered as appropriate. The fetus in the pregnant female may be exposed to frequencies (such as in the megahertz range), which can penetrate deeply into the pelvis early in the pregnancy, or to shorter wavelengths (e.g., gigahertz), which may penetrate the thinly stretched uterus later in the pregnancy. Overexposure early in pregnancy may be associated with miscarriage (abortion). The effects of overexposure later in pregnancy are not known. Because of the association of RF and ELF

EMF with cancer (IARC, 2002; IARC, 2013) overexposure is likely to be of intense concern to the mother.

Metallic implants (Hocking and Mild, 2008): Medical implants such as orthopedic rods may act as an antenna to concentrate an RF field. Some costume jewelry may act similarly. The associated heating may result in injury to local tissue and low frequencies (<100 kHz) may stimulate nerve or muscle. Dental fillings are not of concern as the teeth are heat resistant.

Electromagnetic interference: RF overexposure may cause interference with medical devices that are often designed to be immune (protected) from normal exposures (Hocking and Mild, 2008).

28.2.5 Extremely Low Frequencies (ELF, 50 Hz)

Management of overexposure to ELF has been discussed in detail elsewhere (Hocking and Gobbo, 2011).

The clinical effects are similar to an electric shock because the fields induce voltage and currents in the body and hence injury can occur in the same way if this is excessive (Lee, 1997).

Low-frequency (20 Hz) electric and magnetic fields are able to interact with synapses in the retina to cause a flickering light sensation called electrophosphenes or magnetophophenes, respectively. The threshold for this effect is between 10 and 100 mV/m in certain tissues. It is thought that synapses in the brain may be similarly sensitive. Other health effects may arise from stimulatory effects on peripheral and central neurons and neural networks. Myelinated nerves are thicker and more sensitive to EMF than unmyelinated nerves (which are mainly found in the gray matter of the central nervous system (CNS)). It has been suggested on general principles that persons with epilepsy may be more sensitive to 50/60 Hz EMF than others.

Cardiac tissue is excitable at relatively high exposure levels (12.0 V/m peak in tissue) as discussed above. Cardiac tissue may be stimulated, usually through contact with an electrical conductor, to cause arrhythmias, which may be life threatening. This requires emergency medical treatment.

Burns may occur with very high levels of exposure to fields or from contact currents (Lee, 1997). They may be superficial or deep.

Indirect psychological effects such as posttraumatic stress disorder (PTSD) may also occur and be difficult to distinguish from direct effects on the CNS.

Electromagnetic interference of medical devices. 50/60 Hz EMF overexposure may cause interference with medical devices that are often designed to be immune (protected) from normal EMF exposures. These devices may include cardiac pacemakers, insulin pumps, and hearing devices.

28.2.6 Static Fields

For static electric fields, the possible hazards are as above.

Chapter 22 reviews physiological changes associated with strong static magnetic fields, including ECG changes, sensations of vertigo, and nausea. High-field and interventional MRI medical procedures are becoming increasingly common and these can expose medical staff to static fields similar to those experienced by the patient (ICNIRP, 2009): guidelines now advise such staff how to avoid these symptoms (ICNIRP, 2014), but it is important that non-medical staff (carers, accompanying family members) who may be in the vicinity of the magnet are acquainted with this advice.

The possibility of injury or even death due to the movement of unrestrained metallic objects in magnetic resonance imaging suites has been known about for some time (Landrigan, 2001), but accidents can still occur due to "hidden" metallic components (Ulaner and Colletti, 2006). Procedures are in place to minimize the chances of such injuries occurring, but the presence of unsuspected metallic objects within the body is always a possibility (Metterlein et al., 2014).

For static magnetic fields, the development of intensely strong (and small) rare-earth magnets has increased the possibility of pinch injuries, especially if the magnet is allowed to accelerate toward a metal surface or to another magnet of opposite polarity. Ingestion of multiple magnets may cause serious gastrointestinal morbidity, such as pressure necrosis, perforation, fistula formation, or intestinal obstruction due to forceful attraction across the bowel wall. In one series, 72 cases of children swallowing rare-earth magnets were documented and 70% required surgery (De Roo et al., 2013).

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29

Preventive Surveillance Programs

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29.1 Introduction

This chapter deals with programs that are in place to influence behavior: to alert people to actual dangers of NIR and appropriate measures that can be taken to reduce the chance of injury or illness. These programs can in the form of formal or informal training, both for occupational groups and the general public. The chapter is in three parts: ultraviolet radiation (UV), laser safety, and RF.

29.2 UV Protection – Influencing Sun Protection Behaviors across the Populations (Sue Heward)

29.2.1 Introduction to UV Protection

Skin cancer is a significant disease in Australia, the United States, New Zealand, and parts of Europe where outside ambient levels of UV are high; there is a significant number of the population using sunbeds and/or there is a large percentage of the population with sun-sensitive skin (Erdmann et al., 2013; IARC, 2013; Severi and English, 2004). Globally, in the year 2000, overexposure to UV radiation was estimated to have caused the loss of approximately 1.5 million disability adjusted life years (DALYs) and 60,000 premature deaths (Lucas et al., 2006; Sienkiewicz, Haylock, and Saunders, 1994). According to estimates for 2012, there were over 230,000 new cases of invasive melanoma globally and an estimated 55,500 deaths from the disease (IARC, 2013).

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Australia and New Zealand are often labeled as the skin cancer capitals of the world. Two in three Australians will be diagnosed with skin cancer before the age of 70 (Staples et al., 2006) with more than 2000 people dying annually. More than 3.2% of Australians are treated for skin cancer each year (Fransen et al., 2012) – over 2000 people each day. Treatment of non melanoma skin cancer (NMSC) in this country was estimated to increase to $703.0 million in 2015 (Fransen et al., 2012).

UV is both the major cause of skin cancer and the best natural source of vitamin D. UV cannot be seen or felt. It is not like the sun's light (visible spectrum) that people see or the sun's warmth (infrared radiation) that can be felt. The human senses cannot detect UV so it can be damaging to the skin and eyes without an individual knowing.

29.2.2 Health Effects of UV Radiation

29.2.2.1 Too Much UV and Overexposure

Overexposure to UV radiation can cause skin and eye damage, premature aging, photosensitivity, sunburn, tanning, and ultimately can result in skin cancer (Armstrong, 2004; Armstrong and Kricker, 1993; Leyden, 2001; US Department of Health and Human Services Public Health Service National Toxicology Program, 2005; Uitto, 1997).

Each time skin is exposed to UV, changes take place in the structure and function of our skin cells. Over time, the skin can become permanently damaged and the damage increases with each exposure. Every additional decade of overexposure to UV further increases a person's risk of skin cancer. Increased use of sun protection against sun exposure will help prevent skin cancer at any age. By reducing recreational sun exposure at any age, the risk of melanoma will also be reduced (Kricker et al., 2007; Veierod et al., 2010).

All skin types can be damaged by overexposure to UV radiation. People with skin types that are less likely to burn can still receive enough UV exposure to risk developing skin cancer (Gloster and Neal, 2006) (Figure 29.1).

Overexposure to UV is the main cause of skin cancer, with 99% of NMSCs and 95% of melanoma in Australia being identified as being caused by sun exposure (Armstrong, 2004; Armstrong and Kricker, 1993). There are three main types of skin cancer. Skin cancer types are named after the skin cell in which the cancer develops: basal cell carcinoma, squamous cell carcinoma, and melanoma. The most serious is melanoma. Basal cell and squamous cell carcinomas are often grouped together and called "common" or "non melanoma" skin cancers (NMSCs). Exposure to UV radiation over long periods can also lead to more serious damage to the eyes (Coroneo, 1993; Moran and Hollows, 1984; Roberts and Coroneo, 1999; Taylor, 1981, 1989; Vajdic et al., 2003; West et al., 1998) such as cataracts, cancer of the conjunctiva,

Skin type chart	1	2	3	4	5	6
Natural skin color	Very fair, pale white, often freckled	Fair, white skin	Light brown	Moderate brown	Dark brown	Deeply pigmented, dark brown to black
UV sensitivity	Highly sensitive	Very sensitive	Sensitive	Less sensitive	Minimal sensitivity	Minimal sensitivity
Tendency to burn	Always burns, never tans	Burns easily, tans minimally	Burns moderately, usually tans	Burns minimally, tans well	Rarely burns	Never burns
Skin cancer risk	Greatest risk of skin cancer	High risk of skin cancer	High risk of skin cancer	At risk of skin cancer	Skin cancers relatively rare, but those that occur are often detected at later, more dangerous stage. Increased risk of low vitamin D levels.	Skin cancers relatively rare, but those that occur are often detected at later, more dangerous stage. Increased risk of low vitamin D levels.

Figure 29.1 Skin type chart adapted by SunSmart Victoria from Fitzpatrick (1975). Images courtesy of Cancer Research, UK.

pterygium,[1] solar keratopathy,[2] and skin cancer of the eyelids, and around the eyes.

29.2.2.2 Too Little UV and Vitamin D

Vitamin D is a hormone that controls calcium levels in the blood. It is needed to develop and maintain healthy bones, muscles, and teeth and is also important for general health (Calvo, Whiting, and Barton, 2004; Papadimitropoulos et al., 2002).

Vitamin D is made through a series of biochemical processes starting when the skin is exposed to the sun's UV rays. Vitamin D also naturally occurs in fatty fish, fish liver oil, and eggs. When vitamin D was recognized as important for the prevention of rickets in the 1920s, vitamin D fortification in the United States and Canada was initiated including fluid milk and margarine (IOM (Institute of Medicine), 2011; Sienkiewicz, Haylock, and Saunders, 1994). In 2008, it was reported that almost all milk (fluids), approximately 75% of ready-to-eat breakfast cereals, slightly more than 50% of all milk substitutes, 25% of yogurts, and between 8% and 14% of cheeses, juices, and spreads were fortified with vitamin D in the US market (Yetley, 2008).

In countries where fortification is not in place food is estimated to only make a small contribution (5–10%) to the body's overall vitamin D levels (Nowson et al., 2012). In instances like this, such as in Australia, government

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[1] A fleshy overgrowth of the conjunctiva that may affect one or both eyes.

[2] Cloudiness of the cornea.

guidelines recommend that it is difficult to get enough vitamin D from diet alone (Department of Health, 2011).

The body can only absorb a certain amount of vitamin D at a time. Prolonged sun exposure does not result in vitamin D levels increasing further but does increase a person's risk of skin cancer. Short periods of sun exposure may be more efficient at producing vitamin D (Norman, 1998). Daily exercise will also assist the body to produce vitamin D (Scragg and Camargo, 2008).

Low vitamin D may have no obvious symptoms, but without treatment, it can have significant health effects including bone and muscle pain, and poor bone mineralization (softer bones), leading to rickets (bone deformity) in children and osteomalacia (bone softening) in adults. There have also been links with an increased risk of bowel cancer, heart disease, infections, and autoimmune diseases, although more research is needed to determine whether increasing vitamin D levels can prevent these conditions (Department of Health, 2011). Recent research has suggested that the paucity of intervention studies showing improved outcome with increased vitamin D levels indicates that low vitamin D may be a by-product rather than cause of associated conditions (Autier et al., 2013).

29.2.3 Managing Personal UV Exposure

Sun protection messages directed at individuals vary across the world but basically the aim is to reduce a person's exposure to UV radiation. Typically, people use heat to determine when they think that sun protection is required. This is particularly dangerous when it is cool or cloudy but the UV remains high enough to cause damage to a person's skin and eyes (International Agency for Research on Cancer, 2012; Liley and McKenzie, 2006).

Across Australia, messaging and public education campaigns occur annually raising public awareness to the use of the World Health Organization's Global Solar UV index (UVI) and sun protection times. The UVI was developed through an international collaboration by the World Health Organization (WHO), the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS). The UVI is a measure of the UV radiation level at the Earth's surface and an indicator of the potential for skin damage. The INTERSUN program promotes the harmonized use of the UVI and advises governments to employ this educational tool in their health promotion programs; its aim being to serve as a vehicle to raise public awareness and to alert people about the need to adopt protective measures when exposed to UV radiation (World Health Organization, 2002). The UVI is measured via 30 UVI sites worldwide.

In Australia (at more than 300 locations nationally), a daily UV Alert is issued by the National Bureau of Meteorology when the UVI forecast is 3 or above, a level that can damage human skin and lead to skin cancer (World Health Organization, 2002). The UV Alert, an initiative of Cancer Council Australia and its state members, the Bureau of Meteorology, and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), indicates the maximum predicted UV for that day and the time of the day people need sun protection.

Increased sun protection against UV over exposure will help prevent skin cancer at whatever age of the person that it is applied to (Armstrong, 2004). WHO recommends people implement different (graduated) skin cancer prevention actions depending on the level of the UVI. Recognizing behavior change for better health outcomes is complex; this messaging has been simplified in Australia to one set of recommended actions. During the daily sun protection times (released by BOM) when the UVI is at 3 or above, public messaging recommends using a combination of all five sun protection measures including the following:

1) Slip on some sun-protective clothing that covers as much skin as possible.
2) Slop on SPF30 sunscreen or higher – make sure that it is broad spectrum and water resistant. Application is recommended 20 minutes before going outdoors and reapplication should be every 2 hours (Green et al., 1999, 2011; van der Pols et al., 2006).
3) Slap on a hat: Broad brimmed and bucket hats provide the best sun protection for the face, head, ears, and neck. Legionnaire hats also provide good UV protection. Baseball caps do not protect the face, head, ears, and neck. A good sun-protective hat will also provide protection to the eyes (Gies et al., 2006; Rosenthal et al., 1991).
4) Seek shade. Staying under shade, such as a tree or umbrella, can reduce a person's overall exposure to UV by up to 75%. The most effective shade can reduce exposure by over 90% – but this only occurs when exposure to the sky is eliminated, such as in dense forest or low wide overhanging structures. As a rule of thumb, if the sky can be seen by a person from where they are positioned then there is not full protection (Parsons et al., 1998).
5) Slide on sunglasses. UV radiation exposure to the eyes can differ dramatically from the pattern of ambient UV radiation, depending on factors such as the angle of sunlight reaching the eyes and facial geometry (Sasaki et al., 2011). Given the sensitivity of the eyes to UV exposure, it is recommended that the eyes be protected from UV at all times when outdoors during daylight hours (Cancer Council Australia, 2013).

WHO messaging regarding avoiding time outside when the UV level is 8 and above is generally not used in campaigns across Australia (except in cases where there might also be extreme heat days) because it is simply not practical. For example, there are some parts of Australia where this would mean that people are not recommended to go outside at all through the daytime hours across the whole year. Also, it does not encourage physical activity that obviously has considerable health benefits.

Trying to balance communication between the risks and benefits of UV radiation remains difficult, particularly given a range of ongoing controversies, uncertainties, and large interpersonal variations in how much vitamin D will be made for a given dose of UVB (Department of Health, 2011; Diffey, 2006; Gilchrest, 2007). Some of the contributing factors are skin type (Clemens et al., 1982), age (about 50% less vitamin D will be made by an 80-year-old compared with a 20-year-old) (MacLaughlin and Holick, 1985), obesity (as vitamin D is stored in fat tissue) (Blum et al., 2008), and baseline vitamin D status (in response to a given dose of UVB, vitamin D levels increase more when the baseline levels are low than when baseline levels are higher) (Bogh et al., 2010).

Messaging and education programs do vary depending on location (latitude), time of year, and local factors and are updated as best as possible in line with emerging evidence. For example, in summer in the southern parts of Australia, and all year round in the north, only a few minutes of mid-morning or mid-afternoon sun exposure is suggested to help with vitamin D. In northern parts of Australia, it is recommended that most people can maintain vitamin D levels year round just by going about their day-to-day activities, so it is not necessary to deliberately seek UV radiation exposure. However, during winter months in the southern parts of Australia, the emphasis is focused on sun protection not being required (when the UV levels are below 3) unless people are near highly reflective surfaces such as snow or water or outside for extended periods (most of the day).

29.2.4 Multicomponent Programs Promoting UV Protection across Populations

In 2012, the US Community Preventive Services Task Force[3] recommended multicomponent community-wide interventions to prevent skin cancer by increasing UV-protective behaviors, based on sufficient evidence of effectiveness in increasing sunscreen use. These programs aimed at preventing skin cancer included combinations of individual-directed strategies, mass media campaigns, and environmental and policy changes across multiple settings within a defined geographic area (city, state, province, or country) in an integrated effort to influence UV-protective behaviors (Guide to Community Preventive Services, 2012).

Multicomponent skin cancer prevention programs are being implemented across the world including in Australia, Canada, Denmark, France, Germany, New Zealand, Spain, Sweden, United Kingdom, and the United States. They variously include a wide range of partners, mix of funding, program objectives, and demographic coverage.

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[3] This body is an independent panel of public health and prevention experts that provides evidence-based findings and recommendations prevention. The Taskforce is appointed by the Director of the Centers for Disease Control and Prevention (CDC).

29.2.4.1 Case Study: The Skin Cancer Prevention Story from Australia

Skin cancer prevention programs are probably most recognized from Australia. Prevention activities first commenced in the Australian states of Victoria and Queensland in the late 1970s. In 1980, the iconic Slip! Slop! Slap! campaign was first launched as a limited public education program funded by public donations in Victoria. In 1988, with the support of the Victorian Health Promotion Foundation, a new broad based, skin cancer control program, the SunSmart program, was first introduced.

Today, SunSmart is a multifaceted program recognized for providing leadership and innovation in UV protection. Internationally, Cancer Council Victoria (CCV) was designated a WHO Collaborative Centre for Ultraviolet Radiation in 2004 and redesignated in 2008 and 2012. The program aims to influence individual sun protection behaviors; those with responsibilities for protecting others; and broader environmental change. It also takes a balanced approach to UV exposure and implements strategies to improve the community awareness of vitamin D issues and the link with UV. Sister programs also operate in each state and territory of Australia by respective Cancer Councils, all using common principals but tailored implementation depending on jurisdictional priorities and capacity.

Similarly across the world, the SunSmart name and elements of the program have been implemented in other countries including Canada, New Zealand, the United Kingdom, and the United States. The introduction and popularization of the campaign tagline still retains very high recognition in the Australian population. Versions and variations of the Slip, Slop, and Slap slogans are now also used internationally, for example, in the United States (Slip, Slop, Slap, and Wrap campaign conducted by the America Cancer Society) and New Zealand (Slip, Slop, Slap, and Wrap campaign conducted by the Health Promotion Agency of New Zealand).

Major cultural change has been attributed to more than a generation of SunSmart activities, which has occurred in relation to melanoma prevention in Australia (Australian National Preventive Health Agency (ANPHA), 2013).

Skin cancer prevention is quite unique when compared to other prevention issues; there is a clear mix of interventions that continue to be effective in achieving sustained behavior change. Again, specific examples from Australia show clear illustration of this including the following:

- *Mass media advertising and public relation activities*: Television advertising campaigns are one of the key interventions to effect broader cultural and behavioral change. Research shows that sun protection attitudes and behaviors directly correlate with skin cancer prevention television advertising (Dobbinson et al., 2008, 2014].
- *Key-settings-based health promotion action*: Examples of this include workplace education, information provision, and policy development; early childcare and schools programs; and support for local government and sporting

clubs, particularly in relation to shade planning and policy development. The SunSmart primary school program has a participation rate of 90% – one of the highest of any public health program in Australia, reaching approximately 430,000 children in one state alone (Sharplin, Smith, and Roth, 2012).

- *Advocacy strategies that go beyond the individual and community setting to effect change in environments and infrastructure*: A recent advocacy example in Australia is the role the program has played over many years to restrict the use and availability of sunbeds. The International Agency for Research on Cancer (IARC) includes ultraviolet emitting tanning beds in its highest cancer risk category and labels them as "carcinogenic to humans" [El Ghissassi et al., 2009). The introduction of sunbed legislation in Victoria in 2008 then saw the snowballing of legislative change across Australia. From January 2015, commercial solarium operations are now banned in most states of Australia.
- *Ongoing program funding with dedicated resources to evaluation and research* to guide the program and measure effectiveness. While programs across Australian can show clear cases of population change (Volkov et al., 2013), this is not always the case world wide. From 1992 to 2010, the US National Cancer Institute reported that there was a nonsignificant increase in the percentage of adults reporting use of one or more sun-protective behaviors. Buller et al. (2012) also reported that "Between 2004 and 2008, there is little improvement in sun safety behavior over time. National skin cancer prevention efforts have not failed, there just have not been enough".

Investment is prevention programs like SunSmart result in considerable human and economic benefits. The program has been assessed to be extremely cost effective with a $2.30 net saving for every dollar spent in the Australian health system (Shih et al., 2009). An intensive SunSmart campaign was identified as one of a handful of cost-effective interventions for the future that would have a large impact on Australia's health (Vos et al., 2010). The program was estimated to generate a net saving to government of $180 million, in reduced costs for treatment and management cost in skin cancer (Shih et al., 2009). Ensuring that skin cancer prevention programs are funded adequately and for long enough to see measurable behavior change and ultimately a reduction in skin cancer remains an ongoing issue even in a "sunburnt" country like Australia.

29.3 Preventative Surveillance Programs – Laser Safety (David Urban)

29.3.1 Risk Assessments

Hazards arising from the use of lasers present inherent risks to the safety of operators and bystanders. These risks need to be assessed so that they are well characterized and understood. The process of risk assessments is the first step in developing a preventative surveillance program to assist in maintaining a safe working environment where lasers are used.

The objective is to minimize the potential for harm should any changes in operations or unexpected events occur. Changes in operations could involve the introduction of new equipment, modification to existing equipment or changes to the working environment. Unexpected events may include operator error resulting in an accident, instrument or equipment failure, or drifts in optimal operations.

Periodic and reactive (in the case of injury or near misses) reviews of the risk assessment form the basis for long-term surveillance and continued safety improvement. This may then assist in preventing the possibility of injury from operating lasers.

In the operation of lasers, the most obvious hazard is from the laser radiation itself. However, there are additional hazards that can be associated with a laser including the following: electricity, fire, thermal damage, fumes, cryogenic or high-pressure gasses, exposure to toxic chemicals, and even the generation of collateral radiation such as X-rays, ultraviolet, infrared, and radiofrequency (RF) radiations from interactions with target materials.

The risk assessment in the context of laser operations can be handled conventionally, where risk is a combination of the likelihood of harm occurring weighed against the severity of an injury resulting from the potential hazard. An important factor to take into account is that it is not always necessary or possible to remove that risk. The requirement in risk management is to reduce the risk as far as reasonably practicable.

