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Non-Ionizing Radiations – Sources, Biological Effects, Emissions and Exposures

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ABSTRACT

Non-Ionizing radiation (NIR) refers to radiative energy that, instead of producing charged ions when passing through matter, has sufficient energy only for excitation. Nevertheless it is known to cause biological effects. The NIR spectrum is divided into two main regions, optical radiations and electromagnetic fields. The optical can be further sub-divided into ultraviolet, visible, and infra-red. The electromagnetic fields are further divided into radiofrequency (microwave, very high frequency and low frequency radio wave).

Non-Ionizing radiation originates from various sources: Natural origin (such as sunlight or lightning discharges etc.) and man-made (seen in wireless communications, industrial, scientific and medical applications).

The basics of biological effects seen with NIR relevant to human health is reviewed, including the optical biological effects of photochemical and heating; the electromagnetic fields of surface heating, electrical burn and shock. A survey of the current emissions from various sources and exposures from human activities involving NIR based on the National Radiological Protection Board (NRPB) of the United Kingdom and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is presented.

Finally, a brief review of the standards and guidelines for NIR is presented. Further research based on epidemiological studies, experimental biology, volunteer studies and dosimetry are needed. These areas of science play an essential role in identifying possible health effects and in providing information on appropriate exposure guideline levels.

INTRODUCTION

Non-ionizing radiations (NIR) encompass the long wavelength (> 100 nm), low photon energy (<12.4 eV) portion of the electromagnetic spectrum, from 1 Hz to 3 x 10^{15} Hz. Except for the narrow visible region, NIR cannot be perceived by any of the human senses unless its intensity is so great that it is felt as heat. The ability of NIR to penetrate the human body, the sites of absorption, and the subsequent health effects are very much frequency dependant.

The NIR part of the electromagnetic spectrum is divided into four approximate regions [1-3]:

? static electric and magnetic fields, 0 Hz;
? extremely low frequency (ELF) fields, >0 Hz to 300 Hz;
? radiofrequency (RF) and microwave (MW) radiation, 300 Hz to 300 GHz;
? optical radiations: infrared (IR) 760 - 10^{6} nm
visible 400 - 760 nm
ultraviolet (UV) 100 - 400 nm

(On the other hand, ionizing radiations, with wavelengths less than 100 nm, constitute the high photon energy portion of the electromagnetic spectrum.)

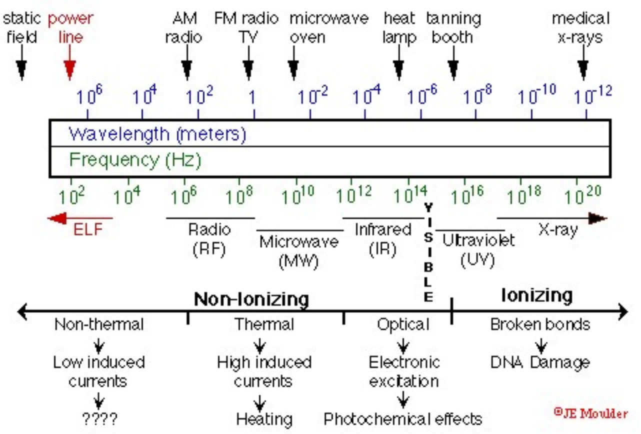

Fig. 1 Electromagnetic Spectrum and associated Biological Effects (Reproduced with permission from John Moulder and Begell House [1])

SOURCES OF NIR

Non-Ionizing radiation originates from various sources: Natural origin (such as sunlight or lightning discharges etc.) and man made (seen in wireless communications, industrial, scientific and medical applications). The NIR spectrum is divided into two main regions: optical radiations and electromagnetic fields.

Optical radiations

The optical radiations are centred around visible light; those with higher energies are termed UV radiation and those with lower energies IR radiation.

Sources of UV radiation are the sun, arc welding, oxy-gas welding, sun lamps, lasers (UV), sterilization (germicidal) lamps, low pressure gas discharge lamps, high pressure discharge lamps. Sources of IR radiation are from hot processes such as steelmaking, glassmaking, welding, and also lasers (IR). The application of laser as a coherent light source is increasing rapidly.

Medical applications include UV and neonatal phototherapy, surgical and therapy lasers, physiotherapy heat lamps

Electromagnetic fields

Microwaves are used in telecommunications, radar/satellite links, mobile phones, microwave ovens, TV transmitters. RF is used in radio communications, visual display units, television sets. Extremely low-frequency (ELF) electric and magnetic fields (EMFs) surround electrical machinery, home appliances, electric wiring, and high-voltage electrical transmission lines and transformers.