The best way to prevent introducing uncharacterized risks into an existing situation is to assess the risk associated with the particular laser of interest before purchase if practicable to do so. This aids in making the prospective operator aware of the safety implications of the equipment's use and may assist in planning safe work practices and safety design.

Useful resources include Sliney and Wolbarsht (1980), IEC (2004, 2014).

29.3.2 Equipment and Working Environment

As a first step, a risk assessment of the hazards from laser devices requires knowledge of the emissions and power levels to assess the potential risks. This information may be obtained from the manufacturer and should also appear as a label as shown in Figure 29.2 on the laser itself. In cases where this information is not given then the output of the laser needs to be quantified for properties such as maximum power, energy, pulse duration, and wavelength(s), depending on the type of laser in question.

Classifying the laser according to the classification system given in Chapter 8 will assist in making an informed decision about what safety measures might

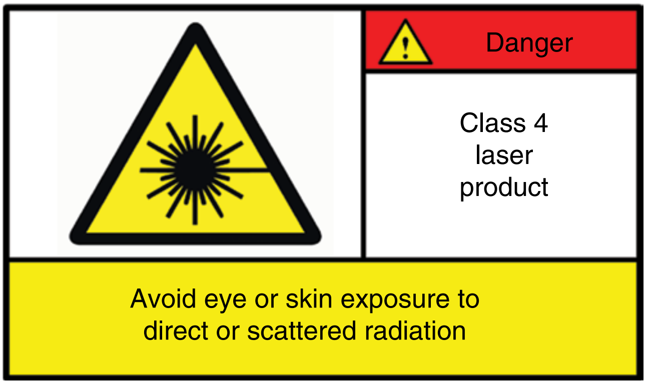

Figure 29.2 Examples of classification and safety signage that may be found on a laser product.

be put into practice during operation of lasers products. The parameters that need to be monitored as part of the preventative measures against injury can also be determined. A robust surveillance program can also promote continuous improvement of safety systems and practices based on lessons learned during operations.

Combining these concepts facilitates the basis for a preventative surveillance program focused around the lasers in use and the operational environment. For example, if a Class 4 laser were in operation in a laboratory environment, the hazards associated with the equipment are given as part of the classification description. In this case, injuries to the eyes and skin will result from direct exposure to the emission. In addition, there is a potential for injuries to the eye from specular and diffuse reflections of the laser radiation. Part of a surveillance program might involve the following:

- periodic or routine adjustments of laser optics (i.e., mirrors, filters, and lenses) and optical table alignment to assure that the emission is behaving in a predictable manner;
- measurement of reflections/stray light in areas of occupancy;
- examinations and testing of engineered safety features such as interlocks, shields, shutters, and emergency stop buttons to assure that they perform their function as intended; and
- monitoring of secondary effects such as fume or collateral radiation generation.

Records of maintenance and optimization applied to laser equipment and the operational environment should be maintained as part of an ongoing monitoring program. This process helps to ensure the currency of safety systems and identify any deficiencies that may be revealed over time.

29.3.3 Medical Examinations as a Component of Surveillance

29.3.3.1 Routine Examinations

Routine ophthalmic examinations of laser operators have no value in a preventative surveillance program. In some cases, ophthalmic examinations may be carried out for medicolegal reasons. This is primarily done to protect an employer from false claims of workplace injuries or to assist an employee with appropriate compensation claims in the case of laser-related injuries.

A base line examination of ocular health is sometimes conducted. These examinations are of no value to a laser operator who receives an eye injury from laser radiation but may assist in determining if pre-existing ocular degeneration or damage was present prior to exposure to the laser hazard. It should be noted that some of the procedures used in ophthalmic examinations present their own set of hazards. Therefore, it is advisable to only carry these examinations when medically recommended.

For the reasons discussed, routine ophthalmic examinations are not recommended as an integral part of a preventative surveillance program.

29.3.3.2 Reactive Examinations

Where there is a suspected or confirmed case of exposure to laser radiation the person(s) should be assessed by a medical specialist as soon as possible after the incident. In the event that medical assessment of the eye is required, then referral to an ophthalmologist is recommended. It is also important for post exposure management of an injury that the exposed person is fully advised and understands the nature of the exposure.

29.3.4 Accident and Incident Reporting

One of the cornerstones of preventative surveillance programs designed to monitor safety is accident and incident reporting. Events with implications on safety should be recorded in an appropriate workplace incident register maintained by the organization. The information in this type of register may even be reported to a relevant safety regulator for the purpose of assessing regulatory compliance or investigating noncompliance. The observations can be used to understand inherent risks and generate trends to assist in investigation and performance improvements. In the instance of an exposure to laser radiation, the incident must be investigated. The investigation should determine the level and extent of exposure to the laser radiation and the potential for a systematic problem or recurrence of the event. Appropriate corrective action or changes to procedures and/or equipment need to be implemented as soon as is reasonably practicable to prevent future exposures while working in similar situations. The exposure may need to be reported to a relevant authority.

29.4 RF Training Programs (Ray McKenzie)

29.4.1 Background

Radio communications for broadcast, telecommunications, point to point, and other myriad purposes relies on a network of radio transmitting infrastructure. This infrastructure may exist as stand-alone structures or, as is more commonly the case within the telecommunications industry, is attached to existing infrastructure, in particular buildings and rooftops, in commercial, industrial, and residential centers.

Radio communications technology produces RF electromagnetic fields to which users, technical operator and maintenance personnel, and the general public are exposed. To provide protection from excessive exposure to such fields, health agencies, governments and safe work authorities in many countries have established safety standards designed to limit exposure levels beyond established safe levels.

Many safety standards around the world are based on the International Commission on Non-Ionizing Radiation (ICNIRP) Guidelines (ICNIRP, 1998), which distinguish between "general public" and "occupational" exposure. This architecture of general public and (higher) occupational limits is a feature of many nationally developed safety standards around the world, including, for example, the US-based IEEE C95.1 2005 (IEEE, 2005), which is not based on ICNIRP, but is similar in many respects.

29.4.2 Training for RF Workers

The construction, operation, and maintenance of radio communications infrastructure require that personnel undertake duties within the immediate vicinity of the RF fields produced by this infrastructure. In some cases, duties necessitate exposure to RF fields in excess of the limits for general public or "uncontrolled exposure" to fields such as specified in the relevant RF safety standard in operation in any given jurisdiction. (Note: The term "uncontrolled" is used in some standards such as IEEE C95.1 to reflect that no particular restrictions, controls, or monitoring are required for individuals to be permitted access to that environment and is analogous to "general public" in ICNIRP-derived standards.)

To ensure the safety of personnel undertaking duties that entail exposure to such fields, safety standards and regulators impose conditions on the operation of such facilities to ensure personnel are either restricted from accessing areas where general public safety limits are exceeded (therefore "controlled" environments) or that recommend training and information be provided to individuals that may be described as "RF workers" or "occupationally exposed" personnel.

In establishing the limits for occupational exposure, which exceed those for the general public by a factor of up to five times in terms of power density of the ambient field, ICNIRP makes the assumption that:

> The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions.

Some safety standards, such those in effect in Australia and New Zealand (ARPANSA, 2002; Standards New Zealand, 1999), specifically limit occupational or controlled exposure to an "RF worker". One of the requirements of meeting the definition of an RF worker incorporates the training mentioned above (i.e., access to areas above general public limits is only permitted for those who have undertaken appropriate training). Other safety standards, such as IEEE C95.1, define the controlled environment itself as one where an RF Safety Program is in place (and therefore permits higher tier exposure limits), which may (but also may not) include RF awareness training, an implicitly similar, although less stringent, requirement. A *de minimus* requirement would be that the worker be sufficiently trained to comply with the controls that define the controlled environment.

29.4.3 Training for Non-RF Workers

More generally, while purpose-built infrastructure such as radio broadcast masts and antenna farms has a clear and obvious purpose, **in the case** where buildings and other utilities such as power poles are used as support infrastructure, the presence of radio transmitting equipment may not be obvious to the casual observer. In the former case, personnel accessing the infrastructure are likely to have an explicit interest and knowledge of the radio transmitting equipment *in situ*, fitting the RF worker category as interpreted above. However, in the latter case, access to the building rooftop or utility structure may be for an entirely different purpose; personnel may have no explicit awareness or knowledge of the radio transmitting equipment and therefore may not be aware of safety precautions required when operating within the vicinity of live transmitting equipment. Personnel accessing a building rooftop to undertake painting, window cleaning, air conditioning, or lift maintenance, for example, may need to access areas close to RF transmitting equipment but would not be expected to have any technical knowledge of it or the safe work practices related to it.

For this class of exposed individual, essentially a member of the general public, ICNIRP and derived standards assume:

> … the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their

> exposure to EMF. Moreover, individual members of the public cannot reasonably be expected to take precautions to minimize or avoid exposure.

In this case, where personnel not engaged directly in RF duties are nevertheless exposed to fields produced by radio communications infrastructure, the requirements of various work place safety regulating bodies may overlap or be unclear.

In many EU jurisdictions and also other countries such as in Canada, for example, work safety authorities regard any exposure to a potentially harmful agent or situation, including RF fields, which may occur during the undertaking of a worker's normal duties to be an occupational exposure regardless of what the duties actually are. For access near radio communications facilities on rooftops therefore, the limit applied would still be the occupational limits, but the worker would require training to manage risks outside of their own area of expertise. This differs from the case as mentioned in Australia and New Zealand where such a general worker would be *restricted* to areas of lower exposure where the general public limits are met (i.e., they are not regarded as an "RF worker" and the permitted exposure is not regarded as occupational).

Whether the worker requires training to manage their safe access to RF fields in compliance with either the occupational (controlled) limits or the general public (uncontrolled) limits, the provision of RF safety training to provide RF *awareness* would still be prudent if not mandatory.

Consequently, RF safety training programs must serve dual purposes of informing competent technical personnel and also the lay public, placing unique demands on the scope, style, and delivery of content.

29.4.4 General Requirements for RF Safety Training

Where RF training is an explicit requirement for accessing occupational or controlled environments, standards may make further statements about such training. For example, in ARPANSA (2002), Section 5.1.4 *Training and Supervision* notes:

> RF workers must be trained in safe work practices, and supervised when appropriate. They must also be trained about the controls in place to manage the potential RF hazard. There must be appropriate procedures in place to ensure that the safe systems of work are utilised.

In Section 5.3 of ARPANSA (2002) *Provision of Information to Employees*, there is also a requirement for the provision of certain information to employees:

> Employees must be advised about the following:
>
> a) The precautions and procedures to be followed if they become pregnant or have/receive metallic implants or medical devices during the time they are engaged in RF work.

b) The known biological effects of RF fields as summarized by WHO (1993), preferably with a written explanation (see (d)).
c) The procedures to be followed in the event of any overexposure, including a contact point (medical specialist knowledgeable in medical effects of RF field exposures).
d) That if they become sick, they should approach their own general practitioner (as for any illness or medical condition) and inform their doctor that they work with RF fields and give the doctor the information about RF fields referred to (b).

While most RF safety standards do not make such explicit statements about the requirements of RF safety training, ARPANSA (2002) undoubtedly offers a sound model for any RF safety training program in any jurisdiction. Much of this model is also applicable to personnel who are not RF workers, but are required to be RF aware due to their working in the vicinity of elevated RF fields.

In light of the above, a good RF safety training program should include as a minimum training on understanding and utilizing the various safety controls implemented for RF safety (e.g., the specification of areas above occupational limits in RF site documentation, RF warning signage and access restriction, and the use of RF monitoring devices). As background to these topics, the training should also explain the upper tier limits for occupational (or controlled) exposure and define an RF worker and the use of controlled areas. It may also include general information on RF safety policies, which may be specific to a particular organization or industry and the overall rationale for the need to observe RF safety in the first place (i.e., the physical hazards that RF safety limits are designed to avoid).

29.4.5 RF Training Delivery and Assessment

There are many options for developing and delivering suitable safety training. However, given the large numbers of personnel from a wide range of industries who are likely to need such training as outlined above, then the provision of online curriculum, instruction, and assessment is likely to be favored for cost and efficiency reasons.

Since the objective of RF safety training is to provide the necessary training and information required to enable staff to operate safely in work environments that necessitate access to elevated RF fields, the content of the training material must be formulated to satisfy the requirements of the relevant RF safety standards with regard to the procedures adopted to ensure safe work practice for RF workers or other personnel (depending on jurisdiction) who may be exposed up to the occupational limits of the standard (and likewise for those that are restricted to only general public exposure). The details of these practices will differ among jurisdictions, industries, and organizations and so must necessarily be tailored to specific applications.

It is critical that the information provided is accurate and credible and that the courseware is sourced from a reputable and accredited provider. Accreditation independent of both the provider and the industries seeking the training is preferable. Nonprofit professional associations, academic organizations, or government agencies may typically take on this role on a minimal cost recovery basis.

An important consideration for RF safety training to be effective is that participants are tested for competency in the course material. Competency-based assessments may be conducted in the online environment, typically as topics are completed, so that new topics cannot be commenced until competency in the current topic is successfully demonstrated. Given the safety-based significance of this training, it is suggested that a high level of competence (significantly higher than a mere "pass") be required of participants to successfully complete the course.

29.4.6 List of Recommended Topics for RF Safety Training

To meet the dual purposes of training RF workers in RF safety management systems and provide general RF awareness for non-RF workers, it is highly desirable that an adequate RF safety training program should include the list of topics below. The topics are organized into general subject headings although the structure of any training program need not follow the particular example provided. The content of each topic point is beyond the scope of this chapter and indeed is likely to be specific to any given organization, industry, or safe work authority in any given jurisdiction. The reader is directed to the specialist RF standards literature and their own work safety regulator for further information on this subject.

Note: This list of topics was developed by the Australian Centre for Electromagnetic Bioeffects Research (ACEBR) at the request of the Australian mobile telecommunications industry as part of an accreditation scheme for RF Awareness training delivered by independent courseware providers to Australian mobile telecommunications industry staff and contractors.

Unit 1 – RF EME Hazards and Standards

- Propagation of RF electromagnetic fields as transverse E and H fields
- Ionizing and non-ionizing radiation
- Established mechanisms for RF biological effects (i.e., heating, electrostimulation, and microwave hearing effect)
- RF energy absorption in the body and variation with frequency
- Potential health effects of high exposure to RF fields
- Applicable standards for ensuring RF safety
- Identifying the limits within the RF safety standard for public and occupational exposure

- Definition of who may enter occupational exposure or “controlled” environments
- Explaining the use of controlled environments for exposures above public limits.

Unit 2 – RF EME Safety Policies

- Location of company/organization RF EME policies and how they may be obtained
- Medical preplacement tests for RF workers
- Specific requirements for pregnant RF workers
- Company/organization procedure for suspected overexposure
- Roles and responsibilities in the company for managing and ensuring RF safety
- Procedures for supervising non-RF workers on RF sites
- Use of safety signs and barriers to control access to RF hazardous areas.

Unit 3 – Identifying Hazards

- General characteristics of an RF source that affect its RF EME hazard potential (transmitter power, antenna performance, effective aperture, and frequency)
- RF hazard characteristics of typical RF sources encountered in the company/organization environment
- Company/organization process for documenting RF source details and of change notification for RF sources
- Identification of a location as an RF EME hazardous area
- How RF EME safety controls can be determined for a site
- Important information components for inclusion in RF site safety documentation.

Unit 4 –Site Procedures

- Company/organization policy on site entry procedures
- Correct use of company/organization site safety procedures
- Procedure for outages/equipment shut down if required
- Procedure for commissioning new equipment
- Procedure for RF EME safety on sites not managed by the company/organization including interim safe working practices where site status cannot be confirmed.

Unit 5 – Personal RF Monitoring Equipment

- Reasons for using personal RF monitoring equipment
- Characteristics of the personal RF monitors used by the company/organization
- Correct use of the personal RF monitors, including service and calibration checks
- Precautions to be observed when using personal RF monitors.

29.4.7 Importance of Training Programs

Effective safety standards that are properly implemented ought to reduce or eliminate the potential for exposure of individuals to RF fields that are injurious or hazardous to human health, whether this arises in an occupational or general public (population) setting. Other chapters in this book discuss the current state of the science on health effects from exposure to RF electromagnetic fields but an overall conclusion is that the limits prescribed in safety standards such as (ICNIRP, 1998 or IEEE, 2005) provide significant protection from harmful effects to all individuals including workers and the general public.

Such protection can only be provided where compliance with these safety standards can be reliably achieved. Therefore, to realize the full advantage of these standards, an important step is the implementation of a comprehensive safety program that incorporates implicit safety for the general public who will not be required to take any particular precautions or instructions, and training for personnel who may be required to access areas near radiocommunications infrastructure on the practices and controls implemented to ensure compliance with the safety standards in a work setting.

Only when such training is provided, understood and monitored for subsequent implementation in work practices can compliance with safety standards be reasonably assured. This requires that training programs be pitched at the appropriate level for the participants and the particular work place and that a competency-based assessment is conducted to demonstrate the successful completion of the training program.

While often overlooked, RF safety training programs are a vital link in the critical path to achieving RF safety for workers and meeting the duty of care incumbent on employers and infrastructure managers.

29.5 Conclusion

This chapter has reviewed some of the programs in place to help reduce the chance of injury or illness in three specific areas of non-ionizing radiation.

In the case of UV, the concern is as much the general public as with the occupational group most at risk: the outdoor worker, particularly in people with fairer skin and in latitudes nearer to the equator.

Workers at risk of eye and skin injury from lasers are largely confined to specialist laboratories, and most worksites have procedures, training, and administrative and engineering controls in place to minimize the chance of accident. With RF, the ubiquity of telecommunications infrastructure and the need to access areas where the possibility of overexposure exists (because of requirement for equipment maintenance or testing, or general building maintenance) makes RF awareness programs essential. Because there could be some uncertainty in where responsibility lies (building owner or owner of RF-emitting equipment: how this applies to self-employed workers), there should be process in place to ensure that all who need training do, in fact, receive it.

In all the three areas, the importance of familiarity with the nature of the exposure and awareness of appropriate behavioral and environmental measures to minimize the chance of overexposure has been emphasized. In addition, critical is an underlying organizational policy commitment for risk minimization and clear identification of responsibilities so that personnel at risk are identified and appropriately trained. Allied to this is the need to have in place a system of independent evaluation and validation, to ensure that these programs are fit for purpose and effective in bringing about change.

Tutorial Problem

1 List three hazards that may be associated with setting up and operating high powered lasers in a laboratory. For each hazard listed what are some potential consequences?

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Part IX

Legal and Community Issues

30

Public Consultation and Dissemination of Information. Risk Perception. Public Involvement in Decision-Making Regarding Placement of Broadcast Antennas and Power Transmission Lines

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30.1 Introduction

Anyone communicating with the public about nonionizing radiation (NIR) knows that perception is reality. No matter what the scientific data says to experts, members of the public perceive risk in a way that reflects their own knowledge and personal values (Lee, 1997). Simply telling people "the facts" in scientific terms rarely, if ever, satisfies all of them (Moffat and Pless-Mulloli, 2003). Issues of stakeholder participation and trust have become increasingly more important.

There is now a large body of literature dealing with risk communication (Slovic, 2000; Del Pozo et al., 2007; Morrow, 2009). Increasingly, NIR has taken its place in this literature during the past two decades.

It is therefore appropriate to include in a book dealing with NIR a chapter on risk perception, risk communication, and public consultation. This chapter is written from the viewpoint of a practitioner, who, for 20 years, dealt with these difficult policy issues about NIR local community concern on a daily basis rather than that of an academic pursuing research interests.

30.2 Why Communicate on NIR?

The increasing importance of risk communication in NIR is illustrated by the fact that the World Health Organization (WHO) published a handbook on the

Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.

subject entitled “Establishing a Dialogue on Risks from Electromagnetic Fields” (World Health Organization, 2002). The handbook was authored by a panel of international academics including experts in the science of NIR and risk communication. Target audiences were decision-makers in WHO member states. The handbook’s Foreword states:

> This handbook is intended to support decision-makers faced with a combination of public controversy, scientific uncertainty, and the need to operate existing facilities and/or the requirement to site new facilities appropriately. Its goal is to improve the decision-making process by reducing misunderstandings and improving trust through better dialogue. Community dialogue, if implemented successfully, helps to establish a decision-making process that is open, consistent, fair and predictable. It can also help achieve the timely approval of new facilities while protecting the health and safety of the community.

The publication of the WHO handbook was a timely and important development in NIR risk communication and has since become an extremely useful tool to assist in the implementation of best practice risk techniques in communicating effectively with concerned citizens.

30.3 Public Perception

It is well established from social science research that members of the public view risk differently from experts (Lee, 1997). This is so especially with new technologies with which the public is unfamiliar and whose benefits they may question initially. This can become more complicated when a new technology is highly popular, but questions about its safety are raised, for example, mobile telephony and other wireless connections and their supporting infrastructure of base stations, towers, or masts.

The worldwide growth in the popularity and use of personal mobile phone technology has been very fast. For example, in 1999 when I accepted a position to work in London, there were 23 million mobile phone subscribers in the United Kingdom. Now there are 83.1 million mobile handsets and data connections in that country (Mobile Operators Association, 2015).

According to British market research conducted for the UK Mobile Operators Association (MOA) (which represents the collective interests of the country’s five mobile network operators on health and local authority planning issues), 84% of respondents regarded mobile phones as a necessity of modern life and 80% of them claimed that having a good mobile signal is important to them personally (YouGov, 2014).

Similar growth rates and attitudes have been experienced throughout the world – in 2014, there were 7.1 billion mobile connections in the world with 3.6 billion unique subscribers, about half of the world’s population (Bouveret, 2014).

With the rapidly increasing worldwide use of this new and highly popular technology over the past two decades, there has been huge customer-led demand for mobile phone and wireless device network operators to build an infrastructure of base stations to support it. This fast wireless and cellular network expansion has brought with it many instances of local community opposition to nearby base station siting and the growth of both national and local community activist groups opposed to various aspects of such network development.

Community opposition has usually been based on environmental grounds such as visual amenity and also, in many instances, on a public perception that exposure to radio wave emissions from base stations might adversely affect the health of those living or working near them. This opposition has increased when children have been involved, particularly in the siting of base stations on or near to schools, kindergartens, play centers, and the like. This has been so despite the fact that human radio wave exposures from a base station are substantially lower than those from a mobile phone (Stewart, 2001) and international and national health authorities have issued reassuring messages to the public about the safety of the technology (WHO, 2014; HPA, 2012; ARPANSA, 2015).

Public perception about the possible adverse health effects of mobile phones, other wireless devices, and base stations is remarkably similar to that experienced during earlier decades in the electricity supply industry and even in the present day where, depending on proximity, human exposures to extremely low frequency (ELF) electromagnetic fields (EMF) from overhead power lines are generally much lower than from household wiring and everyday domestic electrical appliances such as vacuum cleaners, shavers, and hair dryers.

A key question for government and industry has been how to address that public perception in order to bring about a meaningful dialog with members of local communities to enable the necessary infrastructure to be built in order to keep pace with rapidly increasing customer demand for personal wireless devices including mobile phones?

Certainly, in the electricity supply situation, the use of handheld personal dosimeters has been highly successful in a number of countries. The technique has usually involved a representative of an electricity utility visiting the home of a member of the public and demonstrating that the ELF EMF experienced within the home are much greater than those that will be experienced from the proposed power line. This information has been found to carry greater weight when the measurements have been actually undertaken by the householder rather than the utility representative.

Apart from increasing the technical knowledge of the householder, the sessions have opened up a dialog in which other concerns of the householder can be addressed in personal conversation with the utility representative. The technique has also been used successfully by government agencies such as the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), which makes meters available on short-term loan to members of the public to enable them to take their own EMF measurements in their home (http://www.arpansa.gov.au/meterhire/index.cfm).

There is a similar example from the field of mobile telecommunications. In the United Kingdom in 2001, the Radiocommunications Agency (now OFCOM) (an independent agency of the government) carried out an audit of radio wave emissions from mobile phone base stations and the results were posted on its web site (www.ofcom.gov.uk). By the end of 2003, there were results available from more than 250 base stations across the United Kingdom (OFCOM, 2003). The primary purpose of the OFCOM audit was to demonstrate to local communities mobile operator compliance with relevant UK radio wave emission exposure guidelines. Similar audits showing compliance with official EME exposure guidelines for base stations have been carried out in Australia by the mobile phone carriers (http://www.rfnsa.com.au/nsa/index.cgi) and the Australian Communications and Media Authority (http://www.acma.gov.au/Citizen/Consumer-info/Rights-and-safeguards/EME-hub/the-acmas-eme-compliance-strategy).

30.4 Stakeholder Dialog

Trust and credibility is the cornerstone of effective dialog and risk communication with concerned members of the public.

In a paper delivered to a WHO seminar in Vienna (Kemp, 1997), UK risk communication expert Professor Ray Kemp described it thus:

> Central to the risk debate in the past ten years have been the issues of trust and credibility. In other words, it has come to be recognized that in the modern era, the credibility of governmental, regulatory, and advisory can no longer be taken for granted in the public mind. To the extent that risk based decisions are seen to be decisions based on expertise, the level of public trust can no longer be guaranteed.

Trust must be earned and is like money in the bank. It is hard to accumulate, very easy to spend, and, once spent, difficult to replace. Trust is about personal values and ethics and, if these are not addressed directly in stakeholder dialog, it is unlikely that the dialog will be meaningful.

How do you ascertain who is a stakeholder? A stakeholder is any person or organization with an interest or perceived interest in the outcome of the decision to be made. While this definition has the potential to produce a long list, if all stakeholders are not involved in the process of dialog, it is likely that the communication process will be flawed and the decision made will be less legitimate. This can cause project delays, extra costs, and political intervention.

In the area of NIR stakeholders are likely to be members of local communities affected by infrastructure development, users of products such as mobile phones and household electrical devices, nongovernmental organizations, community groups, politicians (local and national), local government bodies, national governments, regulators, trade unions, industry, the medical and scientific communities, and the media.

Each of these groups is important and, where appropriate, must be addressed if risk communication is to be successful. In this regard, it is important to ascertain what it is that a stakeholder is seeking from the dialog rather than what the communicator wants to communicate and achieve. If this is not clear, it is likely that there will not be a meeting of minds and the attempted dialog will fail.

Stakeholder dialog forms part of active risk communication. There is also passive risk communication. Examples of passive risk communication include leaflets, position statements, fact sheets, media releases, and internet websites. These can all be useful as communication tools, but the best form of risk communication is active dialog where attempts are made to engage with stakeholders clearly and effectively (World Health Organisation, 2002).

US risk communication expert Covello (1997) has set out a series of principles of good practice to achieve the primary goals of risk communication, which he has described as:

- Achieve mutual understanding
- Establish and maintain trust and credibility
- Establish a dialog about risk, benefits, and process
- Produce an informed public that is involved, interested, reasonable, thoughtful, solution oriented, and collaborative.

Covello has outlined the following principles of risk communication practice (originally published by the US EPA in 1988):

- Accept and involve the public as a legitimate partner
- Listen to the audience
- Be honest, frank, and open
- Co-ordinate and collaborate with other credible sources
- Meet the needs of the media
- Speak clearly and with compassion
- Plan carefully and evaluate performance.

These principles are all based on achieving effective stakeholder dialog and are self-evident.

Another noted US risk communication expert Dr Peter Sandman has developed a model of risk communication based on addressing *public outrage*. The model assumes two parts to risk. The first is the traditional technical hazard aspect of risk and the second is *everything else* that Sandman describes as *outrage*. As Sandman puts it, experts respond to hazard and members of the public respond to outrage. When hazard is high and outrage is low, the experts will be concerned and the public will be apathetic. When hazard is low and outrage is high, the public will be concerned and the experts will be apathetic. Sandman has called his model of risk communication "Risk = Hazard + Outrage" (http://www.psandman.com/).

The approaches of Covello and Sandman cover similar ground and they have coauthored a book chapter summarizing their views (Covello and Sandman, 2001). In that publication, Covello and Sandman have identified 20 principal outrage components to determine how the public perceives activities as "safe" and "risky". These are as follows:

- Voluntariness
- Controllability
- Familiarity
- Fairness
- Benefits
- Catastrophic potential
- Understanding
- Uncertainty
- Delayed effects
- Effects on children
- Effects on future generations
- Victim identity
- Dread
- Lack of trust
- Media attention
- Accident history
- Reversibility
- Personal stake
- Ethical moral nature
- Human versus natural origin.

Many of these outrage components apply to the NIR situation. While most people willingly accept the benefits of electricity and mobile phone technology, many are often reluctant to accept the infrastructure required to support it on the basis that they perceive any possible risk as involuntary, they have no control over it, they do not understand how it works, they do not perceive any benefit from it and therefore regard it as unfair, they believe that it has potentially catastrophic consequences involving children and dread diseases, it receives constant media attention, and so on.

In short, people can become outraged very quickly when a new power line or base station siting proposal in their area is announced. This can include concern about the proposal causing falling house values in the neighborhood. How can this public outrage be reduced?

Sandman has identified six principal strategies to reduce outrage. They are as follows:

- Stake out the middle, not the extreme
- Acknowledge prior misbehavior
- Acknowledge current problems
- Discuss achievements with humility
- Share control and be accountable
- Pay attention to unvoiced concerns and underlying motives.

A more detailed description of Sandman's model and its approach to outrage reduction may be found on his web site.

The general principles enunciated by Covello and Sandman and other risk communication experts were used by MOA as the basis for its approach to risk communication in relation to the safety of mobile phone handsets and their supporting network of base stations (often referred to in the UK media as "masts").

In 1999, the MOA introduced a policy of stakeholder interaction based on a "middle ground" approach to the mobile phone health issue. The MOA and its members (the UK's five mobile network operators) moved out of a "denial" approach to the health issue, acknowledged the concerns of the public, and put in place policies and practices designed to gain public trust.

This new approach involved significant financial support for an independent research program managed independently by the UK government, the implementation of precautionary approaches recommended by an independent expert government advisory panel, and the ongoing engagement of national stakeholders in a series of round table meetings and discussions. At the operational level, all operators put in place teams of dedicated community liaison officers whose task it was to engage in dialog with local communities and local planning authorities about proposed base station locations.

A key part of this increased active stakeholder engagement involved the adoption by all of the mobile network operators in September 2001 of a series of self-regulatory consultation initiatives called "The Ten Commitments to Best Siting Practice" (Mobile Operators Association (MOA), 2001a) plus two reviews of their implementation by an independent firm of auditors whose reports were put into the public domain (Deloitte & Touche, 2003).

The recommendations of the Deloitte & Touche reports (which were accepted in full by the MOA and its members), and how they were going to be put into practice, were then discussed with stakeholders in a round table meeting chaired by a distinguished independent UK academic.

Stakeholder comments were considered carefully before final decisions were made. The Ten Commitments, the Deloitte& Touche Reports, and the industry responses can be viewed at the MOA web site (www.mobilemastinfo.com).

The MOA and its members believed that the key to successfully addressing public concerns about base station siting lay in improved dialog with affected communities based on proactive communication and consultation carried out at an early stage of the siting process.

The Ten Commitments were based on improving transparency in the process of building mobile networks, providing more information to the public, and increasing the role of the local community in the siting of base stations. Part of that transparency involved the independent review process outlined above.

The MOA also published on its web site a Risk Communication Handbook authored by Professor Ray Kemp and Ms Tamsin Greulich of Galson Sciences (Kemp and Greulich, 2003). The primary audience for the handbook was and is the staff of the site acquisition agents employed by the UK mobile phone network operators who acquire suitable sites for base stations.

The handbook is a practical tool for those working in the area of mobile telecommunications network development. It is written in clear and easily understood language and was designed in such a way that it is easy to navigate and quickly find answers to the daily challenges faced by those interacting with local communities affected by mobile phone network development. A Community Consultation Manual by the same authors was produced subsequently for the Australian Mobile Carriers' Forum (http://www.raykempconsulting.com/page5c.htm).

30.5 When to Communicate

The short answer is the earlier the better. One of the main causes of local community outrage when faced with new infrastructure development projects is bad process. In other words, the public finds out about a new project when it is too late for them to have their views considered.

Often, it is this "angry" factor more than any other factor that causes very strong public opposition, and developers simply do not understand why this is so. The answer lies in human nature and personal values. Most people do not like decisions being made, which they perceive will adversely affect their daily lives taken without having had the opportunity to make their views known. The ability to be heard underpins democracy and forms the cornerstone of fair process in most legal and quasi-legal situations.

Many developers (and even government agencies) are reluctant to involve the public at an early stage because they believe that to do so will cause too many problems and introduce delays into a project. Sadly, what they fail to realize is that picking up the pieces after outraging a local community also involves many problems of its own including delays, damage to corporate reputation together with often significantly increased financial cost caused by government or regulatory intervention.

Early dialog with affected stakeholders can in fact be very beneficial provided that it is undertaken in a genuine and proactive manner. This does not mean that there will not be community opposition to a project, but it does mean that all parties can work toward constructive solutions rather than engage in prolonged trench warfare (Moffat and Pless-Mulloli, 2003).

For example, since September 2001 and as part of the Ten Commitments, the UK's mobile phone network operators have sent their annual network rollout plans to every local planning authority in the country in the September/October timeframe. At the time of doing so the authority is invited by letter to meet with the operators to discuss the plans.

As the ensuing year progresses, and specific network building projects come closer, the operators or their agents again approach the local planning authority to discuss possible specific siting options and to seek agreement on plans for local community consultation. In specified cases, the consultation is then undertaken by the operators or their agents before any application for planning permission is lodged with the authority.

This process was designed to ensure that local community views are sought at an early stage of the process in order to enable them to be taken into consideration before formal planning processes are commenced. This does not mean that local communities have absolute rights of veto over proposed projects, but it does mean that their views can be considered before final project decisions are made and formal planning permission sought.

30.6 What to Communicate

Stakeholders have the right to know sufficient information to enable them to assess the situation and to provide meaningful input to the decision-making process.

When scientific or health issues are involved, as they are with NIR, then the matter becomes more complicated. In the past, experts often approached the public on the basis of telling them what the science said and expecting members of the public to accept that assessment without qualification – "trust us, we are the experts".

Unfortunately, there have been enough historical instances of the experts being wrong to cause the public to become increasingly skeptical about their views. Prominent examples include BSE and asbestos. As Professor Sir William Stewart said in evidence to a UK House of Commons Select Committee (Stewart, 2001):

> Never again will any scientific committee say that there is no risk.

Scientists have learned that it is best not to communicate in absolutes because that is not the way in which they think or debate issues in science (Gregory and Miller, 1998). Life is not free of risk. Scientists know that as do members of the public who are quite able to accept it as long as the scientists are honest about their descriptions of what they know, what they do not know, and what they are doing to improve their knowledge and thereby protect public health. In the end, like all aspects of risk communication, it is about trust. It is also communicating about uncertainty.

The decision on what to communicate relies heavily upon an assessment of the audience and its expectations. A technical audience may want detailed technical information with solid data addressing formal risk assessment criteria. An audience of outraged parents worried about the possible adverse health effects on their children of a new power line or mobile phone base station is far less likely to be influenced or persuaded by technical arguments and scientific data. Such an audience will usually be asking for guarantees of safety and be far more accepting of dialog that takes into account emotional and social issues and addresses personal values.

From the perspective of an outraged audience, such a dialog may often focus on whether the development process itself is or is not perceived by the audience as fair. The WHO has illustrated this in its handbook with a simple diagram setting out the components of a risk communication message (WHO, 2002).

Whatever the audience, it is always necessary to work out in advance "key messages" for the situation. Covello has long argued that there should never be more than three key messages in risk communication on the basis that research has shown that an audience cannot absorb more than that number at any one time. Covello argues that if there are more than three key messages then, whatever else it might be, it is not a risk communication message. However, each of the three key messages may be supported by two facts. Covello's advice is that when you have completed delivering the three key messages and supporting facts then go back and start again.

It is important to get the key messages in correct order. When communicating with an outraged audience, it is essential to be empathetic at the outset, for example, acknowledge the concerns of the audience and commit to addressing them in an open and transparent way. This should be followed by a substantive content message and then a commitment to "do" things toward resolution of the issue. For example, an industry body may respond to a new piece of EMF research in the following way:

> We take concerns about health very seriously and welcome all sound research that adds knowledge to this complex scientific subject. However, the study must be seen in the light of ongoing total worldwide research on this subject. The authors of the study themselves acknowledge that their results were based on a small sample size and will need to be repeated by an independent laboratory. We will continue to monitor research on this subject very closely and our members will continue to operate their facilities within approved international health and safety guidelines.

However, it cannot be overemphasized how important it is for any "doing" statement to be backed up by actually carrying out the promised action within a reasonable time. A failure to do so will lead very quickly to an erosion of trust.

30.7 How to Communicate

While the content of communication is extremely important, so is its method. In its handbook, the WHO deals with "setting the tone":

> When dealing with an emotive issue such as the potential health risk from EMF, one of the most important communications skills is the ability to build and sustain a relationship of trust with the other parties involved in the process. To that end, one will need to create a non-threatening atmosphere and set the tone for a candid, respectful and supportive approach to resolving issues. Such behaviour should ideally be embraced by all stakeholders.

Normal human communications skills and good manners are essential to the process. A cardinal rule is to treat your audience as you would wish to be treated in a similar situation. In order to establish and maintain trust always ensure that you are completely honest, open, and transparent. If there is already an existing lack of trust, acknowledge this as a fact, offer an apology if appropriate and commit to work with community members to move toward a mutually satisfactory resolution of the issue.

An example of such an approach being used successfully, and in which I was involved as an advisor, is a power line situation in Victoria, Australia, in which a newly privatized electricity distribution company was seeking to build a new 66-kV transmission line above an existing 22-kV distribution line along a residential street in order to serve the power needs of a major industrial customer. The residents of the street were outraged as they perceived that the ELF EMF emission levels in the street would increase with no advantage to them at all, that is, the line upgrade was not to serve their needs but the needs of a nearby factory.

After the commencement of public controversy, it became apparent that there had been significant process errors by the electricity company in the manner in which it had advised (or failed to advise) local residents of its development plans. In part, this had been contributed to by a change in ownership of the company (from public to private). The local residents asked to meet with the chief executive officer of the company (CEO) to discuss their concerns.

When the meeting took place, the CEO opened it by welcoming the residents and asking for their permission to make an opening statement. The CEO openly acknowledged in detail the process errors of the company and apologized to the residents. He indicated that the company took the concerns of the residents very seriously and committed the company to working with them constructively to achieve a mutually satisfactory outcome.

This approach came as a complete surprise to the residents who had come to the meeting armed with hard evidence of the company's "bad process". In the end, the dialog with the residents resulted in ELF EMF emission levels being taken by an independent consultant both before and after the new transmission line came into operation with regular monitoring thereafter. All of these measurements were shared with the residents who felt that this was a satisfactory outcome.

The CEO took exactly the correct approach with the outraged residents and the company and the residents achieved a mutually satisfactory outcome. However, this is not typical corporate behavior. It was a courageous step by the CEO and certainly achieved the desired outcome his company, that is, the power line was built.

As has been said earlier, risk communication, in order to be successful, must be a two-way dialog and not just a one-way transmission of facts. Stakeholders must be engaged and not talked at. This involves detailed prior planning with careful thought being given as to how to achieve genuine dialog. Large public meetings are not a good forum for meaningful dialog. They are very good at allowing people to express their outrage, but they rarely achieve satisfactory outcomes. Personal communication carried out in fora such as one-on-one meetings, open houses, coffee mornings, and home visits are much more effective in both conveying information and engaging in meaningful dialog.

By way of example, in the 1990s, a major US electricity company KPC&L (personal communication at conference) was planning a new transmission line project, which it felt could become controversial. In order to engage with local communities, the company hired a large hall in a convenient location and set out around the hall a series of displays dealing with many different aspects of the project. The company staffed each of the displays with several people trained to discuss all aspects of that part of the project. There was a reserve team in place to provide back-up to each of the displays if needed. The idea was to never let a visitor to a display be unattended.

Local communities were invited to visit the venue over a period of weeks and to ask questions or raise concerns regarding any part of the proposed development. The displays were open at night and on weekends in order to make it easier for people to attend in their spare time. The consultation exercise was highly successful and the development went ahead with little community opposition. There was, of course, a huge resources commitment to the consultation by the company, but it paid off handsomely and would have been far less than the costs associated with significant community opposition to the project.

In her landmark book "Strategic Reputation Risk Management" (Larkin, 2003), UK-based risk and crisis communication expert Judy Larkin argues that communication must be kept "clear, consistent and credible":

> In an emergency or crisis situation, my essential markers are to express **concern** over what has happened, **commitment** to fix the current problem, and **control** in demonstrating that the company is involved at the

> highest level to assess the risk impact and to put in place safeguards to reduce the potential for future risk. The **three Cs** provide an essential guide when all else fails. It is common sense and about being human!

Lundgren and McMakin (1998) have set out in their book "Risk Communication – A Handbook for Communicating Environmental, Safety, and Health Risks" a set of principles on how to present information in ways that best communicates the risk to the intended audience. These include:

- Know your audience
- Don't limit yourself to one form, one method
- Simplify language and presentation, not content
- Be objective, not subjective
- Communicate honestly, clearly, and compassionately
- Listen and deal with specific concerns
- Convey the same information to all segments of your audience'
- Deal with uncertainty.

Many of these principles have already been touched upon in this chapter, but it is useful to restate them. All go to the fundamental issue of gaining trust, which sits as the cornerstone of all successful risk communication. From a practitioner's viewpoint, one of the most important is to listen and deal with specific concerns. As Lundgren and McMakin point out:

> Besides dealing with the emotions behind concerns, listen to what people are saying about the risk itself. Then deal with each specific concern you hear. Don't discount concerns that seem based on faulty scientific information or are peripheral to the situation.

People who are feeling outraged will only have their outrage magnified if they perceive that their concerns are being trivialized or ignored.

30.8 Evaluation Is Essential

Finally, don't forget to evaluate what you have done so that you can learn how to do it better next time. As Larkin (2003) puts it:

> Risk communication strategies deal with important issues of public health and safety. They also deal with relationships and the existence of trust, so anecdotal information isn't enough. In order to help achieve objectives, research and evaluation are essential elements of the navigation plan as a means to:
>
> - Demonstrate accountability and cost justification
> - Identify whether and why strategies are working

- Provide an empirical basis for planning, the need to change course or fine-tune
- Support learning and improvement.

It is often difficult for managers within companies to justify internally why they are spending money and resources on risk communication and evidence from evaluation studies will assist in that process.

30.9 Conclusion

While sound science must underpin NIR risk management, it is essential that risk perception and risk communication are taken into account when responding to local community concerns associated with power line or mobile phone and other wireless device base station development.

Much has been written on this subject and its importance to NIR is underscored by WHO taking the step in 2002 of publishing its handbook on establishing a dialog on risks from EMF. Readers are referred to the publications listed in the bibliography to this chapter for more in-depth discussion of the topic.

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31

Mitigating Nonionizing Radiation Risks

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31.1 Introduction

In Chapter 29, methods of limiting exposure, or reducing the risk of overexposure, by public information or occupational training were discussed, specifically in relation to UV, laser, and radiofrequency (RF) exposures. In this chapter, ways of reducing the risks of overexposure primarily via low- or modest-cost engineering solutions and also other methods are discussed. The main areas where this can be done are lasers and other optical sources, RF fields, and extremely low-frequency (ELF) electric and magnetic fields. These are mainly carried out in occupational settings as part of general occupational health and safety requirements, but risk mitigation also has benefits to the general public, both in the prevention of inadvertent overexposure and as part of a general strategy to eliminate incidental unnecessary exposure.

31.2 Mitigation Strategies – Lasers and Other Optical Sources (David Urban)

31.2.1 Hazard Mitigation and Control Measures

Chapter 29 outlined the purpose and general guidance for undertaking a risk assessment when operating lasers. In the same way, these assessments can be applied to other optical sources such as light emitting diodes (LEDs) and intense pulsed light (IPL) sources. Once the inherent risk associated with the hazards presented by these sources has been determined or categorized, appropriate

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control measures and priorities can be put into place to reduce or mitigate the risks during laser installation, operation, maintenance, and final disposal.