Medical applications include: microwave hyperthermia, therapeutic and surgical diathermy, and magnetic resonance imaging (MRI).

BIOLOGICAL EFFECTS OF NIR

A biological effect occurs when a change can be measured in a biological system after the introduction of some type of stimuli. However, the observation of a biological effect, in and of itself, does not necessarily suggest the existence of a biological hazard or health effect. A biological effect only becomes a safety hazard when it "causes detectable impairment of the health of the individual or of his or her offspring" [3]. Biological effects could be physiological, biochemical or behavioural changes induced in an organism, tissue or cell.

NIRs usually interact with tissue through the generation of heat. The hazards depend on the ability to penetrate the human body and the absorption characteristics of different tissues (Table 1). There are still much uncertainties about the severity of effects of both acute and chronic exposure to various types of NIRs. Generally the public is concerned about the risks from ELF, RF and MW. However, the greatest risk to the public probably arises from natural UV radiation.

Damage from optical radiations is largely confined to the eye and skin, and fall into two categories – thermal damage and photochemical damage. Despite having insufficient energy to ionise atoms, single photons of ultraviolet radiation can damage tissue through disruption of bonds within DNA molecules and give a long-term risk of cancer. This must be borne in mind when determining allowable exposures. Visible light and IR only produce damage through high-intensity multi-photon interactions. The biological effects induced are essentially the same for both, but lasers (coherent light) are capable of producing higher irradiances and can heat localized volumes of tissue to a high enough temperature to produce rapid physical change. [2]

Table 1. Biological Effects of Different Non-Ionizing Radiations (Reproduced with permission from Martin & Sutton, 2002 [2]).

	Wavelength, frequency	Biological Effects
	100 nm	
UVC		Skin – Erythema, inc pigmentation
	280 nm	Eye – Photokeratitis (inflammation of cornea)
		Skin – Erythema, inc pigmentation
UVB		***Skin cancer***
	315 nm	Eye – Photochemical cataract
		Photosensitive skin reactions
UVA		Skin – Erythema, inc pigmentation
	400 nm	***Skin photo-ageing, Skin cancer***
Visible		Eye – Photochemical & thermal retinal injury
	780 nm	Eye – Thermal retinal injury
IRA		Eye – Thermal retinal injury, thermal cataract
	1.4 µm	***Skin burn***
IRB		Eye – Corneal burn, cataract
	3 µm	***Skin burn***
IRC		Eye – Corneal burn, cataract
	1 mm	Heating of body surface
Micro-wave	300 GHz	
		Heating of body surface
	1 GHz	Heating with penetration depth of 10 mm
		Raised body temperature
	<100 KHz	Cumulation of charge on body surface
		Disturbance of nerve & muscle responses
Static	0 Hz	Magnetic field – vertigo/ nausea
		Electric field – charge on body surface
Long-term effects are given in italics.		

The nature, extent, and physiological importance of biological effects from NIR exposures will depend on many factors such as the energy of the incident radiation (determines the penetration depth), the power density of the field or beam, source emission characteristics, duration of exposure, environmental conditions, and the spatial orientation and biological characteristics of the irradiated tissues (molecular composition, blood flow, pigmentation, functional importance, etc.).

In the lower frequency range (300 Hz to 1 MHz), induction currents may interfere with the functioning of the central nervous system. In the intermediate frequency range (100 kHz to 10 GHz), the absorption of EMF generates heat. At the upper frequency range of 10 GHz to 300 GHz, heating of superficial tissues is possible. It is generally recognized that, except for optical radiation, there is scarce data on the quantitative relationships between exposures to different types of NIR and pathological responses in humans.

Biological effects that result from heating of tissues by RF radiation are referred to as *'thermal' effects*. The body has effective ways to regulate its temperature, but if exposures are too intense the body no longer copes.

Much of the current debate is about relatively low levels of exposure to RF radiation from mobile phones and base stations producing *'non-thermal' effect*s. Some experiments have suggested that there may be biological effects at non-thermal exposure levels, but the evidence for production of health hazard is contradictory and unproven [4-8]

The scientific community and international bodies acknowledge that further research is needed to improve our understanding in some areas. Meanwhile the consensus is that there is no consistent and convincing scientific evidence of adverse health effects caused by RF radiation [4-8].