Risk reduction or mitigation is usually applied once the degree of risk has been shown through assessment to be unacceptable. In some cases, such as operation of Class 2 lasers, exposure to the beam triggers the blink aversion response of the eye. This response is sufficient to avoid injuries, and the addition of extra control measures is therefore unnecessary. Further, Class 1 and Class 2 lasers do not normally require an in-depth risk assessment to be conducted around their use because the risk of injury is inherently low. The substitution of lasers in these lower class categories can significantly reduce the control measures needed to reduce the risks of injury. Therefore, the first step in mitigating the hazard should be, wherever possible, to use lower power lasers (by reducing the emission, increasing beam diameter, or using a different wavelength) or lower power optical sources in general.

Where higher power lasers or other optical sources have been determined to be necessary or preferred from an operational perspective, risk mitigation measures can be broken down into three broad categories. These include, in order of priority, the following:

- engineering controls (enclosures, fail-safe interlocks, protective barriers, and emergency stop switches);
- administrative controls (policy, procedural issues, training, instructions, access management, and signage);
- personal protective equipment (PPE) (safety eyewear, protective clothing, ear plugs, and respirators).

Any policy governing laser use should consider engineering controls as a primary risk mitigation measure for reducing the risk of laser-related injury. Administrative controls should then be considered covering procedural issues and appropriate access management. PPE should be used in conjunction with adequate engineering and administrative controls especially where these controls may not provide sufficient levels of protection.

In applying best practice, these risk mitigation strategies should also be used in a risk-informed manner with lower hazard lasers and optical sources.

31.2.2 Engineering Controls

Engineering controls aim to prevent access to the optical radiation being emitted. The best engineering controls isolate the radiation so there is no chance of an exposure during normal operations of the laser equipment. These may include imbedding or enclosing the laser within a system where there is no access. Other engineering controls such as the use of low reflecting surfaces, viewing windows, and curtains are put into place to reduce the level of direct or indirect exposure through the design of the environment in which the laser is being operated. Further, some engineering controls such as interlocks are designed to terminate the hazard completely if there are any interruptions in the routine use of the equipment. It is important to note that engineering controls such as enclosures, and viewing windows may not, have sufficient optical density at the wavelength of the laser radiation to provide effective hazard mitigation for high-powered lasers.

31.2.2.1 Isolation and Enclosure

Isolation and enclosure that prevent access or contain the laser beam are one of the most effective control measures that can be put in place to prevent exposure to laser radiation. As such, this technique should always be considered for integration into the safety management system during operations.

Beam enclosures can be made of materials such as glass, fabrics (curtains), or plastics, but various types of metal are most commonly used. Regardless of the type of material chosen, it is important that it is fit for the intended purpose and robust in case of any reasonably foreseeable changes in the local working environment. To this end, materials should be stable enough to resist impacts, heat, or other environmental pressures and have an appropriate optical density (the extent to which a material transmits light) to attenuate the laser radiation at the particular wavelength(s) of interest.

The room can also act as a protective enclosure by preventing access to the laser during operations.

31.2.2.2 Viewing Windows

Viewing windows are a method of isolation whereby laser operations are observed through a transparent barrier with an optical density appropriate to the lasers in use. The balance between being able to clearly observe the working environment through these media and ensuring that they provide adequate protection mean that they are not ideal barriers for protection. The use of remote viewing TV cameras is often considered a safer observation method.

31.2.2.3 Activation Keys

Activation keys are used to render a laser system inoperative after their removal usually by cutting the supply of power. The keys should always be removed from the lock and placed in a secure location such as a locked cabinet to ensure that no inadvertent or unauthorized activation of the beam occurs.

31.2.2.4 Emergency Beam Stops

In the case of emergencies (fire and accidental exposures) or unintended occurrences (unauthorized access), emergency stop switches are usually incorporated into safety systems. These generally take the form of a labeled push button on the wall of the laser operations room or the equipment itself that interrupt the flow of power to the laser. Automated emergency stops are usually wired into key elements of the laser operating system and activate should any of the components fail.

31.2.2.5 Shutters

Shutters can be activated manually or automatically by hardwiring them into the laser system as an integrated safety feature. While they do not terminate the laser beam itself, they do block the path of the incident light. This allows time to control any unexpected events or make adjustments to the system while containing the laser radiation hazard. The use of shutters has the advantage of not needing to restart the laser system after a sudden power termination that can be time consuming or even damaging to the equipment.

31.2.2.6 Interlocks

Interlocks are designed to terminate the supply of power to laser equipment and thus stop the beam and remove the radiation hazard in case of inadvertent, accidental, deliberate, or malicious tampering with safety features, where the result may be serious injury.

Interlock systems fall into two categories: locking and nonlocking. Locking systems require a deliberate extra input (system reset) in order to reactivate the laser, whereas a nonlocking system only requires the replacement of the safety feature (e.g., replacing a piece of enclosure) to reactivate the emission. Interlocks may be defeated by the use of an override switch, but the use of this feature should be restricted to suitably qualified and authorized users and maintenance personnel for justifiable reasons that do not compromise safety.

31.2.2.7 Reflective Surfaces

Appropriate building and furnishing materials that are nonreflective should be chosen in the workspace in order to prevent specular reflections, especially when using high-power or magnified laser systems. Even surfaces that appear to be diffuse can reflect a considerable part of the laser radiation, especially in the infrared region. In addition, equipment on an optical table such as mirrors, lenses, and other optical modifiers should be mounted securely to avoid unwanted movement that may cause unpredictable specular reflections.

31.2.3 Administrative Controls

Administrative controls are the simplest level of risk mitigation that a workplace can apply when dealing with optical hazards. They may include implementing workplace policies, procedures, and specific instructions governing the use of optical sources. Rules relating to access of the working environment (e.g., laboratory) are intended to limit the number of personnel that can be exposed to the hazards. The use of hazard warning signs promotes awareness of the nature of the hazard and its location while operating procedures and work instructions are provided in order to manage the hazard appropriately. Training would provide an understanding of the equipment and be commensurate with the type of hazard.

31.2.3.1 Policy and Safe Work Instructions

An overall policy governing the use of lasers in the workplace should be put into place at the early stages of process and laboratory design before operations commence. The policy should consist of a simple framework covering broad aspects for the safe use of the laser equipment. Local rules and procedures can be developed from the policy. Some examples of what may be covered as a result of this development include the following;

- training requirements
- outlining and allocating a radiation safety officer within the organization
- access management into restricted areas
- procedures for laser operation and maintenance
- emergency actions and incident reporting.

A more ubiquitous form of safety documentation is safe work instructions (SWIs). The most obvious type of information that is contained in an SWI is a formalized step-by-step procedure for the safe operation of the equipment. Other information that may be present is contact information for emergency services, radiation safety officers within the organization, and qualified service personnel. They should also contain a description of the equipment and its use and the name of all personnel authorized to use it. SWIs may be maintained electronically and should also be displayed on or near the equipment itself.

All documentation including policy, procedures, and SWIs should be reviewed periodically as part of an ongoing surveillance and continuous improvement program and the revision number and date should be clearly displayed within the documentation.

31.2.3.2 Signage and Access Restriction

Laser safety signage should be clearly displayed at the boundary of areas where lasers are in operation and on the laser equipment itself. Information contained on safety signage should include the laser hazard symbol or the NIR hazard symbol for other optical sources, the type of hazard (e.g., the class of the laser(s), UVR source, operating wavelength, noise, and fumes), any imposed restrictions on access (e.g., list of authorized personnel), and the necessary precautions that have been determined to be necessary during use of the equipment (e.g., safety eyewear). Figure 31.1 shows examples of safety signage used for laser hazards.

31.2.3.3 Training

Employees should be informed of any hazards to which they may be exposed to when using laser equipment. Accredited laser safety training is available from a range of providers and should be undertaken by all personnel using laser equipment. This will assist in understanding the nature of the risks involved

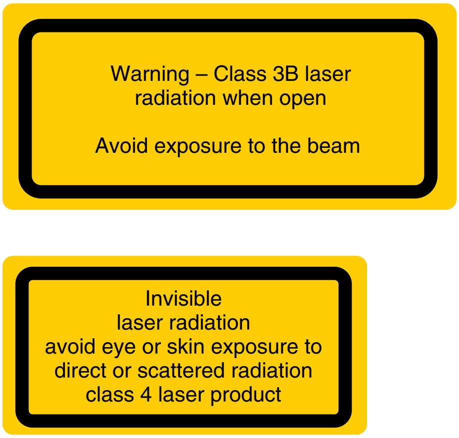

Figure 31.1 Examples of laser safety signage intended for use in laser work areas.

and increase awareness of the hazards and procedures required to minimize these risks. Such training generally covers but is not limited to;

- work procedures
- the risk and sources of harm that the use of lasers presents
- the appropriate use of PPE
- procedures followed for incident management and reporting
- safety warning signage.

Where Class 3B and Class 4 lasers are in use a laser safety officer (LSO) should be appointed within an organization. An LSO should be competent in the evaluation and control of laser hazards and has overall responsibility for managing the risks from laser use. The employer should ensure that the LSO is appropriately qualified and has conducted the necessary formal training for the position. The LSO's responsibilities may include the following:

- the general administration of laser safety matters
- monitoring of compliance with workplace policy and procedures
- keeping maintenance records of the equipment
- maintain appropriate training of users as necessary
- promoting continuous improvement of safety systems.

31.2.4 Personal Protective Equipment

PPE is the most basic element of risk management that individuals working with lasers can apply to minimize the risk of injury from exposure to optical radiation. The use of PPE is essentially the last line of defense when all other systems of risk mitigation fail to prevent an exposure. It is therefore not recommended to rely on PPE alone to reduce the risks when operating laser products.

31.2.4.1 Safety Eyewear

Safety eyewear is designed to protect against specific wavelength ranges of laser radiation. Depending on the lasers in use, multiple types of safety eyewear may be required. The material used to attenuate the laser radiation should have an optical density at the specific operational wavelength that is sufficient to reduce the transmission of radiation to below the maximum permitted exposure (MPE) (see Chapter 8). In Europe, there is an extra requirement that the safety eyewear has the ability to withstand the incident laser radiation. This is referred to as protective density. These criteria should be met under reasonably foreseeable circumstances as any extended or prolonged exposures may still result in eye damage even when wearing safety eyewear.

31.2.4.2 Skin Protection

Skin is able to withstand much higher levels of laser radiation than the eye. On some occasions where higher power lasers are used, protective clothing may be used to attenuate some of the incident beam. These may take the form of items such as laboratory coats and gloves.

31.2.5 Further Reading

For laser users' guide (IEC, 2004), further information on classifications (IEC, 2014), general safety in laboratories Standards Australia, 2004), and signage (Standards Australia, 1994), see the reference list. A standard text in the area of laser safety is Sliney and Wolbarsht (1980).

31.3 Strategies for Radiofrequency Field Exposure Reduction (Michael Bangay)

The previous chapters have established how high levels of RF electric and magnetic fields in the form of radiated waves can cause harm to exposed people. Authorities that are responsible for worker and public safety normally mandate mitigation for those applications of RF where high-level fields are created that have the potential for exceeding the relevant worker and public safety limits. It is important that migration measures reduce the exposure levels below the limits. The reduction of exposure should be achieved by a risk management process that enshrines the precautionary approach. Mitigation of RF fields needs to be part of a comprehensive approach that looks at all the safety aspects of working with high levels of RF fields including assessment, documentation, and hazard control measures. Figure 31.2, which is a common risk assessment chart, illustrates the required outcome of a mitigation

Likelihood	Consequence				
	Insignificant	Minor	Moderate	Major	Critical
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Medium	High	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Low	Medium

Figure 31.2 Typical risk assessment chart.

procedure where the desire is to reduce the possibility of exposure from high to low. A possible "extreme" scenario requiring urgent mitigation could be an unfenced AM radio transmitting tower located nearby residential dwellings, which could cause severe burns if contacted because of the high likelihood of occurrence with a consequence that could be described as critical. A "low" scenario could be a two-way radio transceiver antenna located on a tall tower in a remote location that gives rise to extremely low risk that does not require mitigation.

An example of a precautionary approach is described in the Australian RF standard (ARPANSA, 2002). This is to "minimize, as appropriate, RF exposure, which is unnecessary or incidental to achievement of service objectives or process or process requirements, provided that they can be readily achieved at reasonable expense." The outcome of mitigation of RF exposure needs to reflect the precautionary approach. Application of the five-step risk management process and five-step control process (Figure 31.3) recommended by ARPANSA (2002), will provide a sound basis for the mitigation of RF fields. The hierarchy of control has five levels of control measures, the most effective measure is at the top of the hierarchy and the least effective is at the bottom.

31.3.1 Applying the Hierarchy of Controls for RF Field Mitigation

31.3.1.1 Elimination

When possible, elimination of the radiating source is preferable. This may be possible if, for example, an industrial process using RF welding machines can be changed to impulse heating or similar thermal technology that does not use RF fields to weld. While radio services for broadcast and telecommunications are not able to be eliminated, consideration of alternative transmission technologies such as optical fiber technology should be considered. However, exposure to the radio's transmitting fields can be effectively eliminated by removing the radio's transmitting antenna from a location where it was causing the high exposure. In the case of a transmitting antenna, it will require the antenna to be relocated some distance either vertically or horizontally from the original position. Reduction of the RF field through relocation is aided by

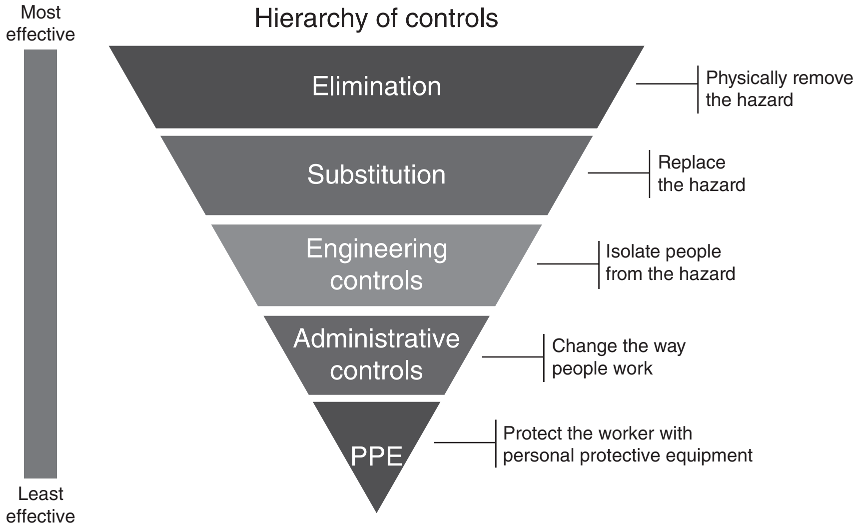

Figure 31.3 Five-step control process for risks. Source: NIOSH – U.S. Department of Health & Human Services.

the inverse square relationship that exists between RF power density and distance from the source. Figure 31.4 shows this relationship where the power density (*S*) at a distance *r* is the product of transmitting power (*P*) times the linear antenna gain (*G*) divided by 4 *π* times the distance (*r*) squared. This

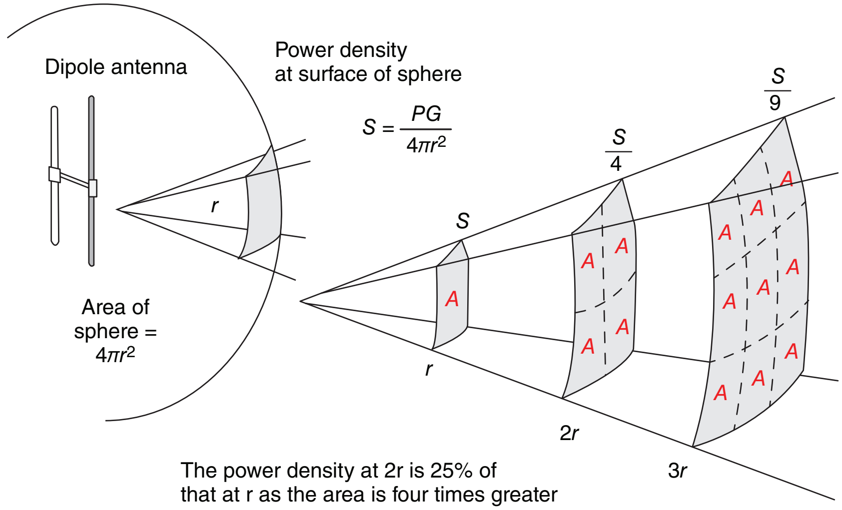

Figure 31.4 An illustration of the inverse square relationship in power density from a dipole antenna.

shows that the inverse square relationship will cause a fourfold reduction of power density when there is a doubling of the distance from the radiating source. Simply redirecting/repositioning the radiating antenna can also cause an additional reduction in exposure levels. The dipole shown in the Figure 31.3 has a directional pattern (Figure 31.5) that causes it to radiate out from the antenna and has minimum (null) signal directly above and below the antennas axis. Positioning a dipole antenna above an accessible area will result in a low level of RF exposure in the area below the dipole. Very directional antennas like a parabolic dish antenna can be safely mounted so that workers are not exposed to the potentially strong fields that exist in front of the dish.

31.3.1.2 Substitution

When elimination is not possible, mitigation can be achieved through the process of substitution. Reduction in high levels of exposure can be accomplished by substituting a high-power radiating source with a lower power source. During maintenance, high-power broadcast towers can either reduce the power to the antennae or turn off the power in the areas that need to be accessed by a technician. It is standard practice to arrange outages when riggers are working around otherwise live antennae. Contact information to arrange outages is usually provided by the site owner and documented in the safety information for the site. It is common practice at broadcast sites to switch the transmission to an adjacent tower to enable workers carry out their work on a tower that has no RF power fed to it.

Earlier RF heat sealers and welders required the operator to stand alongside the welding apparatus and hold the material being welded in place. This practice resulted in high levels of exposure as well as skin burns. By necessity, equipment manufacturers have mechanized the process with the result that the operator is no longer exposed. Wherever possible, mechanical apparatus, in conjunction with remote controls, should be used to prevent unnecessary exposure for an operator.

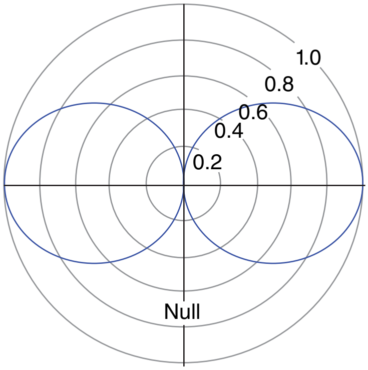

Figure 31.5 The directional radiation pattern from the dipole antenna shown in Figure 31.4.

31.3.1.3 Engineering Controls

This mitigation approach allows the potential hazard to exist but isolates people from hazard through engineering design. This can be the erection of fences, barriers, or by adding guards to equipment to keep people out of high exposure areas. Engineering controls can be expensive and restrictive and highlight the need for mitigation through elimination and substitution. Figures 31.5–31.8 show fences, barriers, and anticlimb devices that are used to control access to areas of high RF exposure.

Unearthed or poorly earthed metallic objects in the near vicinity of a radiating antenna can absorb and reradiate strong RF fields that can lead to overexposure and RF burns if contacted. The reradiation can be minimized if the object is well earthed using a broad copper strapping that is well bonded to either the equipment earth or earth stake (Figure 31.7). Radio frequencies in the HF and VHF band (3–300 MHz) are more likely to create this problem. These radio frequencies are associated with high-power RF welding equipment and broadcast radio/television services that further exacerbate the problem.

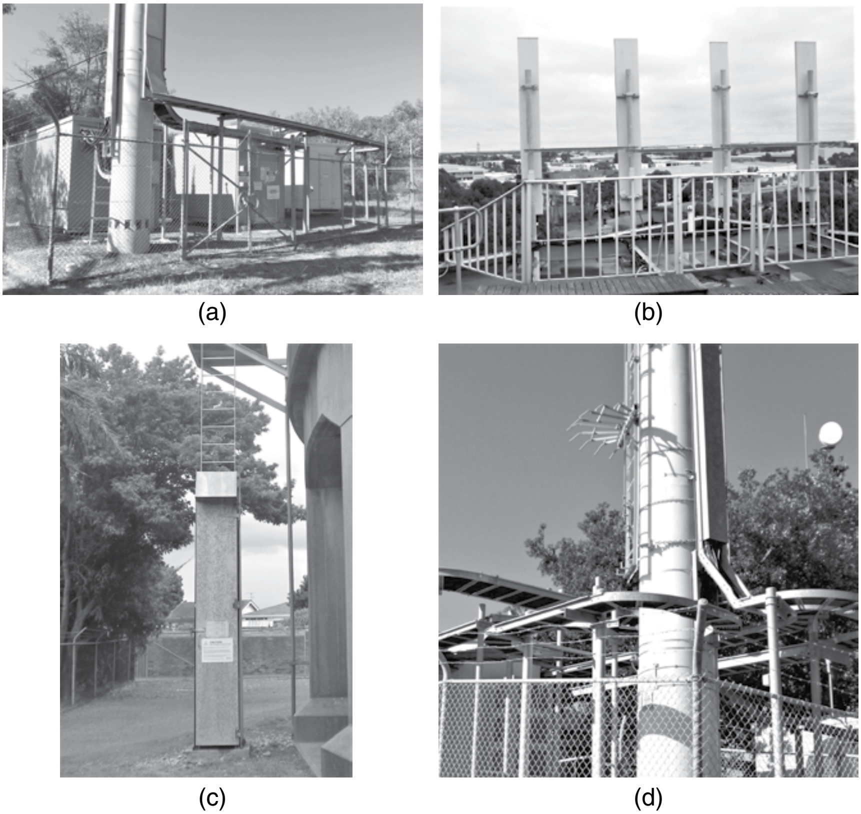
(a) (b) (c) (d)

Figure 31.6 Examples of access controls around telecommunications antennae: (a) fence, (b) barrier, (c) anticlimb enclosure, and (d) anticlimb spikes.

Figure 31.7 Earth strapping to minimize reradiation.

However, even well-earthed metal struts or mounting arms can generate high levels of reradiation if the metallic object is either a quarter wave length or multiple thereof of the frequency being transmitted. Reducing the length of these reradiating objects so as to be nonresonant will significantly reduce the level of reradiation.

The problem of unwanted strong RF fields caused by RF welding equipment can be largely overcome using shields (Figure 31.8) that prevent the spill of RF energy into the operator's work area.

The control measures discussed so far have addressed Occupational Health and Safety issues where the intention of the measures has been to reduce the

Figure 31.8 Mitigation of environmental signals by shielding: example of dielectric welder. Source: Image courtesy of Nemeth Engineering, Crestwood, KY.

RF exposure to either below the general public limit or occupational limit. Many people are concerned over chronic exposure to low-level fields and seek to mitigate the RF fields that exist in their homes due to broadcast, mobile phone base station, and other signal sources.

A reasonable measure of in-building signal level reduction can occur if the principles of Faraday shielding are followed. Faraday shielding requires the complete enclosing of an object in a conductive screen. Commercially available screened rooms for medical/scientific and test purposes can achieve in excess of a million times reduction at frequencies used by mobile telephones. Screening methods for the home use carbon-loaded paint, reflective foil insulation/solar film, and cloth that has metallic threads. This sort of screening can achieve about 100 times reduction, provided all walls, doors, and windows of the building are properly covered.

31.3.1.4 Administrative Controls

Mitigation of RF levels can quite often be achieved by getting people to change their work practices. This may be as simple as asking an RF welder operator to step backward away from the welding electrode when a welding operation is about to begin. It may also include limiting the time a person is exposed to RF fields as the safety standards generally allow averaging of a 6-minute period. For example, a welder operator who is exposed to power density levels six times over the limit will not exceed the 6-minute time-averaged limit if they reduce their exposure time to 1 minute.

Administrative controls are changes to the way people work and where possible used in conjunction with the higher order controls discussed earlier. Administrative controls include procedure changes, employee training, and installation of signs.

It is a work place requirement that workers exposed to RF fields that exceed the general public limits are managed by a risk management process. This process should result in a number of outcomes that include an RF safety manual, training, and signage. Workers planning to enter a site that has high levels of RF fields should perform a Safe Work Method Statement or Job Safety Analysis (SWMS/JSA) to manage their exposure.

31.3.1.5 Personal Protection Equipment (PPE)

While every effort should be made to mitigate the exposure to RF fields, there are situations where people may be required to continue to work in the presence of strong fields. The use of PPE that includes rubber-lined gloves (current burns), RF personal monitors, and special clothing may provide the needed protection from potentially hazardous RF fields and contact currents. The use of PPE is the least effective means of controlling hazards as it relies on the correct use and serviceability of the PPE. PPE should only be used when a prospective user has been adequately trained.

31.4 Mitigation Strategies for ELF Electric and Magnetic Fields (Thanh Dovan)

In Chapter 25, the principle underlying "Prudent Avoidance" strategies was summarized as "doing what can be done without undue inconvenience and at modest cost to reduce fields." This section reviews practical methods for doing this. The detailed strategies are beyond the scope of this chapter, but the chapter includes a list of useful resources where additional information can be obtained if required. These resources include the use of computer modeling to predict what the field values might be, especially in occupational areas where the fields are expected to be high, and also in the design of new infrastructure, as a way of minimizing exposure or avoiding unnecessary exposure, following the principles of Chapters 25 and 26.

The use of high-voltage conductors or wires and equipment in open-air creates environmental *electric* fields in areas under powerlines and in switchyards or substations. In broader living and working environments, smaller electric fields are produced by electrical wiring/lightings and electrical equipment and appliances. Similarly, electric currents flowing in both wires/cables and equipment/appliances create *magnetic* fields in the surrounding environments. These fields can in turn, via electric or magnetic induction coupling, create voltages and currents in adjacent living systems as well as physical objects including electronic equipment and communications, water, and gas infrastructure.

31.4.1 Environmental Electric Fields

Inside residences, ambient electric fields typically range from few volts per meter to few tens of volts per meter and can be higher near lighting/wiring and some electrical appliances. Depending on voltages, measured electric fields directly under high-voltage transmission lines and in switchyards/substations typically range from one to several kilovolts per meter and, in occasional locations, up to 10 kV/m. In terms of predicting the electric field by calculation, it is not a straightforward process. However, it is important for the understanding of reduction strategies to theoretically examine the influences of principal parameters such as voltage, distance on the predicted field level associated with the electric field source. Some discussion on the topic is given in Chapter 19. A simplified calculation can be used for simple cases such as a straight conductors (infinitely long and parallel to the ground) using the "equivalent charges" method. This approach is outlined in Appendix A. Note that, in general, the electric field is not given by simply dividing the conductor voltage by the distance the conductor is off the ground (e.g., the field below a 400-kV transmission line, with conductors 8 m from the ground, will be much less than $400/8 = 50$ kV/m, due to a number of factors, including phase cancellation).

31.4.2 Environmental Magnetic Fields

The widespread use of electricity in the distribution networks including grounding systems using water pipes, the earth, and metal building frames has created a ubiquitous magnetic field environment ranging from a fraction of a microtesla (μT) in most cases to much higher levels in order of millitesla (mT) next to appliances and electrical equipment. The magnetic flux density (MFD) due to a general current-carrying element at a point in space can be calculated using the well-known Biot–Savart law available in many physics and engineering texts. In a three-dimensional, multiphase, and multiconductor system, calculation procedure is lengthy and is effectively handled by computer modeling. To a good degree of accuracy, typical MFD sources can be presented in forms of single-conductor, two-conductor (dipole), multiple-conductor (quadrupole), and three-phase-line sources. Simplified equations for calculation of MFD associated with these sources are discussed in this section to illustrate various aspects of magnetic field reduction strategies (Kaune and Zaffanella, 1992).

It is important to note that the MFD associated with the "reversed-phase" or "low-reactance" double-circuit line in a balanced three-phase system (see Chapter 25 for further explanation) is inversely proportional to the cube of the distance from the conductors to the point of measurement (D^3) rather than squared distance (D^2) as in the case of a "same phasing" double-circuit line; hence, the MFD falls off more rapidly with distance, as shown in the graphs in Chapter 25 (See Appendix B in this chapter).

A number of computational tools (modeling software) are available to assist in the estimation of both electric and magnetic (see Appendix B of this chapter) fields for more complex configurations. These tools allow for the optimization of parameters at the design phase to ensure the most effective mitigation strategies. More specific strategies are described in the following sections.

31.4.3 Electric Fields - Reduction and Mitigation Strategies

Extra high-voltage (EHV) switchyards of several hundreds of kilovolts (kV) or higher were built in response to the much higher capacity for bulk transfer of electrical energy the higher voltages offer. This has created a working environment with higher electric fields for HV substation workers. In such electric fields, in addition to the buzzing noise from corona on the surface of energized equipment, the sensation or perception of the electric fields due to vibration of skin hairs, painful shocks can also occur in the working environment. These capacitive-discharge shocks are discussed further in the following paragraphs.

As environmental electric fields are principally created in the region between objects carrying different charges (e.g., having different voltages), by introducing a shielding object or structure in between the two original objects, the electric field between the shielding object and the ground will be eliminated as there is now no charge-difference exists in shielded region. This type of shielding method is commonly used in electrical/electronic equipment due to their small sizes and the shielding can be incorporated at the production stage, but this approach has only been used in a limited manner in applying to existing electricity infrastructures.

For a typical overhead transmission line, its conductors are energized with a voltage of several hundreds of kilovolts and a vertical electric field established between the conductor and the earth plane. As discussed in the following section, a person (or any unearthed object) acts as a capacitor in the field and will acquire an electrical charge. An electrical discharge can occur if a person and another object (including another person) come into contact (in fact, just before contact, in the form of a spark).

For safety reasons, minimizing spark discharge effects including avoidance of startle reactions is important in the design and operation of HV systems. The mitigation techniques can be carried out by firstly dealing with the design of the sources of electric field, secondly by shielding or reducing the electric fields at locations of interest, and thirdly by preventing/providing alternate conductive paths for the charge transfer/touch current or reduction of capacitive coupling. The latter approach includes mitigation through earthing, bonding, using protective clothing, applying working practices, training, and information program. These mitigation methods will be briefly discussed. Further details, along with a number of case studies, can be found in other sources (CIGRE, 2016; EPRI, 2005).

31.4.4 Electric Field and Charge Transfer Phenomena

31.4.4.1 Capacitance and Coupled Voltage

In the vicinity of air-insulated conductors of a transmission line, a capacitor is naturally formed between the line's overhead conductors and the earth plane or any nearby conductive object. The capacitance of such a capacitor is determined by the distance from the conductors and the size/effective area of the object. In the case that the object is isolated from the earth another capacitor is also formed between the object and the earth plane, and the value of this capacitance is principally determined by the size of the object involved (e.g., car, truck, fence, or tank).

In a similar pattern for a person with footwear under a transmission line, there would be an electrically equivalent "line-person" capacitor and a "person-earth" capacitor. These two capacitors in series, acting as a voltage divider between the overhead-line and the earth, couple a voltage onto the person/object that is not physically connected to the conductor (see Figure 31.9). It is often referred to as "induced' or "capacitive coupled" voltage on the person or object. The net charge existing on a person or an object will be redistributed or transferred when contacts are made between person/object leading to a number of scenarios of spark discharging and contact current. The term "capacitive coupled" voltage will be used in this chapter to differentiate from the

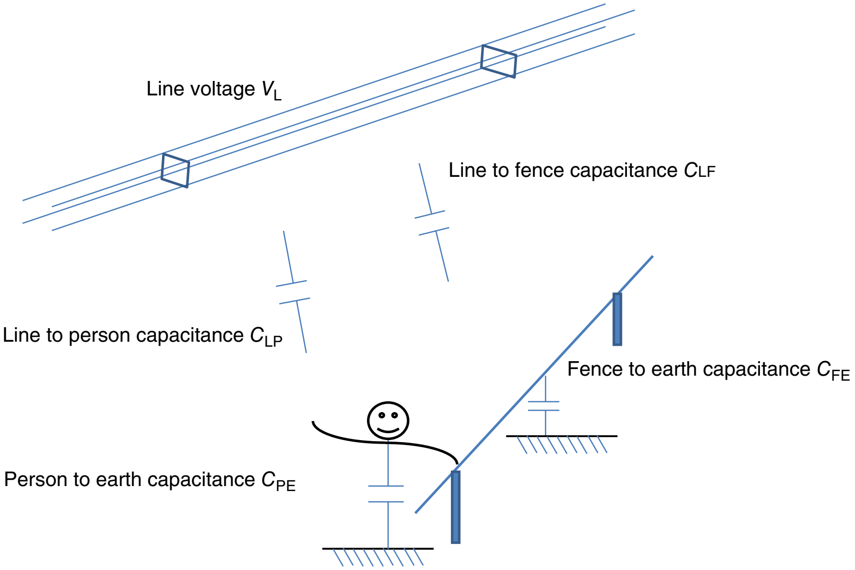

Figure 31.9 Showing a typical scenario of a person touching an unearthed metal fence below a transmission line. See Table 13.1 for typical values for C_{PE} and C_{FE}. C_{LP} and C_{LF} values are usually about 100 times smaller.

"magnetically induced" voltage on an object from the electric current flowing in the transmission line under load/fault conditions.

In the case of human contact, the typical charge transfer via finger or skin at first instant as a spark with a short submicrosecond transient current (in order of amperes) followed by a small steady-state current a fraction of a milliampere) on full touch/contact. Depending on the amount and pattern of the transient charge transfer (coupled voltage level, capacitances, touch method, etc.), the sensory effect can range from perception, annoying/discomfort shocks to painful muscle reaction.

In relation to transmission line capacitive coupling, because of the larger distance/separation involved, the "line-object" capacitor would be much smaller than the "object-earth" capacitor. For example, in case of a fence under a transmission line, the "line-fence" capacitance would be in order of few percent(%) of the "fence-earth" capacitance. Similarly, the "line-person" capacitance would be much smaller than the "person-earth" capacitance leading to a small proportion of the line's voltage developed on the person with reference to earth. Typical capacitance values of some common items under transmission lines are illustrated in Table 31.1.

31.4.4.2 Spark-Discharge Scenarios and Locations

Typical locations associated with electric transmission system where such spark discharges and contact currents can occur are presented in Table 31.2.

Table 31.1 Capacitance values of typical objects.

Object/structure	Typical capacitance	Note
A person	100–200 pF	Insulated shoes
Car	1000–2000 pF	On nonconductive tires
Bus	3000–5000 pF	On nonconductive tires
Wire fence (100-m long and 1 m above ground)	500–1000 pF	On wooden post

31.4.5 Electric Field and Spark-Discharge Mitigation Techniques

31.4.5.1 High-Voltage Transmission Lines

Various mitigation techniques have been developed over the years for the management of electric fields for their effects on human safety, as well as for fuel-ignition fire risk and other compatibility issues (EPRI, 1996, 2005; CIGRE, 2016). This section focuses on mitigation measures relating to spark-discharge effect on humans and common methods that have been used ranging from design, shielding/screening, earthing, operations and maintenance (O & M) practices, and lastly miscellaneous means of training and public information programs.

Table 31.2 Locations of potential discharges.

Installation/activity	Location/situation
Transmission line	Fence and gate, parked vehicles
Easement	Using umbrella, riding bicycle/horse
General Public (residential/commercial areas)	Bus stop, playground, sport ground Fuel-filling station Clothes line, person to person Person to earthed/unearthed object
General usage (construction/road work)	Structure, metallic road barriers/rails Machinery/earth-work vehicles Above-ground work Loading/unloading from vehicle
Farming/agriculture	Trellis, electric fence Equipment and machinery Bee hives
Transmission lines: climbing and working on towers	General maintenance work Insulator washing from tower

31.4.5.1.1 Design and Screening

For a given coupling condition, the level of spark-discharge effect is proportional to the magnitude of the unperturbed electric field at the location of interest governed by the separation or height of HV equipment in a substation or of conductors above ground.

A number of mitigation measures are illustrated in the transmission line case studies presented in Table 31.3. It is important to note that raising conductor height of an existing transmission line, whether by increasing tower height or number of towers, can pose significant problem in term of cost and visual impact. In term of physical design of towers, added mesh/frames to the tower structure can reduce electric fields in the "window area" near conductors. A climbing ladder built inside the tower structure is also another practice for reducing electric field effects associated with tower climbing.

Behind or below an earthed shielding structure or screen, there is no longer any capacitive coupling to the overhead conductors and thus, the possibility of spark discharges or annoying contact currents is practically eliminated. In the case where mitigating of the field source is not feasible, reduction of electric fields at locations of interest can be a most applicable option for situations developed after the installation. In practice, the size, shape, and construction method for the shield/screen vary depending on the required protection and the relevant situation. Stringing of earth/ground wires under the transmission line's conductors for mitigation of ground-level electric fields has been presented in a few analyses as a general area shielding methodology, depending on the availability of clearances and spaces. Alternatively, one of the less complex shielding approaches would be to use a freestanding structure. It is important to assess clearance requirements and other O & M short and long-term constraints in all cases prior to shielding/screening installation.

Table 31.3 Conductor height, electric field, and impacts.

Case	**Additional height**	**Cost/impact**
Existing 400 kV lines ~8.1 m (farmland and general road) 9 m (high-usage roads)	Extra 2–4 m height required for 2.5 kV/m design • By higher towers	For retrofitting: practical difficulty with large cost and visual and other impacts
10 m (recreation area)	• By shorter spans	For retrofitting: practical difficulty with large cost as more towers and land required and impacts to existing landscape and land availability
Contemporary horizontal single circuit 500 kV lines of 12–13 m conductor height	Newer lines with conductor height increased to 15+ m for 5 kV/m compliance	Higher towers required. New design feasible with moderate cost increase

31.4.5.1.2 Earthing and Bonding

In addition to dealing with electric field sources or reduction of electric field at locations of interest, mitigation of charge transfer/spark discharge can be managed by providing alternative current paths or controlling the current flowing through control of touch/contact points and their associated impedance and elimination of the relevant capacitive coupling through earthing or bonding.

Earthing of objects such as fence wires and other structures is one of the simpler methods compared to others. For *electric* fences, this connection must be removed while the electric fence is in use and the connection is to be re-established when the electric fence is turned off. Alternatively, a 50/60 Hz by-pass filter can permanently facilitate the earthing process. Flexible earthing for moving structures/objects (e.g., dragged chains or flexible straps) can be used. Conductive clothing, harnesses, and footwear can also provide means for mitigation of spark discharges on a personal level.

Live working on substation equipment or conductor of transmission lines involves bringing objects such as work platform and persons (in conductive clothes) to close proximity of energized conductors. Bonding or temporary connections will equalize the voltage on all items, hence will eliminate charge transfer while working.

31.4.5.1.3 Working Practices, Training, and Information Programs

Grasping contact (as opposed to touch contact) provides a larger contact area, spreading current (and possible heating) over a larger area/volume of tissue. This reduces the local current density and it can also increase the contact skin resistance. Grasping contact resulting from awareness of spark discharge also reduces the probability of multiple discharges. Since current thresholds for perception and pain are greater for grasp contact (Reilly, 1992, 1998), a grasp/touch ratio of 2 has been used in contemporary standards/guidelines. In some utilities, information on elevated electric field locations and grasping contact when working in high-voltage substations and climbing towers of transmission line has been included in training and work practices to avoid discomfort associated with spike discharges. Information such as electric field contour drawings for ground-level working and certain above-ground working locations in substations can be posted at individual substations to provide relevant electric field data. Additional signage can also be used to reinforce the information on site.

Spark discharges associated with bicycle riding have been reported to several transmission utilities where riders experienced electric shocks when riding past or under overhead HV transmission lines. A common spark-discharge scenario occurs when a rider, initially electrically isolated from the bicycle (e.g., nonconductive seat, handlebar grips, and insulating gloves), makes contact with the bicycle's frame causing a spark discharge, between the rider and the bicycle causing the reported "shock." The contact can occur when fingers brush against the brake lever, or upper thigh touches bicycle seat/frame while pedaling. To a rider not aware of the spark-discharge mechanism, the experience can be painful and/or startling because it is unexpected and not understood. This would not occur if the rider was either insulated or alternatively in contact with the bicycle the whole time while by keeping hand/fingers on the brake lever or metal part of the bicycle. Public information/education is an effective mitigation method for this and reporting to the relevant utility should be encouraged for further investigation/mitigation.

Similarly, the mitigation process discussed earlier can apply to reported cases for horse riding and horse keeping under transmission lines. Under the influence of the electric fields, there is potential for spark discharges between rider (unearthed and wearing clothes) and the horse's body. In a few examples, residents have reported that horses (both with and without a cart) seem uncomfortable (bucking and jumpy) under transmission lines. It is not known what the mechanism is, as experimental investigation is difficult to carry out. It is suspected that this will occur in an area of elevated electric field (5 kV or higher) due to charge transfer/spark discharge between horse and cart or metallic object such as mouth bit and rings (e.g., cart on nonmetallic wheels and metallic mouth guard). General shielding or earthing may not be practical and public information on electric field effects including spark discharges can help to manage these cases.

In summary, there is a wide range of scenarios in which spark discharges can occur in both occupational and general public setting. Principal parameters involved are levels of equipment voltage and electric field, distance/separation from the source, size of object, the degree of capacitive coupling, characteristics of the discharge path (particularly its impedance), and contact area. Various mitigation methods have been developed by a number of electric utilities to manage both the electric field sources and spark discharge scenarios. Depending on the case involved, costs and impacts of mitigation are generally low, in particular when of mitigation can be done as an integral part of the design and can generally be low in cost compared to the overall project cost.

31.4.5.2 High-Voltage Substations

In an occupational environment, elevated electric fields exist in certain locations in particular areas under busbars/equipment of HV substations/switchyards. Mitigation methods in this section are discussed in Sections 31.4.5.2.1–31.4.5.2.3.

31.4.5.2.1 Design

The principal parameter for minimization of electric field at a location away from the conductor would be the conductor-object distance.

In electrical facilities, electric potentials (voltages) on overhead air-insulated equipment, busbars, and conductors produce electric fields in regions between the equipment and adjacent earthed structures and the earth surface. Due to complex geometry of equipment and support structures, the distribution of ground-level electric field in a station is spatially nonuniform and has localized maximum locations. Although system voltage and the overall physical layout will determine the resultant field levels, the major influencing factors are the voltage and the height above ground of equipment and busbars. Conventionally, physical and other electrical requirements of substation design can also govern the basic layout of station equipment including their heights. Computer modeling can readily be carried out at the design stage while field measurements can be conducted in existing installations for electric field evaluations. Ground-level electric fields commonly can be controlled by selecting height of busbars while managing of local peak electric fields can be further achieved by equipment layout and phasing arrangement, as in the case for transmission lines.

31.4.5.2.2 Shielding/Screening

The approach is similar to shielding and screening approaches for transmission lines, discussed earlier.

31.4.5.2.3 Earthing of Structures and Other Means

For substation work, there are a number of specific approaches to earthing, but these are similar to those used in transmission line situations, described in the previous section. Firstly, bonding or temporary connections will equalize the voltage on all items hence will eliminate charge transfer while working; secondly grasping rather than touch contact and thirdly, the availability of field contour maps, signage, and other information.

In general, the causal mechanism for spark discharge, while technically well understood and explained, is often not known to the general public or nonutility workers, so training and educational programs can offer effective managing means. Spark-discharge scenarios associated with working above-ground levels in HV substations are less known and mitigation methods should be considered as a part of work plan to avoid ad hoc solutions to be applied on site.

31.4.6 Magnetic Fields – Reduction and Mitigation Strategies

The complexity of equipment, wiring, and cable arrangements in the electric distribution system, including the grounding networks, makes it difficult to generalize common solutions to specific situations. In practice, field reduction associated with existing installations has been largely dealt with on a case by case basis. A balanced approach taking into account considerations such as selection of suitable locations; shielding of equipment or installation, hardware modification, and effective building space usage can provide effective reduction solutions. For new installations including transmission and distribution lines and cables, appropriate design and installation practices at the outset can reduce or eliminate subsequent modifications.

Research on magnetic field reduction design has mainly been focused on transmission lines using alternative configurations, phase splitting, phase conductor compacting, and field cancellation by impressed shield currents. The possibilities and constraints of field reduction methodologies need to be evaluated at the outset due to significant implications on the design, performance, and financial impacts of various proposed field reduction schemes (Burke, 1991). Research on the use of high-phase-order transmission lines has also been investigated for MFD reduction design options (Day, Steinar, and Klein, 1993). Development of active and passive cancellation techniques has also occurred, due to its appeal when applied to only short sections of line where required (Spherling et al., 1996). Optimization of line configuration and use of shield or ground wire/conductors with and without controlled currents have been studied. In one of these investigations, a significant field reduction was obtained for a section of 400 kV line for about 20% increase in cost (Tsanakas et al., 1994). Walling et al. (1993) reported a series-capacitor compensated overhead shielding loop encircling a transmission line could provide substantial MFD reduction on and off the easement/right-of-way.