EMISSIONS AND EXPOSURES

Optical radiations

Prolonged human exposure to solar UV radiation may result in acute and chronic health effects on the skin, eye and immune system. Sunburn and tanning are the best known acute effects of excessive UV radiation exposure; in the long term, UV radiation-induced degenerative changes in cells, fibrous tissue and blood vessels lead to premature skin ageing. UV radiation can also cause inflammatory reactions of the eye, such as photokeratitis. Chronic effects include two major public health problems: skin cancers and cataracts. [9,10]

Furthermore, a growing body of evidence suggests that environmental levels of UV radiation may increase the risk of infectious diseases and limit the efficacy of vaccinations. Sun protection programs are urgently needed to raise awareness of the health hazards of UV radiation, and to achieve lifestyle changes that will reverse the trend towards more skin cancers. [9,10]

Recently the Global Solar UV Index (UVI) was developed by the World Health Organization (WHO) in collaboration with the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). The UVI is a simple measure of the UV radiation level at the Earth s'surface and aims to aid public understanding of exposure levels and to raise public awareness of the risks of exposure. [10,11]

Radiofrequency and Microwave

RF radiations transmitted from base stations and mobile phones have received a lot of attention. Typical locations where the public is exposed are at ground level, in buildings beneath antennas and in buildings facing antennas mounted on masts or other buildings.

NRPB has made many measurements of exposure levels at publicly accessible locations around base stations. One study [12] reported measurements taken at 118 locations from 17 different base station sites. Average exposures were found to be 0.00002% of the ICNIRP public exposure guidelines and at no location were exposure found to exceed 0.02% of the guidelines.

The maximum exposure at any location was 0.00083 $mWcm^{-2}$ (on a playing field 60 meters from a school building with an antenna on its roof). Typical power densities were less than 0.0001 $mWcm^{-2}$ (less than 0.01% of the ICNIRP public exposure guidelines). (See Fig. 2) Power densities indoors were substantially less than power densities outdoors. When RF radiation from all sources (mobile phone, FM radio, TV, etc.) was taken into account the maximum power density at any site was less than 0.2% of the ICNIRP public exposure guidelines. [12, 13]

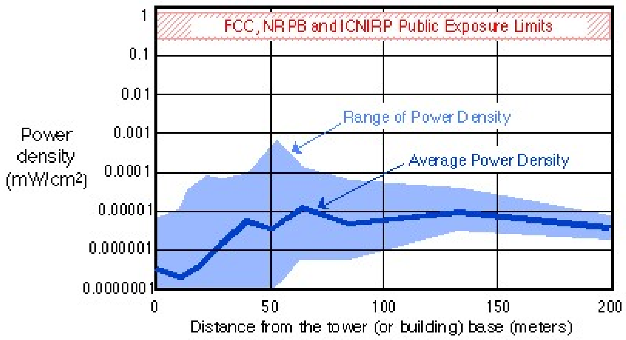

Fig. 2 The relationship between the RF power density and distance from the base of the tower or building on which the mobile phone base antenna was located. [13]
(Reproduced with permission from John Moulder)

A mobile phone transmits RF radiation in all directions and a proportion of it is directed to the body. It does not operate with a fixed output power level when a call is made. The maximum output powers of GSM phones operating at 900 MHz and 1800 MHz are 2 W and 1 W respectively but can be reduced by a factor of 1000 during calls.

Electric and Magnetic Fields

Exposure can arise at home, work, or school and is measured using personal or environmental monitoring. The
Electric fields depend on the magnitude of the voltage and distance from the source. Generally, voltages are stable and remain the same; however electric fields are easily perturbed by many common objects.

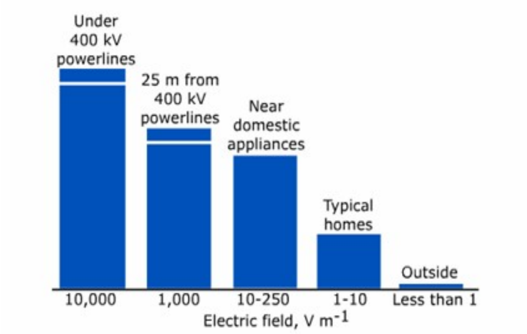

Fig. 3 Exposures to Electric Fields [14]
(Reproduced with permission from NRPB)

Exposure to magnetic fields arises from power lines and the use of electrical appliances. Ambient fields from the supply to the house are always present and expose the whole body, whereas those from appliances are intermittent and expose part of the body. The magnetic field strength depends upon the magnitude of the current and on the distance from the appliances.