31.4.6.1 Shielding of MFD Sources or Electrical Installation

Techniques for shielding of MFD sources and development of power frequency shielding materials have also been investigated (EPRI, 1993a,b; ESAA, 1996). A review of European research into techniques to control ELF magnetic fields by conductor arrangements and various shielding methods was presented by Conti (1996).

Shielding of MFD sources or the rooms they are in can be used to significantly reduce the MFD level external to the sources. However, for physically large magnetic field sources such as substation cables, transformers and switchrooms, this often poses a costly option. The shielding efficiency is dependent on the extent of the shielding carried out (the geometry of the shielded region), the thickness, and 50/60 Hz magnetic property of the shield material. Ferrous and/or conducting materials can provide some degree of shielding by the induced current effect. Higher permeability materials such as Supermalloy, Permalloy, or Mumetal provide higher shielding efficiency; however, their costs are often prohibitive for large installations. In some cases, lower cost conducting materials of medium permeability such as copper, Galvabond sheets, or large laminated transformer steel sheets in composite or multilayers can be used for large shielding areas. Progress has been made on development of more highly efficient multilayered shields that consist of alternating high conductivity and high permeability materials.

Careful considerations must be given to effects of induced currents in shielding material, shield configuration and its support, shield joining, and edge effects where high localized fields can be inadvertently introduced. In addition, while it is possible to theoretically predict the shielding efficiency or the MFD attenuation afforded by shielding materials, the analysis can be difficult and sometime inaccurate due to the complex physical arrangement and the multiple MFD sources found in installations such as building substations or large main switch rooms.

31.4.6.2 Relocation/Modification of MFD Sources or Installation

This is often the highest cost option for an existing electrical installation. The scope of work and the cost vary considerably depending on the number and types of MFD sources involved and the required field attenuation. Feasibility investigations including cost estimates are necessary when this type of option is selected. A general procedure to conduct such an investigation is discussed in the following:

Initial magnetic field measurement survey: Detailed magnetic field measurements are conducted to identify major contributing magnetic field sources and areas with ambient field levels above a target-field level.

Determination of field reduction target level and affected areas: This step requires the determination of a magnetic field target level (e.g., 1 μT or 10 mG) for the control of external interference. The affected areas that require field reduction can then be identified from the results of the initial magnetic field survey together with considerations of office space usage requirements.

Examination of field reduction options: This stage involves theoretical and engineering calculation for the development of practical field reduction options including reconfiguration and shielding of the installation to satisfy the requirements set out in the abovementioned steps. Laboratory tests on cables and equipment relocation and rephasing or shielding can also be set up to simulate the theoretically developed options.

Feasibility and cost estimate of field reduction options: Development of field reduction options often involve hardware modifications or changes to the building electrical supply system. Electrical system designers and building owners will need to assess the costs and the feasibility of the field reduction options for other electrical constraints and building requirements before any field reduction modifications can take place. This is an iterative process, as inputs and feedback are required from different groups to achieve optimal solutions.

Implementation of field reduction scheme: Modifications or changes of hardware for the selected field reduction scheme. During this stage, interruption to the building electricity supply may occur unless an alternative supply is available.

Final magnetic field measurement survey: A second magnetic field measurement survey is needed to characterize the ambient magnetic fields after the completion of the field reduction scheme and to assess the effectiveness of the mitigation scheme.

31.4.6.3 Location of MFD Sources – New Installations

One of the parameters having significant influence on the MFD levels at location of interest is the distance to magnetic field sources. Elevated exposure thus can be avoided by placing major MFD sources away from areas that can be potentially used by people and this can be considered with minimal impact to the building or electrical installation design. For example, in a new indoor substation high current cables, fuse racks and isolators or overhead powerlines outside office buildings should be placed as far as possible from high occupancy areas.

31.4.6.4 Line/Cable/Equipment Configuration and Layout

In multiple three-phase plus neutral conductor applications, phase sequences and separation distances have a significant influence on the resultant field at given locations. Design considerations to take this advantage should be used providing the procedure is consistent with other electrical and mechanical design constraints.

Transmission line configuration: As it was pointed out in Chapter 25, the reversed-phase arrangement on a double-circuit transmission line can reduce significantly the associated MFD. In general, design considerations taking into account double-circuit configuration, phase sequences, split phase, compact form, and so on can be used for magnetic field reduction purposes. Magnetic field reduction methods for overhead transmission lines using passive and active loops or shield wires developed for general field reduction applications can also be considered for mitigation purposes (EPRI, 1996).

Shielding: In some instances, shielding of equipment or of substation cables can be implemented at the building construction stage to obtain the required mitigation.

Load balances: In three-phase applications, additional MFD is produced by the neutral current due to the load imbalance of the system. The MFD level at a given point is directly proportional to the neutral current and the distance between center of phases and the neutral conductor and inversely proportional to the square of the distance to the source. Depending on the degree of the load balance, this will result in elimination or reduction of the MFD component produced by the neutral current.

Grounding/earthing: Inevitable neutral currents can flow in grounding networks and faulty neutral clamps can also cause unwanted ground currents. In some cases, significant MFD sources are created by these ground currents. Design considerations should be given to elimination of ground current path or loop near protected areas.

31.5 Conclusion

The three areas of nonionizing radiation discussed in this chapter are concerned with sources over which there is some scope for control (as opposed to UV from the sun, for example). The first line of mitigation is to consider the power levels required to deliver service or function and not to exceed these unnecessarily. In this regard, ELF is somewhat different since the fields are a by-product of the transmission and distribution of electric power, whereas for lasers and RF, the radiation itself is delivering service or function. For ELF, the reduction of fields via phasing arrangements and consideration of earth loops is clearly a way to achieve mitigation of field intensities without compromising power delivery. Screening also has a place in ELF mitigation and in laser safety (the latter also allowing the complete enclosure of laser beams), but in the case of RF, the wide dispersion of electromagnetic energy is often the main requirement. However, beam formation and gain control (such as occurs in mobile phone handsets to extend battery life) contribute to reduction of unnecessary exposure. On the other hand, in RF welding equipment where the energy is localized, screening is an effective measure. Mitigation inevitably brings in extra expense and Chapter 27 discussed some important considerations on the balance between costs and benefit. Nevertheless, if there are low or modest cost options available to reduce unnecessary exposure or the possibility of accidental overexposure, they should be implemented, even if the detriment to human health caused by these exposures is uncertain.

Appendix A Method of Estimating Electric Field Values Associated with Straight Conductors (Assumed to Be Infinitely Long and Parallel to the Ground)

Effectively, this approach is to perform a calculation firstly of the equivalent charges per unit length of conductor and then the electric field produced by these charges.

The general relationship that is used to calculate the charges carried by the conductors of a multiconductor line is the matrix equation is

$$\{\boldsymbol{q}\}=[\boldsymbol{C}]\{\boldsymbol{V}\}$$

where $\{\boldsymbol{q}\}$ and $\{\boldsymbol{V}\}$ are the single-column matrices of the charges and potentials of the conductors (the ground being at zero potential) and $[\boldsymbol{C}]$ is the square matrix of the characteristic and mutual capacitance coefficients.

Once the charges per unit length are determined, the intensity of the electric field is calculated by means of Gauss's theorem $E=\frac{q}{2\pi\varepsilon_0 p}$, where p is the distance from the point at which the field is calculated to the conductor, carrying charge q per unit length. A fuller discussion of this approach can be found in Bonwick et al. (1993).

Appendix B Simplified Equations for Estimating Magnetic Fields Near Long, Straight Conductors

Single-conductor source: The MFD source of this type would be a single cable or a net current in a group of cables including ground currents in water pipes or the earthing system. In certain cases, the ground currents (which cannot be identified or located easily) can be a major source of magnetic fields. The simplified equation for calculating of MFD for the single-conductor source is

$$B = \frac{2I}{D} \tag{B.31.1}$$

where

B = Magnetic flux density in mG (1 mG = 0.1 μT)
I = Current in A
D = Distance from conductor to point of calculation (m)

The field level at a given point away from such an MFD source is directly proportional to the current (or the net current) and inversely proportional to the distance to the source (D). The units come about because of a factor $\mu/2\pi$ or $4\pi \times 10^{-7}/2\pi$, where μ is the permeability of free space. In SI units, this formula becomes $B = 0.2 \times I/D$, with the answer in microtesla.

Two-conductor source (dipole): In case of a two-conductor source with a small conductor separation (a typical single-phase application), the simplified equation for calculating of the MFD at a given point is

$$B = \frac{2Id}{D^2} \tag{B.31.2}$$

where d is the dipole conductor separation distance (m).

Since the MFD is inversely proportional to the square of the distance (D^2) to the source, the distance in this case has a stronger influence on the field attenuation pattern compared to a single-conductor or a net current situation.

Multiple-conductor source (quadrupole): This type of MFD source is equivalent to two dipoles or two sets of two-conductor source.

$$B = \frac{4Idd_{12}}{D^3} \tag{B.31.3}$$

where d_{12} is the separation distance between two dipoles (m).

MFD sources such as electrical devices or appliances exhibit this type of rapid field attenuation ($1/D^3$) pattern.

Three-phase distribution line source: For a simple three-phase line (ABC or "Red White Blue") without neutral and earth current, the MFD at a distance from the line can be estimated by

$$B \approx \frac{\sqrt{2}I}{D^2}\sqrt{d_{\mathrm{AB}}^2 + d_{\mathrm{BC}}^2 + d_{\mathrm{AC}}^2} \tag{B.31.4}$$

where

I = Phase current in A
D = Distance from conductor to point of calculation (m)
$d_{\mathrm{AB}}, d_{\mathrm{BC}}, d_{\mathrm{AC}}$ = Phase separation distance (m)

The MFD at a given point is inversely proportional to the squared distance (D^2) and is also dependent on the line root-sum-square (RSS) phase separation. A more compact overhead configuration would result in a smaller line RSS phase separation and thus a lower MFD for a given line with the same load current. In the case of insulated cables, the RSS phase separation is very much smaller due to the small cable separation.

Three-phase transmission line source (double circuit): In case of a single circuit transmission line, the MFD at a distance from the line can be estimated using equation (Eq. (B.31.4)). For a double-circuit line with same current and same phase sequence (ABC, ABC) for both circuits, the following formula can be used:

$$B \approx \frac{2kI}{D^2}\sqrt{d_{\mathrm{AB}}^2 + d_{\mathrm{BC}}^2 + d_{\mathrm{AC}}^2} \tag{B.31.5}$$

where $1.0 < k < 1.4$ (*line configuration or geometry factor*).

On a double-circuit line where the phase sequence of the two circuits is *reversed* (ABC, CBA), the MFD at a distance from the line can be estimated by

$$B \approx \frac{4I}{D^3}\left(d_{GM} \times d_{12}\right) \tag{B.31.6}$$

where d_{GM} *(line geometric mean phase separation)* = $(d_{\mathrm{AB}} \cdot d_{\mathrm{BC}} \cdot d_{\mathrm{AC}})^{1/3}$, d_{12} = *distance between two circuits* (m)

Tutorial Problem

1 A single cable carries 400 A. Using the formula $B = 0.2 \times 10^{-6} \times I/D$, show that the field at a distance of 20 m from this cable is 4 μT. Now, use Eq. (B.31.4) to show that, for a three-phase system with the three cables 2-m apart, each carrying 400 A, the field at the same location is reduced to 0.5 μT (5 mG), approximately.

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32

Some of the Controversies Regarding NIR

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32.1 Why Should NIR Attract Such Controversy?

From earlier chapters, it should be evident that, at the levels encountered in daily living, it has not been proven that non-ionizing radiation (NIR) (with the possible exception of UV) poses a major risk to human health, even allowing for possible links to hypersensitivity or cancer. Unlike ionizing radiation, which in the public's mind is generally understood to cause DNA damage and which is perceived only to be encountered in hospitals or nuclear power plants, NIR is ubiquitous and is an integral part of modern everyday living. Suggestions that familiar items of modern technology such as power transmission assets and mobile phones and base stations are harmful to human health are understandably bound to cause public and media controversy, especially if the technology is perceived to be imposed on people, especially children. On the other hand, solar UV exposure has existed since the dawn of time. This chapter summarizes some of the controversies in recent decades. Unlike the rest of the book, the topics will be in descending order of wavelength rather than frequency.

32.2 Extremely Low Frequency

The year 1979 saw the publication of the Denver study on electrical wiring configurations and childhood cancer (Wertheimer and Leeper, 1979): however, wire codes were seen as being poor surrogates for magnetic fields, and the finding was received with some skepticism. However, at roughly the same time,

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some early epidemiological studies of electrical workers reported a raised cancer risk (reviewed in AGNIR (2001) and IARC (2002)), which prompted a repeat of a study in the Denver area, using more rigorous estimates of historical magnetic field exposures. This study gave broadly similar results (Savitz et al., 1988). A few years later, a study in Sweden (Feychting and Ahlbom, 1993) was published in which the entire study population was within 300 m of transmission lines and in which estimates of magnetic field exposures from both measurements and calculation were used, further strengthened the notion that the association was not spurious, despite the lack of coherent mechanistic or long-term animal data. The two combined analyses of 2000 (Ahlbom et al., 2000; Greenland et al., 2000) were highly influential in the IARC "Possibly carcinogenic" classification for extremely low frequency (ELF) magnetic fields in 2002 (see IARC (2002) and Chapter 20). Subsequent to this, the large UK study (Draper et al., 2005) showed associations between power lines and childhood leukemia at distances where the magnetic field is indistinguishable from background, which weakened the hypothesis of the magnetic fields being causative.

Nevertheless, the search for a credible mechanism gave rise to the "Melatonin Hypothesis", (Reiter, 1991), which connected pineal gland sensitivity to the geomagnetic field alterations to decreased levels of its principal secretion, melatonin. The free radical scavenging properties of this compound were linked to possible anticancer function (Stevens, 1987) (Stevens, Wilson, and Anderson, 1997): for a number of years, this hypothesis provided hints of a possible mechanism (although the nature of the "magnetic field receptor" was never identified (Wood et al., 1998). By the time of the US Government EMF-RAPID review (Portier and Wolfe, 1998), because of the high (and unphysiological) levels at which melatonin displays significant scavenging properties, this "explanation" of the epidemiological findings had largely been abandoned. The other candidate mechanisms that attracted some scientific and media attention were the effect of power line electric fields (and specifically corona discharge) on the rate of "plate out" of naturally occurring radioactive particles and pathogens (Henshaw et al., 1996; Fews et al., 1999) and secondly, the possibility of magnetic fields altering the lifetime of free radical species (Brocklehurst and McLauchlan, 1996).

One of the reasons that ELF, or more specifically power line fields, has been firmly linked to the possibility of cancer in the minds of certain sections of the community is the combination of an unknown or mysterious risk with a tragic outcome (childhood leukemia) (Slovic, 1987). This, coupled with a tendency of those benefiting most from the delivery of electric power (heavy industries) being a separate group of people from those suffering the possible health consequences (those with houses next to power lines), has made the outrage factor high (Sandman, 1987). The concept of Prudent Avoidance (Nair, Morgan, and Florig, 1989) emerged at this time and is covered in Chapter 25. A number of books catering for the mass market contributed to the overall sense of public outrage: foremost among these were Paul Brodeur, who in 1990 wrote a series of articles for the "New Yorker" on Meadow St, Guildford, Connecticut (Calamity on Meadow Street), the venue of an alleged cancer cluster caused by electric and magnetic field (EMF) exposure (subsequently published as a book (Brodeur, 1993) entitled "The Great Power-Line Cover-Up"). Other books alleging the need for greater caution include (Becker and Marino, 1982; Shallis, 1988; Smith and Best, 1990).

At around this time, some governments called on distinguished scientists or members of the judiciary to bring an independent viewpoint to resolving the perceived uncertainty. The retired High Court of Australia Chief Justice Sir Harry Gibbs produced a comprehensive report in 1991 leading to Prudent Avoidance policy being adopted by the electricity supply industry in Australia. In the United Kingdom, Sir Richard Doll chaired the NRPB expert scientific panel, producing a series of reports over the period 1992–2001. In interviews, Sir Richard concluded that the studies provided "weak evidence" of a link but that "the risks, if any, however, would be small".

This did not prevent a number of legal cases alleging the contribution of EMF to illness going to court. Prominent among these were the following: a couple in Manchester, the United Kingdom, who alleged personal injury damage against the local power company with respect to their son's leukemia and subsequent death. This began in 1993, but was discontinued in 1997. In San Diego, the parents of a girl alleged a rare kidney cancer due to EMF, but a jury rejected the claim in 1993. In Fresno, California, the family of a deceased person alleged power lines contributed to her death due to brain tumor, but this was dismissed in 1993. Another person alleged that Georgia Power had contributed to her non-Hodgkin's lymphoma. This claim was rejected in May 1994, recommitted in November of the following year, and then rejected again a month later. Cases involving a Texas group of children suffering leukemia and other forms of cancer and three separate cases of adults suffering chronic myeloid leukemia all failed to award damages in favor of the claimants.

In the United States, as a result of stakeholder pressure, Congress enacted the EMF Research and Public Information Dissemination (EMF-RAPID) Program in 1992. The US Department of Energy (DOE) administered the overall EMF-RAPID program, but health effects research and risk assessment were supervised by the National Institute of Environmental Health Sciences (NIEHS), a branch of the US National Institutes of Health (NIH). Altogether, US $45 million was spent on research via an Interagency Committee. Chapter 21 covers the reports that resulted from this program, which were released in 1998 and 1999, and some of the other reports that were released around this time. When the International Agency for Research on Cancer released an evaluation in 2002 that magnetic fields were "possibly carcinogenic", this was seen as somewhat at odds with the conclusions of EMF-RAPID that "the scientific evidence suggesting that ELF EMF exposures pose any health risk is weak". It was also seen as somewhat controversial that IARC (a division of WHO) was coming to conclusions different from the WHO

International EMF Project, whose on-line statements were, at that time, similar to those of NIEHS.

There was earlier controversy in 1995, when a US radiation protection agency was forced to issue a press release (extract as follows): "Contrary to many erroneous sources of information, the National Council on Radiation Protection and Measurements (NCRP) has not made recommendations on extremely low frequency electromagnetic fields (ELF EMF). Draft material formulated by NCRP Scientific Committee 89–3 on ELF EMF has been improperly disseminated and does not reflect NCRP recommendation". The working draft referred to was advocating limits based on epidemiological evidence rather than short-term effects. However, the WHO-sponsored Environmental Health Criteria monograph (WHO, 2007) is clear that the health risk assessment has taken the possibility of causality into consideration: "Although a causal relationship between magnetic field exposure and childhood leukemia has not been established, the possible public health impact has been calculated assuming causality in order to provide a potentially useful input into policy" (p 12).

Some of the more controversial aspects of the epidemiological data have included the following: (i) in the (Feychting and Ahlbom, 1993) study, the elevated risk was limited to those living in single residence dwellings; those living in apartments had no elevated risk; (ii) in the (Draper et al., 2005) study, there were elevated risks identified at locations so far away from the power lines that the magnetic fields were essentially normal ambient levels; and (iii) the suggestion that vehicle exhaust fumes could be a confounder, given that transmission lines often follow major arterial routes (Pearson, Wachtel, and Ebi, 2000). However, a subsequent study (in a different location) showed no such evidence (Langholz et al., 2002).

Despite the IARC "possibly carcinogenic" classification in 2002, this seems to have had little impact on the roll out or upgrade of electrical power infrastructure, although improved public relations approaches (see Chapter 30) may have been a major contributor to this.

In the United Kingdom, the government, together with the electricity industry and childhood cancer charity, provided funding in the period 2004–2011 for a stakeholder group to advise the government how to respond to recommendations from the nation's peak radiation protection agency. This group was known as the Stakeholder Advisory Group on ELF EMFs or ELF-SAGE (http://www.emfs.info/policy/sage/). The process was led by a facilitator rather than a traditional chairperson and sought to be as inclusive as possible to all stakeholders. The reports from this group, together with the agency's response, can be found at the URL above. The SAGE process stayed focused on the ELF health issue: it is important in stakeholder forums that the radiofrequency (RF) health issue, which has similar concerns, but involves a very different biological interaction mechanism, is not allowed to confuse the issues.

32.3 Radiofrequency

The possibility of low-level RF giving rise to health effects predated the power frequency debates just outlined. Concerns of the safety of radar and high-power radio transmitters were raised in the 1970s (Becker and Marino, 1982). The review article by Adey (1981) brought the possibility of such effects to the attention of a wider scientific readership and sparked a scientific program at the US Environmental Protection Agency during the 1980s. However, it was the advent of cellular or mobile phones during the late 1980s and throughout the 1990s that involved the general public in a debate on safety. As with ELF, lawsuits alleging the contribution of RF to the development of cancer served to bring the possibility of low-level harm to the general public. Among several cases attracting worldwide publicity were the following: a person who blamed his wife's fatal brain tumor on cell phone use in 1993 and a Motorola employee in respect to his own use in 2000. Italy's high court determined a "causal link" between an individual's phone use and a benign trigeminal nerve tumor in 2012. In relation to noncancer outcomes, an employee at the Australian national research laboratory was awarded compensation in 2013 "on the balance of probabilities that (the person) has suffered either an aggravation of his sensitivity to EMF or an aggravation of his symptoms *by reason of his honest belief* that he suffers from the condition of EMF sensitivity and that his exposure to EMF associated with the trials has worsened his sensitivity".

A number of studies investigated the possibilities of apparent cancer "clusters" being linked to RF exposure. Some of these are discussed in Chapter 15. Among early controversies, increased risk of childhood leukemia associated with radio transmitters in Hawaii (Maskarinec, Cooper, Swygert, 1994) and within a 6 km radius of the Vatican City Radio transmitter (Michelozzi et al., 2002) rank among the more prominent. In suburban Sydney, three municipalities with higher incidence of leukemia were those in which TV transmitters were located (Hocking et al., 1996, 1997). A similar raised cancer rate was reported in relation to a particular radio/TV in the United Kingdom (Dolk et al., 1997b); however, a wider survey of high-power transmitters by the same team revealed no general pattern of raised risk (Dolk et al., 1997a). Australia has had its share of perceived cancer clusters, with a specific building of a university in Melbourne and offices of the national broadcaster in Brisbane investigated for possible involvement of RF (and ELF) behind (perceived) higher than normal incidence of cancers (specifically breast cancers in the Brisbane case); subsequent investigations of these found that the case in Melbourne was not a cluster (LaMontagne et al., 2006), but the case in Brisbane was (Armstrong et al., 2007). In a commentary on this case, Stewart (2007) noted that "no specific cause of the cluster was identified, but staff concerns were allayed by relocation from the site".

Somewhat debated has been the use of ultra-high frequency microwaves (millimeter waves) as a nonlethal weapon or “active denial system”. The so-named Silent Guardian (Raytheon Corp., MA, USA) directs millimeter-wave energy at individuals via a steerable parabolic reflector. Since this energy (at 95 GHz) is absorbed within millimeters of the skin surface, the skin heat and pain receptors are stimulated, giving sensations of unbearable pain. Since the millimeter-wave generator can be mounted on a truck, its use in crowd control has been suggested, but to the authors’ knowledge has not been yet deployed. One issue is that individuals with metallic body piercings or tattoos could possibly absorb enough energy to cause burns rather than mere discomfort.

The place of precaution in recommendations regarding the use of cell/mobile phones by children has been contentious. For example, one of the recommendations of the 2000 wide-ranging Stewart report in the United Kingdom (Independent Expert Group on Mobile Phones, 2000) was

> If there are currently unrecognised adverse health effects from the use of mobile phones, children may be more vulnerable because of their developing nervous system, the greater absorption of energy in the tissues of the head … and a longer lifetime of exposure. In line with our precautionary approach, at this time, we believe that the widespread use of mobile phones by children for nonessential calls should be discouraged. We also recommend that the mobile phone industry should refrain from promoting the use of mobile phones by children.

There are three parts to this argument: firstly that because children’s nervous system is still developing, it is more susceptible to environmental influences and secondly because the different anatomical and tissue composition in children makes RF absorption greater. The third argument, that the lifetime exposure will be longer if started earlier is incontestable. In modeling work, research by Gandhi, Lazzi, and Furse (1996) showed greater absorption by children (modeled as scaled-down adults), but later work by another group using child models derived from MRI data showed no such differences (Schönborn, Burkhardt, and Kuster, 1998). Anderson (2003) further questioned the notion that the altered tissue composition would enhance absorption within brain tissue specifically. This debate still continues to the time of writing (Foster and Chou, 2014; Gandhi, 2015). Certainly, the notion that children are more susceptible or more deserving of special protection has been a driving force behind siting mobile base stations away from schools and in some areas the banning of Wi-Fi in schools, in parts of France, for example. Community pressure has often been behind these siting and banning issues, as has opposition to AMD “smart meter” installation, particularly in jurisdictions where there was no “opt out” provision.

As Chapter 27 points out, there are examples of precautionary policies and limits that are not science driven. These may be derived by introducing arbitrary extra factors in deriving limit values or by using very long averaging times. In the former USSR and other Eastern Bloc countries, although the limit values were considerably less than in Western nations, the averaging time was 4 hours rather than 6–30 minutes. Some jurisdictions have determined the levels required to deliver the present level of service in telecommunications and made these the exposure limits (despite nontelecoms applications at the same frequency being unable to operate under these strict limits).

There is a ready market for the so-called mobile phone shields, with claims of reduced RF absorption, particularly in the user's head. Some of the earlier devices were worn around the neck rather than being attached to the phone, but in general, any device designed to reduce the RF transmitted by the phone causes reduced efficiency of communicating with the base station. In fact, because phone handsets automatically reduce their power output once a satisfactory signal-to-noise ratio is established in the communication with the base station, a shield will limit this attenuation and thus drain the battery quicker. However, some of the newer shields achieve minimal drop in signal strength at large distances while reducing the SAR value in the head. This appears to be achieved by altering the electric to magnetic field ratio in the so-called reactive near-field region, since SAR depends only on the former and not the latter.

During the late 1990s and to a certain extent up to the present, there was much more controversy about mobile phone base station siting than about cancer being caused by mobile phone exposure. This was why one of us (MD) was appointed to the role in the United Kingdom to co-ordinate the response of the UK mobile phone operators to the increasing public objection to base station siting at a time in which the operators had paid GBP 22 billion for their 20-year third-generation licenses to the UK government. The UK 3G mobile network was being rolled out at a very fast pace. A paper published at around this time (Dolan and Rowley, 2009) discusses the use of the precautionary principle in relation to the RF health base station siting controversy. As pointed out in earlier chapters, the provision of precautionary advice may actually increase the level of public concern, particularly if the controversy is over roll-out process rather than specifically health concerns. Added to this is the view among scientists that the relevant sources of RF to study are mobile phone handsets, whereas the overwhelming concerns among the general public relate to base station exposures.

With respect to research, it is often held that if there has been industry funding, the results cannot be relied on. Although there are many examples in both RF and ELF of industry-funded research resulting in findings adverse to the industry, it is essential to avoid a perception of bias. Several national research programs on RF safety in recent years have involved industry contributions (e.g., MTHR in the UK, BfS in Germany, and NHMRC in Australia) but have sought to distance the source of funding from decisions on what research should be undertaken and which research groups should receive the funding.

32.4 Laser

The main controversy regarding lasers has been the use of laser pointers (usually used by lecturers) to distract racehorses and sportspeople by people in crowds. There have also been incidents of pilots coming in to land being distracted by laser and other bright light sources. Some of the perpetrators have been caught and jailed. In some jurisdictions, lasers with more power than 1 mW are classified as “weapons” and there are restrictions on importation. The use of lasers in outdoor and indoor entertainment also can represent a hazard if not installed or controlled adequately. State or national OH & S and other regulations usually extend to the use of such lasers.

32.5 Ultraviolet

The availability of tanning salons (or solaria) for use by people under 18 has been limited in some jurisdictions for a number of years, following WHO advice in 2003. The death, in Melbourne, of a 26-year-old girl, following development of melanoma, which she associated with solarium use led, via her advocacy, to a further tightening up of previously voluntary regulations. At the start of 2015, all solaria were banned in most states of Australia. Prior to this, the industry organization for solarium operators had argued that the (global) health burden of low vitamin D (which is boosted by UV exposure) far outweighed that of skin cancer. However, it is to be recognized that the amount of sunlight (or UV) required to boost vitamin D to acceptable levels is quite modest. When the UV index is 3 or above a few minutes, outdoors is quite adequate. Certain foods are also important sources of vitamin D.

32.6 What We Can Learn from These Controversies

- The folly of “we’re the experts: trust us”; the importance of stakeholder forums and inclusion.

As the general public becomes more aware of environmental issues, there has been a concurrent distrust of scientists and their expert advice as well as governments and their protection policies. It follows that it is an ineffective strategy for the scientific community, regulators, and relevant industry groups to merely preach to the community that they should be trusted since they are the “experts” and should be listened to. An effective system of health information includes engagement with a wide range of different stakeholders that includes listening to concerns and having honest and robust discussions. An example is the electromagnetic energy (EME) reference group in Australia, which has been established to enable input from the community and other stakeholders on issues relating to EME and health.[1] Engagement with different stakeholders has enabled the Australian Government to better understand the sources of community concern and to determine the type of information required to address it. The UK Department of Health SAGE stakeholder group in the early 2000s is another good example.

- The difficulty the public at large has to appreciate the nature of scientific debate and uncertainty.

The public's perception of risk is not normally based on scientific assessments that are centered on an evaluation of the currently available research and include a level of uncertainty. In particular, involuntary exposures from NIR sources (e.g., mobile phone base stations or smart meters) may be alarming to some people concerned about possible adverse health impacts at some unknown future time. For example, people have labeled exposure to RF fields from telecommunications sources as the new smoking or asbestos. Although the causal link between these latter two agents and cancer now seems obvious, the connection was not established till the second half of the twentieth century. This long time delay between earliest use of these agents and the eventual proof of harmful effects has fueled concern that RF could be a similarly harmful yet largely unrecognized agent (Karipidis, 2007). As mentioned earlier community engagement that includes listening to and acknowledging people's concerns in a respectful manner should form an essential element of communicating about the science to the members of the general public.

- The importance of communicating correct information to the public.

Some members of the public have significant concerns about exposures to all types of radiation. However, the widespread deployment and high visibility of certain NIR technologies, together with a high public profile in the media and range of opinion expressed on the Internet (including social media) about possible health risks, has increased the need for additional education and information, beyond that needed to simply ensure the protection of the public from established harmful effects. Reliable information on the issue of EMR and health that is based on peer-reviewed research can usually be obtained from universities, government health bodies, and scientific organizations. Health authorities such as WHO and ICNIRP, in particular, assess all of the available evidence and provide appropriate advice on an ongoing basis.

- The media needing to sell what they have to sell: adverse health effects are always a drawcard.

The role of the media in this debate is an important one. The media will claim that they report the truth. However, the truth is often dull and uninteresting for the intended audience. For example, many studies have been

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[1] http://www.arpansa.gov.au/AboutUs/collaboration/emerg.cfm.

published showing no health effects from using mobile phones and it is rare that these are even mentioned in the mass media. However, studies have been published, often of bad quality, showing mobile phones being associated with adverse health outcomes, and these are widely commented in the mass media. This is a clear indication that bad news sells and although the media is reporting the truth they are only reporting a small part of the truth. To the unsuspecting public who are not aware of all the other studies failing to report adverse effects, the truth is distorted.

- The need to co-operate proactively with the media to assist it in providing accurate and balanced reporting.

Given the shortcomings of science reporting by much of the media as described above, it is important that the correct information is provided to the mass media. In order to provide accurate and evidence-based information about science, particularly, on controversial and headline news stories when most confusion and misinformation occurs, Science Media Centres have been established in six countries (the United Kingdom, Australia, New Zealand, Canada, Japan, and Germany) with others about to open or are actively being considered in a host of countries including Denmark, China, Norway, Italy, the United States, and Pakistan. The centers collaborate extensively and are in the process of developing a global network that has the potential to become an international force for evidence-based science reporting in the media.

- The role of scientific organizations to promote high standards of research design, particularly dosimetry.

Because of unanswered scientific questions and a level of concern about NIR exposure, research is continuing into the possible adverse health effects associated with NIR. However, research is expensive and repetitive research with methodologies that continue the shortcomings of earlier research is a waste of valuable community resources. In order to avoid unnecessary research duplication and to ensure that all important questions are being studied, research coordination on a global level is important. An example is the World Health Organization International EMF Project that periodically publishes research agendas for electromagnetic fields. The WHO research agendas identify knowledge gaps where further research could improve health risk assessments and present a focused research program to potential funding agencies. Other organizations such as the Bioelectromagnetics Society and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) also have a role of promoting high standards of research design and conduct. A particular problem in much of the research is the poor dosimetry and exposure assessment in general. It is the role of all the relevant scientific organizations with the support of governments and regulators to promote the highest methodological standards in health research.

- Importance of declaration of possible Conflicts of Interests.

It is important to realize that no one is completely unbiased, thus personal interests, preheld views, and even personal gain can be associated with research. Many scientific publications require authors to declare conflicts of interest and sources of research funds. Some will dismiss completely research funded from industry sources, but others will see it as appropriate industry-funded research. Many research projects are set up so as to provide "arms-length" funding whereby the funds come from industry, but there are transparent and effective "firewall" procedures in place aimed at maintaining the independence of research decisions (ARPANSA, 2016). Note that industry links are not the only CoIs. Most scientists are driven by a need to publish "interesting" results in order to secure further funding; community activists can be selective in reporting; those with links to the so-called protective devices are keen to present the "problem" in its worst light.

- The importance of Governments to adhere to science-based public policy.

International exposure guidelines have been developed to provide protection against established effects from NIR by various scientific organizations, and these have been outlined in different chapters of this book. In order to prevent or reduce possible risks related to NIR exposure, some national governments or local authorities have adopted measures that replace or complement science-based exposure limits (Vecchia, 2007). The problem with promoting arbitrary limits and disproportionate safety factors is that reliance on logical, science-based policy is undermined by fear-based, often politically motivated actions. Such actions, rather than providing reassurance, may trigger concerns, amplify unwarranted anxieties, and can divert limited resources into areas producing little or no public health benefit. Despite unavoidable uncertainty and other limitations of scientific methods, scientific research remains society's best source of knowledge about how the world works and how we understand interactions among physical agents and humans, animals, and the environment (Valberg, 2007). It is the WHO's view that scientific assessments of risk and science-based exposure limits should not be undermined by the adoption of arbitrary precautionary approaches and particularly arbitrary precautionary limits (WHO, 2002).

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33

Summary and Prospects

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33.1 Comparison of Nonionizing Radiation with Ionizing Radiation

There is a perception that ionizing radiation (IR) is intrinsically more hazardous when compared to nonionizing radiation (NIR). This is because, by definition, IR initiates events leading to ionization of atoms or molecules. This is followed by the formation of free radicals and subsequent breaking of atomic bonds, especially in key biochemical molecules such as DNA and RNA. Although parts of the UV spectrum can generate free radicals directly, the majority of the NIR spectrum is not able to do this and thus, the risk of immediate or long-term transformation of genetic material seems remote. While IR causes these bond-breaking events even at very low levels, including background natural radioactivity, the same is not true for the majority of NIR, where massive intensities are required to observe unequivocally hazardous bioeffects. The exception is UV radiation, where large portions of populations receive sufficient intensity from the sun to cause sunburn and subsequent increased risk of melanoma. UV is an exception in that it represents the only *natural* form of NIR that presents a public health challenge: all other challenges are from sources that are the product of technology. Whether infringing safety standards or exceeding the limits should carry penalties such as fines (which is for IR) is a matter of some debate. Some jurisdictions do impose penalties for allowing NIR sources to exceed exposure standards. This is in distinction to penalties for the use of unlicensed transmitters, where the concern is not over possible health consequences but on interference.

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33.2 Could the Same Protection Framework Be Applied to Both Ionizing and Nonionizing Radiation?

IR protection has at its core three main principles: justification (intentional exposure must do more good than harm), optimization (exposure should be As Low As Reasonably Achievable or ALARA), and limitation (individual exposure should be kept below defined limits). At a number of forums (e.g., http://www.icnirp.org/en/workshops/article/workshop-principles-2014.html), consideration has been given to whether the same principles could be extended to NIR by the international community. However, there are important differences between IR and NIR. Even within NIR, there are important fundamental differences between UV and the bulk of the NIR spectrum. Table 33.1 is a comparison of some of the key similarities and differences among IR, UV, and the bulk of NIR (described as "Radiofrequency Radiation", but other forms such as extremely low frequency (ELF) also apply). The main differences appear to be in terms of risk perception versus actual hazard (in the case of UV) and the chance of unregulated exposure, which in the case of solar UV is high. Table 33.2 summarizes how the fundamental safety principles formulated for IR (ARPANSA, 2014) could be extended to NIR. Again, there are a great deal of similarities, but perhaps the most significant area of difference is in optimization, in which, apart from the "precautionary principle" and "sun smart" campaigns, there is no requirement to reduce exposure wherever possible. In fact, in the case of the sun, moderate exposure to reduce the possibility of vitamin D deficiency is encouraged in some countries.

While there is good understanding of the long-term risks of IR (except for an uncertainty regarding possible benefits at low doses), there is poor understanding of whether chronic low doses of radiofrequency (RF) or ELF could lead to

Table 33.1 Key differences between Ionizing and forms of Nonionizing Radiation.

Key issues	Ionizing radiation	Radiofrequency radiation	Ultraviolet radiation
Acute health effects	Yes Quantitative	Yes Quantitative	Yes Quantitative
Chronic health effects	Yes Quantitative	No Unknown	Yes Quantitative
Health effects from low dose or low-dose rates	High uncertainty	Long-term effects unknown	Qualitative
Perceived public risk for public exposure	Hazard low because of control, perception high	Hazard low, perception high	Hazard high, perception low

Table 33.2 Applicability of the 10 safety principles of ionizing radiation to NIR Radiation (ARPANSA 2014).

Safety principles of protection (IAEA, 2006)	Ionizing radiation	Radiofrequency radiation	Ultraviolet radiation
Clear division of responsibilities	Yes	Yes	Yes
Legislative and regulatory framework	Yes	Yes	Yes
Leadership and management for safety	Yes	Yes	Yes
Justification	Societal benefit to offset detriments	Societal benefit to offset detriments	Societal benefit to offset detriments (Banning Solaria)
Optimization of protection	Optimization based on LNT model	No established health effects below threshold	Optimization based on UVI thresholds
Limitation of risks (measures)	Yes – effective dose (Sv)	Yes – specific absorption rate (W/kg)	Yes – UVI (J/m^2)
Protection of present and future generations	Yes	Limited	Limited
Prevention of accidents and malicious acts	Yes	Yes	Yes
Emergency preparedness and response	Yes	Limited	Limited
Protective actions to reduce existing or unregulated radiation risks	Yes	Limited	Yes (solar UV)

Key: LNT, linear no threshold; UVI, ultraviolet index.

increased cancer risk. For both RF and UV, there is uncertainty (and considerable debate) on whether the types of standards currently employed will lead to effective protection of present and future generations.

33.3 Might We Expect a Definitive Answer Soon?

Dealing with scientific uncertainty, especially in regard to a possible link between RF and ELF and forms of cancer, has been covered in several chapters, including those included in Part VII. Understandably, those who need to decide on policy matters are looking for a point at which these debates could be considered “settled”. There is no doubt that within the scientific community there are diverse views on what the policy implications of their research should be. There has been a tendency in legal disputes (involving possible health detriments due to RF or ELF) for expert witnesses to be pitted against each other. This has the unfortunate effect of leading some among the general public to conclude that since there is no agreement then the maximum amount of protection should be enforced; although others might disagree particularly if their lifestyle is affected, for example, loss of good mobile phone reception.

This debate should be set in context with assessing risks from the impact of modern technologies in general. There are many factors, especially chemical and biological, where a clear hazard can be identified and where large numbers of people are affected. Nevertheless, a perceived risk from a pervasive and involuntary (at least as far as sources such as mobile phone towers and smart meters are concerned) source needs to be carefully investigated. Epidemiological studies with appropriate controls are a major undertaking and there is a feeling that when the current series of RF/ELF studies are concluded, there will be few unstudied populations, in other words, all that can be done has been done. Certainly, over the years, methodologies have improved. The lack of a clear sequence of mechanistic events from field interactions with biological tissue through to adverse health effects has inhibited epidemiological study design, since there is no clear definition of “dose”. If this sequence can be identified then obviously some adjustment to standards or guidelines will take place. If the overall outcome is still uncertain the present “prudent avoidance principle”. which was enunciated as an interim measure may need to be extended indefinitely. As early as 1987, the view was expressed (Foster and Pickard, 1987) (in relation to microwave risk research) that “searches for hazards can go on too long and guidelines for ending them must be established”. Epidemiological and other studies are expensive to carry out and there may not be significant gains in knowledge from them. Policy may thus need to be developed with recognition of this uncertainty but also recognizing that specific risks appear to have been ruled out. For example, the MTHR report (2012) stated: “We see no need for further research in any of the areas addressed by the research that is summarized in this report”. It is also important to emphasize that if, for example, a causative link between ELF magnetic field exposure and childhood leukemia were to be established, then the numbers affected in the population are quite modest and the fraction of cases attributable to ELF exposure are calculable. In fact, this exercise was carried out in an annex to the WHO EHC Monograph (WHO, 2007), showing that of the world population of children under 14, only 1×10^{-6} would be affected by contracting leukemia from ELF exposure if the risk was proven to be causal. However, in terms of RF, there are large-scale prospective cohort studies presently underway. One of these is the COSMOS study (see www.thecosmosproject.org) with around 300,000 mobile phone users across Europe, which will extend beyond 2020. Another is the GERoNiMO project (Generalized EMF research Using Novel Methods: http://www.crealradiation.com/index.php/en/geronimo-home), which seeks to integrate epidemiological with biological and dosimetric studies. Results from the NTP study, mentioned in Chapter 16, will continue to emerge over the next few years.

33.4 Comparative Costs and Benefits of Mitigation Measures

When limits or restrictions to exposure are introduced, the community need to be assured that the benefits in terms of lives saved or morbidity avoided should strongly outweigh the costs associated with introducing these limits, including added costs to service providers of introducing specific mitigation measures as well as administrative costs, including monitoring and public education. Often, these costs and benefits are very difficult to quantify, but it is useful to compare IR with the different forms of NIR in the following examples.

33.4.1 Ionizing Radiation

Since the major source of IR exposure in the general public is to medical sources, there is a cost to the community by not optimizing equipment. Undoubtedly, significant limitations in collective dose can be brought about by having control in the form of optimization of practice, monitoring and inspection (Amis and Butler, 2010). This amount of collective dose can be translated to additional healthcare costs, plus many unquantifiable community costs, by use of the fatality risk factor of approximately 5%/Sv (1 in 20,000 mSv^{-1})as defined by the International Commission on Radiological Protection (ICRP, 2007). Although increases in the frequency of occurrence of health effects in populations cannot be reliably attributed to chronic exposure to low levels of radiation, it has been estimated that a net benefit to the community of a few dollars per each person could be achieved if these mitigation strategies were in place.

33.4.2 Ultraviolet

In Australia, there are over 1600 melanoma deaths per annum (AIHW, 2016) and the cost of skin cancer treatment is several hundreds of millions of dollars; 94.7% of outdoor workers in the state of Queensland exceed the minimal erythemal dose (MED) of 30 $\mathrm{J/m^2}$ in 8-hour period (Gies and Wright, 2003). The ratio of melanoma mortality between northern and southern states is nearly 3:1 (Pollack et al., 2014). Even a 10% reduction in mortality would save 130 lives and approximately $1 per each person annually. It is estimated that 20% of cataracts are due to UV: the health care costs due to these alone are of the order of $5 per person.

33.4.3 Laser Burns and Retinal Injuries

Fortunately, these are relatively rare: the rate is roughly 1/year in a research establishment with 800 lasers (Barbanel et al., 1993). Most injuries were temporary. The use of lasers for cosmetic purposes is a concern, but accidents are poorly documented. Eye injuries from laser pointers are not unknown but again are rare (Wyrsch, Baenninger, and Schmid, 2010). The rarity of injury is probably a consequence of efficient management and control.

33.4.4 Radiofrequency

A large proportion of RF plastic welding installations report burns incidents, and injuries from approaching high-power antennas or dishes have been documented (Hocking et al., 1994). Any “precautionary” reductions on emission standards will impact on service delivery without clear benefits in terms of reduced morbidity.