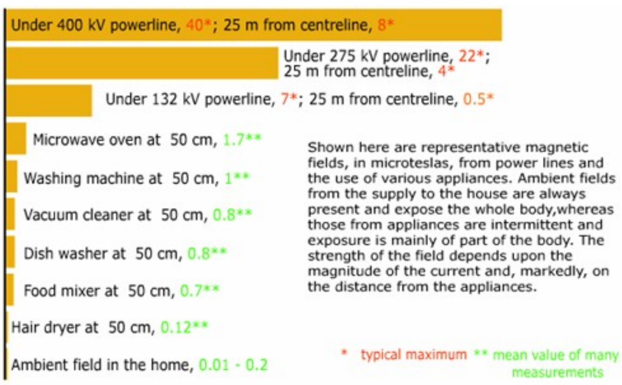

Fig. 4 Exposures to Magnetic Fields [14]
(Reproduced with permission from NRPB)

Occupational exposures to magnetic fields range from levels found in homes to several mT.

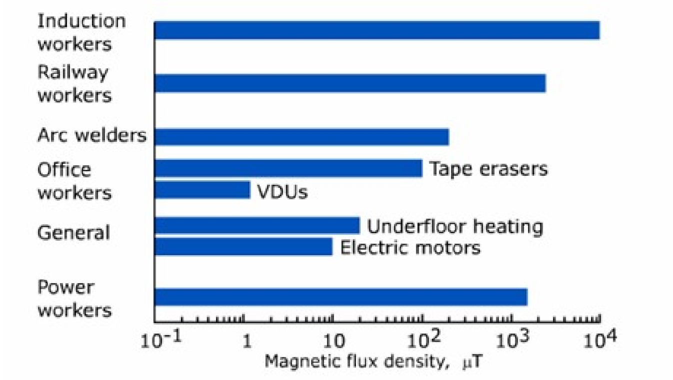

Fig. 5 Occupational Exposures to Magnetic Fields [14]
(Reproduced with permission from NRPB)

STANDARDS AND GUIDANCE FOR NIR

Standards and guidelines for limiting exposure and avoiding known adverse health effects have been drawn up by international and national bodies. These apply in general to characteristic parameters of the radiation field at the point in space where the individual can be or is exposed. They are based on biophysical models and on laboratory and field observations of the biological effects. The standards are *limits* for field parameters (e.g. to limit current density, SAR, and power density) which are designed to protect workers from potentially adverse effects of NIRs and to permit the general use of NIR under safe conditions, though there is no precise boundary between risk and no risk. [2]

The earliest recommendations for exposure limits for NIRs were established in the 1950s and 1960s for microwave and RF radiations generated by military radars and communication equipment. Recommendations for the protection of the eyes from lasers were established in 1970s. As concern for the increasing applications of all forms of NIRs, the International Non-Ionizing Radiation Committee (INIRC) was set up in 1977. In 1992 the INIRC was renamed the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

The ICNIRP works closely with the World Health Organization (WHO) to assess health effects of NIRs and to develop international guidelines on limits to exposure and protection measures.

Guidelines are often presented in terms of two levels of protection [3]:
- basic restrictions-based directly on established health effects
- reference levels - derived from measurements and/or computed predictions. These provide for practical exposure assessment to determine whether the basic restrictions are likely to be exceeded.

If a reference level is exceeded, it does not necessarily follow that the basic restriction is exceeded. However, in such cases, compliance with the basic restriction must be tested.

Guidelines often differentiate between occupational exposure and general public exposure:

- occupational/controlled exposures - appropriate when and can exercise control over it are exposed as a consequence of their employment. These limits also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

- general population/uncontrolled exposures - apply when the general public may be exposed or when persons who may not be fully aware of the potential for exposure or cannot exercise control over it are exposed as a consequence of their employment.

Recommended exposure limit for RF radiation from mobile phone is given in Table 2.

Table 2. Basic restrictions on exposure SAR* (W kg^{-1}) recommended by NRPB and ICNIRP for workers and members of the public

	Worker NRPB/ICNIRP	Public NRPB	Public ICNIRP
Whole body**	0.4	0.4	0.08
Head and trunk**	10	10	2.0
Limbs**	20	20	4.0

* SAR (specific energy absorption rate) is a measure of the rate at which energy is absorbed by unit mass of tissue in an electromagnetic field. It is measured in the units of watts per kilogram (W kg^{-1}).

** For calculating SAR the averaging time is taken to be 6 minutes for all tissues. ICNIRP also uses 6 minutes for the whole body but NRPB uses 15 minutes. The averaging mass is taken to be 10 g by ICNIRP while NRPB uses 10 g for the head (and fetus) but 100 g for the trunk, limbs and neck.

Guidelines for exposure to static magnetic fields

Several guidelines have been proposed by international and national agencies based on criteria such as the need to limit currents induced by movement through the static magnetic field to levels less than those that occur naturally in the body or to limit those induced in the large vessels by blood flow to below levels that result in haemodynamic or cardiovascular effects. ICNIRP [15] recommends limits on occupational exposure:

- short-term: whole body 2 T; limbs 5 T
- continuous exposure: 200 mT

(since these are for occupational exposure only, time-averaging is performed over the working day.)