33.4.5 Extremely Low Frequency

Although a causal relationship between ELF magnetic fields and childhood leukemia has not been established, there are certainly low- or modest-cost methods for lowering exposure to both electric and magnetic fields (see Chapter 27); however, the effects of doing this in terms of a reduction in the rate of childhood leukemia is highly unlikely to be measurable.

33.5 Concept of Acceptable Risk

The risk that we accept as a society is not normally based only on scientific assessments. For IR, setting the public limit at 1 mSv implies that a risk below 5 in 10^5 for induced fatal cancer risk per annum (based on the LNT model) is acceptable. The exposure to natural IR background is a similar amount (around 2.4 mSv/annum), so an increase in a smaller figure than this compared to natural background is considered acceptable, particularly since natural background varies considerably across the globe (as high as 10 mSv/annum in many places and occasionally as high as 100 mSv/annum (IAEA, 2004)). On the other hand, in the case of solar UV, the baseline risk of melanoma mortality is 7 in 10^5 in Australia (AIHW, 2016), which is approximately the same as the IR risk of all-cancer fatality per mSv, but the risk is considered unacceptable and drives public education strategies to prevent sunburn. However, if we add in the risk of fatality from nonmelanoma skin cancer (3 in 10^5; AIHW (2016)) and the costs associated with treatment of nonfatal skin cancers, there is ample justification to regard excess sun exposure as being an unacceptable risk.

For ELF, using the figure from the WHO EHC Monograph annex (WHO, 2007) above as being the possible risk of childhood leukemia from magnetic field sources of 1 in 10^6 (assuming causality), this is effectively deemed unacceptable by the advocacy of precautionary approaches.

33.6 Can We Live in a World without NIR Exposure?

NIR is ubiquitous in the environment. Apart from the sun providing our planet with UV exposure and the valuable light that it needs, there are also natural, albeit very small, levels of RF and ELF also produced from the sun and atmospheric processes. Advancements in technology highlighted by the evolution of electrical power and telecommunications have increased people's exposure to NIR. The human appetite for further advancement, and foreseeably greater exposure, is not looking at abating.

For decades, researchers have been investigating the effects of NIR and comprehensive exposure guidelines protecting humans have been developed on the basis of current scientific knowledge. There is currently a level of concern about certain types of NIR (e.g., RF and ELF), which is not fully alleviated by existing scientific data. The debate over these NIR exposures focuses on the potential detriment but often ignores the benefits to society. Can we really imagine a world without electricity? Similarly, telecommunications have transformed the way we connect to one another and are fully entrenched in our modern way of life. On the other hand, there are clear dangers from UV exposure and people at certain parts of the world have become too complacent. Education needs to continue in this area.

We cannot eliminate NIR from our environment and there are clear benefits from its existence and use. In fact, some may say that we cannot live in a world without NIR exposure. That is certainly true in relation to the sun but what about human made exposures? It is unlikely that we will reverse hundreds of years of technological advancement or regress our way of life. On the other hand, we should not ignore the real dangers of NIR exposure. By having a good understanding of NIR and controlling our exposure, we can reduce any possible risk.

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Appendix A

Answers to Tutorial Problems

Chapter 1

1 300 MHz, 300 GHz, 300 kHz: radiofrequency (VHF), microwaves (THz), radiofrequency (LW)

2 0.61 V/m; 1.6×10^{-3} A/m

3 126 W

4 Photoreactions, tissue heating, and induction of tissue current

Chapter 2

1 RF emissions can be generated by either a signal generator or an actual phone handset controlled in such a way that the RF output is constant and known. Each volunteer participant should have heart rate measured over a set time during exposure to RF or sham exposure to RF (the difference being that in the latter the power is not turned on, everything else being the same). Neither the volunteer participants nor the experimenters interacting with the participants should be aware of whether the RF source is active or not.

2 This is a relatively small sample with a wide range of ages and insufficient numbers to account for possible gender differences (depending on which hormone is being studied). The variation in levels from one day to the next could be influenced by other endogenous and exogenous factors than the magnetic field. It is also unclear whether 60 minutes of exposure would be sufficiently long to influence hormone output. The least poor comparison would be a "paired *t*" test, where each participant acts as their own control.

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3 10.07, 1.04, 0.33

4 In order to demonstrate a change equal to the effect size (SD/mean), a sample size of 21 is needed (see text). Since the sample size in this case is much less than this, the consequence could be that a true effect is not detected (a false negative).

5 Since RF is used in obtaining an image, the effect of an additional RF dose from a handset is difficult to disentangle from any possible effects from the RF dose due to the imaging (albeit at a different frequency and possibly a different spatial distribution). Bearing in mind that both forms of RF are pulsed, if it is assumed that thermal effects are related to the rate of energy deposition (SAR), it would be necessary to ensure that the SAR due to the phone-like source would be significantly greater than that due to the imaging.

Chapter 3

1 Given $P = I \times D$, thus $P = 200 \times 12 = 2400$ per 100,000 or 2.4%. It is a proportion, without units.

2 If mobile phones cause brain tumors, this association could result. But if people who have brain cancer are more likely to report their use of mobile phones than people who do not have brain cancer, this association could also be produced. In addition, if people who use mobile phones have other characteristics that would put them at greater risk of brain cancer, for example, being older than those who do not use them, then this association could also be produced. Thirdly, if the numbers in the study are small, this association could be produced purely by chance variation. The size of the relative risk is no protection against these non-causal explanations.

3

a) Cohort study, prospective;
b) case–control study;
c) intervention trial – not stated if randomized or nonrandomized, or if a control group (e.g., with a sham exposure) was used;
d) case–control, retrospective, carried out within an occupational cohort – sometimes called a “nested” case–control study, or a “case–control study within a cohort.”

4

a) There is a statistically significant association, with a relative risk of 2.8, that is, the exposed group has 2.8 times the rate of the reference group. From this study, we would conclude with 95% confidence that the true association is within the range of a relative risk of from 1.5 to 5.2. However, observation bias, confounding, and the selection of the subjects included in the study need to be taken into account (this applies to all these examples).
b) The odds-ratio is 0.7, that is, the risk of disease in one group is 30% reduced compared to the reference group. This association is not statistically significant, with the 95% confidence limits being from an odds ratio of 0.3 (a 70% reduction in risk), up to an odds-ratio of 1.6 (a 60% increase in risk).
c) The study shows a relative risk of 2.5, that is, there is an association in the direction of an increased risk in one group. However, the confidence limits are wide, the 95% limits being from 0.3 to 20.8, suggesting that the study is very small. The study is therefore rather uninformative.
d) The relative risk is 2.5, and all we know about its precision is that it is not statistically significant at the $P = 0.05$ level. If there is no true association, this or a more extreme result could occur at least one time in 20 simply from chance variation. This could be the same result as in example *C*, but is clearly much less informative. The lower 95% confidence limit could be just very slightly under the null hypothesis value of 1.0 or could be much lower, and the upper limit could be almost anything above 2.5.
e) No, because the RR, being a ratio, is logarithmic. The limits are symmetrical on a log scale.

Chapter 5

1 Basal cell cancer and squamous cell cancer, both from keratinocytes, and melanoma, from melanocytes

2 They are the commonest cancers in predominantly white populations.

3 Yes. Melanoma can arise within the eye, and keratinocyte cancers can arise on the skin around the eye and the eyelids. Both are related to UV.

4 Vitamin D synthesis.

5 Very high levels; extra protection required for skin and eyes.

6 Seek shade, and Slide on sunglasses.

Chapter 8

1 Energy is applied (pumped) to a lasing medium in order to create a population inversion of energetically excited atoms within the material. Photons of energy equal to the difference between the excited- and ground-state energy of the atoms is supplied to the optical cavity containing the lasing medium. This results in the release of photons when the excited atom drops from the excited state to the ground state. Mirrors that form the walls of the optical cavity reflect the released photons back into the lasing medium. This results in the release of more photons (amplification). A fraction of these photons are allowed to escape out of the optical cavity via a partially transparent mirror, which results in the formation of the laser beam.

2 Laser light is coherent, meaning that it is in phase, and monochromatic, meaning that it comprises a single wavelength.

3 Visible and near infrared light is able to penetrate the cornea and lens of the eye and be focused onto the retina. This typically results in thermal injuries. UV light interacts with the cornea and can cause photochemical effects and lead to photokeratitis (welder's flash) and cataract development. Far infrared light above 1400 nm can lead to thermal injuries of the cornea and infrared induced cataracts (glass blowers cataracts).

4

i) Class 2
ii) Class 1
iii) Class 4.

Chapter 11

1 Average radiant power; CW, pulsed
Radiant energy; pulsed
Beam diameter; CW, pulsed
Beam divergence; CW, pulsed
Peak radiant power; pulsed
Pulse duration; pulsed
Pulse repetition rate; pulsed.

2

i) Photodiode
ii) Pyroelectric
iii) Thermopile.

3 Full-width at half maximum
$1/e^2$
Knife-edge measurement
Second moment or $D4\sigma$.

4 A refracting optic such as a lens is used to focus the laser light toward a detector, which is situated at the focal length of the lens. The degree of divergence is calculated based on the distance beyond the detector surface where the beam converges. Nondivergent laser beams will converge at the focal point of the lens at the detector surface. Divergence is important from a safety perspective because it gives information about the area of potential exposure of the beam.

Chapter 13

1 Occupational groups (11 W/m^2 exceeds the public limit of 4.5 W/m^2, but is less than 22.5 W/m^2).

2 The IEEE limit at 10 GHz is 100 W/m^2, which converts to 10,000 mW/m^2, therefore 50 dBm, using the formula given.

3 The value of 0.1 A/m would actually be below the *H*-field limit at this frequency, but could not be used to demonstrate compliance. Compliance is assessed by estimating SAR in the head assuming a 1 cm gap between the antenna and the scalp. The basic restrictions are on SAR value and not on field values. Measurement of magnetic (*H*) field in the near field (3 cm is well within the near field at this frequency) is difficult to do because of interaction between the measuring instrument and the source. Values obtained cannot be linked in a straightforward way to SAR. SAR estimations require specialist equipment.

4 0.21 μW/m^2; 24 μA/m; $100 \times 0.21 \times 10^{-6}/2$ or 0.0001%

Chapter 14

1 An electric field strength of 147.4 dBuV/m and magnetic field strength of 40.3 dBmA/m.

2 The wavelength at 700 MHz is $\lambda = c/700 \times 10^6$, which is 0.429 m. From Eq. (14.8), the distance to the far field is $2 \times 2^2/0.429$ or 18.7 m.

3 Around 5% (see Figure 14.5).

Chapter 15

1 Glioma, arising in the brain tissue; meningioma, arising in the meninges, the lining of the brains; and acoustic neuroma, arising in the acoustic nerve.

2 The Interphone study.

3 The risk of glioma was increased, being 40% higher in that group than in never-users of mobile phones. The result was statistically significant, but only just, at the 5% level: the lower 95% confidence limit 1.03 was close to the null hypothesis value. Whether the result shows causation depends on other considerations, such as the lack of dose-response shown.

4 Women in the highest category of mobile phone use had an incidence rate of brain tumors similar to that of the lowest exposure reference group, being reduced by 9% but the 95% confidence limits being wide, from a 59% reduction (0.41) to a doubling of risk (2.04).

5 The IARC 2B classification means "possibly carcinogenic to humans."

6 A "cluster" is an apparently abnormally high number of cases of disease in a small geographical area and time period.

Chapter 17

1 Using the formulae given above, $E_{\text{int}} = r(dB/dt)/2$ and $dB/dt = 2\pi f B$, we can write $E_{\text{int}} = r\pi f B$, where B and E_{int} are both RMS values. If we take r as half the shoulder-to-shoulder distance (which is highly approximate, since the side-to-side distance at the waist could be considerably lower) we get $E_{\text{int}} = 0.2 \times \pi \times 50 \times 5 \times 10^{-6} = 0.16\,\text{mV/m}$.

2 $I = 9 \times 10^{-11} \times 60 \times 1.7^2 \times 10 \times 10^3 = 1.6 \times 10^{-4}\,\text{A}$, or 0.16 mA. The cross-sectional area of the ankle is $\pi(.075/2)^2$; current density $36\,\text{mA/m}^2$. Dividing this by the conductivity value gives the induced field E_{int} to be 180 mV/m. Note that the basic restrictions pertaining to the periphery will apply in the ankle.

3 The capacitance of the head, using the formula supplied, is $4 \times \pi \times 8.9 \times 10^{-12} \times 0.08 = 8.9\,\text{pF}$ ($1\,\text{pF} = 10^{-12}\,\text{F}$). Putting $\omega = 2\pi f$, we can estimate the current flowing in the neck as $2\pi \times 60 \times 8.9 \times 10^{-12} \times 10 \times 10^3 = 34\,\mu\text{A}$. If we take the radius of the neck to be 6 cm (0.06 m), this gives the current density to be $3\,\text{mA/m}^2$ (compare to answer above).

Chapter 18

1 Under the ICNIRP guidelines, the limits for the general public are 5 and 4.2 kV/m for 50 and 60 Hz, respectively. However, under the IEEE standard, public exposures of up to 10 kV/m are allowed, if the risk of microshock is appropriately managed. The advice would depend on which standard is recognized by the relevant national or state body. Public information should include warning of the possibility of microshock.

2 The general public limit at this frequency is 0.3 mT in the ICNIRP standard and 1.1 mT in the IEEE standard. The advice would be not to allow public in the cab with the locomotive in motion and in jurisdictions where ICNIRP is recognized there would be a significant chance of exceeding the exposure limit. Locations in the cab where this is likely to happen would need to be identified and cordoned off.

3 Since this is referring only to ICNIRP, the procedure is to add the fraction of the occupational standard of the three components:

$$0.5/1 + 0.2/0.429 + 0.2/0.214 = 21.9$$

In other words, although each component is within the standard limit at that frequency, together they exceed by twofold and workers would not comply.

Chapter 20

1 A pooled analysis is a combined reanalysis of several epidemiological studies, using the original data. They are important as they give results based on, ideally, all relevant available studies.

2 The risk of leukemia was increased, by 24%, but this could have easily been due to chance as the confidence limits include 1.0.

3 The IARC 2B classification means "possibly carcinogenic to humans."

Chapter 21

1 The list could include (but will not be limited to the following:

i) The epidemiological evidence of association with childhood leukemia at exposures found in some residences can be taken as indication of possible long-term effects not considered by focusing only on short-term neurostimulation.
ii) Although inconsistent and lacking coherence, evidence for low-level effects is not entirely absent.
iii) The lack of a credible biophysical mechanism is not in itself sufficient grounds for dismissing the possibility of low-level effects, but it does require the epidemiological evidence to the more convincing than is the case at the moment.

Ways of resolving the divergence: it may be the best way is to learn to live with this divergence, since in the recent past doing more research has added little to moving to resolution. ICNIRP, WHO, and other organizations continue to monitor research and identify data gaps.

2 $1 million (or €1 million) does not actually go far as far as good-quality research goes – it will suffice to support one or two 3-year laboratory-based projects but would probably be insufficient to cover an epidemiological study of the kind of scope required to reduce uncertainty (it would also be quite difficult to find a cohort of child leukemia cases not already studied. Public information dissemination via credible authorities and the development of quality educational material might be a more cost-effective route to go.

Chapter 22

1 1–10 mT.

2 In contrast to static magnetic fields, static electric fields do not penetrate the human body or any other conducting object.

3 There is very little theoretical or research evidence to suspect that static magnetic fields encountered in the everyday environment may cause or contribute to cancer or any other health effect.

Chapter 23

1 Guidance is given to avoid annoying effects of direct perception of the surface electric charge and indirect effects such as electric shock.

2 Electrical currents induced by movement through a static magnetic field must be kept to a level less than those that occur naturally in the body. In addition, the electrical currents induced in large blood vessels by blood flow must be kept to a level that will not produce hemodynamic or cardiovascular effects. Lastly, the issue of interference with implanted medical devices must be considered

Chapter 27

1 The TWA magnetic field is $(25 \times 0.4 + 10 \times 0.1)/35 = 0.3\ \mu\text{T}$ for the school week.

2 The expected exposure is $[100 \times 10 \times 0.05 \times 0.5 \times (40/168)] = 6\ \mu\text{T}$ child years. At $\$100\ \mu\text{T}^{-1}$ child year, a reasonable amount to spend on precautionary measures is about \$600. For this situation, it would be worth getting the ELF magnetic fields in the child care center checked.

3 Assuming that the worker is employed for 8 hours per day, the worker's expected exposure is about $[30 \times 1 \times (8/24) \times (5/7)] = 7\ \mu\text{T}$ person years. At $\$100\ \mu\text{T}^{-1}$ person year, if the cost to relocate the worker to another part of the office is less than about \$700, then this would seem to be a reasonable action to take.

Chapter 29

1 Direct beam exposure; skin and eye injuries
Specular reflections; skin and eye injuries
Diffuse reflections; eye injuries.

Chapter 31

1 Answer is given in question: Formula B.31.4 gives result in mG.

Appendix B

List of Suppliers of Survey Equipment

This is not an exhaustive list and should not be taken as representing endorsement of recommendation.

UV/Visible/IR Survey Instruments and Personal Monitors

Edmund Optics (http://www.edmundoptics.com/lasers/laser-measurement/)
Ophir Photonics (http://www.ophiropt.com/laser-measurement)
Solar Light (http://solarlight.com/)
Ocean Optics (http://oceanoptics.com/product/)
Labsphere (https://www.labsphere.com/labsphere-products-solutions/light-metrology/)
International Light Technologies (http://www.intl-lighttech.com/)
Scientarra Limited (http://scienterra.moonfruit.com/#/products/4567276435/UV-Measurement).

RF/ELF Survey Instruments and Personal Monitors

Narda Safety Test Solutions (https://www.narda-sts.com/en/)
ETS.Lindgren (an ESCO Technologies Company) (http://www.ets-lindgren.com/)
FW Bell (www.fwbell.com)
Rohde & Schwarz (https://www.rohde-schwarz.com/home_48230.html)
Keysight Technologies (formerly Agilent) (http://www.keysight.com/main/commonlanding.jspx?cc=AU&lc=eng&cmpid=zzkeyproducts).

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RF/ELF Personal Monitors

Enertech Consultants (http://www.enertech.net/)
Narda Safety Test Solutions (http://www.narda-sts.us/products_personal_nardalertxt.php)
MVG (Microwave Vision Group) (http://www.mvg-world.com/products/field_product_family/rf-safety-3)
fieldSENSE Personal RF Monitor (http://www.fieldsense.com/?gclid=CLbVp8XI58wCFYaXvAod1DkLxg)
LBA Group (https://www.lbagroup.com/products/safeone-rf-monitors).

Appendix C

Websites for Further Information

International

World Health Organization – International EMF Project

http://www.who.int/peh-emf/en/.

Includes factsheets, position papers, and databases of research and standards. Identifies gaps in knowledge requiring further research and promotes a research agenda for researchers and funding agencies.

International Agency for Research on Cancer (IARC)

http://www.iarc.fr/.

IARC is part of WHO. The objective of IARC is to coordinate cancer research and provide expert analysis on cancer causes and prevention. It also maintains extensive databases on cancer statistics and within its extensive publications program produces monographs to evaluate carcinogenicity (to humans) of chemical and physical agents, including ELF (Monograph 80); radiofrequency (Monograph 102); solar and UV (Monograph 55); and forms of ionizing radiation.

International Commission for Nonionizing Radiation Protection (ICNIRP)

http://www.icnirp.org/.

In some ways, ICNIRP parallels the work of the International Commission on Radiological Protection (ICRP), whose focus is on ionizing radiation. In addition to the electromagnetic fields and radiation covered by this book, ICNIRP is also concerned with mechanical waves such as ultrasound and intrasound. The publications program includes Guidelines, Statements, Reviews, and Proceedings of Workshops and Notes, mostly available as downloads. In addition to the Main Commission of 12 persons, a larger Scientific Expert Group provides advice on specified topics.

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Microwave News

http://www.microwavenews.com/.

This publication, starting in 1981, was originally a bimonthly newsletter, mailed to subscribers, but is now entirely online. It has been produced by a journalist, Louis Slesin, for all of this time. The web site contains useful links to national and international organizations concerned with ELF and RF.

EMFacts Consultancy

http://www.emfacts.com/.

This web site is maintained by Don Maisch, Tasmania, Australia. Opinion on issues regarding ELF and RF is provided both in the form of occasional papers and a blog.

National

Public Health England

https://www.gov.uk/government/collections/electromagnetic-fields.

The UK National Radiation Protection Board (NRPB) became part of the Health Protection Agency (HPA) in 2005 which then became part of Public Health England (PHE) in 2013. The PHE web site has links to the more recent publications on NIR, with the earlier NRPB publication being available from the UK National Archives.

EMFs.info

http://www.emfs.info/.

This web site is maintained by the Energy Networks Association (ENA) of the UK. It has extensive resources on the nature of EMF sources, the characteristics of fields, ELF standards, and scientific reviews.

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)

http://www.arpansa.gov.au/.

ARPANSA is a Federal Agency charged with the responsibility of protecting people and the environment from the harmful effects of radiation, including NIR. As well as producing fact sheets on various radiation topics, it undertakes UV measurements, RF and ELF surveys, and other scientific investigations. It produces a series of publications (Radiation Protection Series) including Fundamentals, Codes and Standards, Guides, and Recommendations.

Health Canada

http://www.hc-sc.gc.ca/ewh-semt/radiation/ultraviolet/index-eng.php.

http://www.hc-sc.gc.ca/ewh-semt/radiation/cons/radiofreq/index-eng.php.

http://www.hc-sc.gc.ca/ewh-semt/radiation/cons/electri-magnet/index-eng.php.

These represent links to pages on UV, RF, and ELF forms of NIR. These pages contain links to other HC documents and web pages.

University of Ottawa

http://www.rfcom.ca/welcome/index.shtml.

To quote: "Information provided on RFcom covers sources of radiofrequency (RF) fields emitted from telecommunication devices such as cellular telephones, base stations, and television and radio transmitter masts and potential health effects. Summaries, scientific abstracts, and full references of the latest research papers are made available each month."

RWTH Aachen University EMF-Portal

http://www.emf-portal.de/.

This database contains bibliographic details of over 22,000 research publications (including summaries of around 25% of them) as well as overviews of broader themes relating to RF and ELF.

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Non-ionizing Radiation Protection: Summary of Research and Policy Options, First Edition.
Edited by Andrew W. Wood and Ken Karipidis.