- continuous exposure of the general public (except for those with pacemakers and other implanted devices): 40 mT
- continuous exposure of those with pacemakers and other implanted devices: 0.5 mT.

Guidelines for exposure to time-varying electric fields, magnetic fields, and electromagnetic radiation

ICNIRP [3] guidelines are presented in terms of two levels of protection (Tables 3 & 4). The conditions are:

All Specific Absorption Rate (SAR) values are averaged over any 6-min period and localized SAR values are averaged over a 10g contiguous mass of tissue.

? For pulses of duration *tp,* the equivalent frequency is determined by *1/(2tp).*
? For pulsed exposures in the frequency range 0.3 -10 GHz and for localized exposure of the head, the specific absorption should not exceed 10 mJ kg^{-1}, averaged over 10 g tissue.
? For frequencies up to 100 kHz and for pulsed magnetic fields, the associated maximum current density may be determined from the rise/fall times and maximum rate of change of magnetic flux density.

Table 3. ICNIRP [3] basic restrictions for electric and magnetic fields. The values given are for occupational exposures. Values relating to exposure of the general public are reduced by a factor of 5.

Frequency	RMS current density for head and trunk (mA m^{-2})	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})	Power density (W m^{-2})
Up to 1 Hz	40	–	–	–	–
1–4 Hz	40/*f*	–	–	–	–
4 Hz–1 kHz	10	–	–	–	–
1–100 kHz	*f*/100	–	–	–	–
100 kHz–10 MHz	*f*/100	0.4	10	20	–
10 MHz–10 GHz	–	0.4	10	20	–
10–300 GHz	–	–	–	–	50

f is expressed in Hz.
Current density is averaged over a cross-section of 1 cm^2 perpendicular to the current direction.
Power density is averaged over any 20 cm^2 of exposed area in any $68/f^{1.05}$-min period (*f* in GHz).
Spatial maximum power densities averaged over 1 cm^2 should not exceed 20 times the value above.

Table 4. ICNIRP [3] reference levels for exposure to electric and magnetic fields (unperturbed RMS values)

Frequency	*E* field ($V\ m^{-1}$)	*H* field ($A\ m^{-1}$)	*B* field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
Occupational exposures				
up to 1 Hz	–	163 000	200 000	–
1–8 Hz	20 000	$163\ 000/f^2$	$200\ 000/f^2$	–
8–25 Hz	20 000	$20\ 000/f$	$25\ 000/f$	–
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	–
0.82–65 kHz	610	24.4	30.7	–
0.065–1 MHz	610	$1.6/f$	$2.0/f$	–
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	–
10–400 MHz	61	0.16	0.2	10
400–2000 MHz	$3\sqrt{f}$	$0.008\sqrt{f}$	$0.01\sqrt{f}$	$f/40$
2–300 GHz	1.37	0.36	0.45	50
General public exposure				
up to 1 Hz	–	32 000	40 000	–
1–8 Hz	10 000	$32\ 000/f^2$	$40\ 000/f^2$	–
8–25 Hz	10 000	$4000/f$	$5000/f$	–
0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	–
0.8–3 kHz	$250/f$	5	6.25	–
3–150 kHz	87	5	6.25	–
0.15–1 MHz	87	$0.73/f$	$0.92/f$	–
1–10 MHz	$87/\sqrt{f}$	$0.73/f$	$0.92/f$	
10–400 MHz	28	0.073	0.092	2
400–2000 MHz	$1.375\sqrt{f}$	$0.0037\sqrt{f}$	$0.0046\sqrt{f}$	$f/200$
2–300 GHz	61	0.16	0.20	10

Units of *f* as indicated in frequency column.
E^2, H^2, B^2, and S_{eq} are averaged over any 6-min period for frequencies between 100 kHz and 10 GHz and over any $68/f^{1.05}$-min period for higher frequencies.

ICNIRP guidelines reflect current general consensus. However, other guidelines reflect some differences in the interpretation of the data available.

For the optical exposure limits, the two main organisations are responsible: ICNIRP [16,17] and the American Conference of Governmental Industrial Hygienists (ACGIH) [18].

Current understanding of the health effects associated with personal exposure to optical radiation is sufficiently well developed to enable employers to complete effective risks assessments of their work place activities, and to put in place the engineered and administrative controls necessary to ensure that exposure of their employees and other persons are adequately controlled. Occupational exposure situations must be evaluated individually for risks and benefits. Normally, only a very small number of people would ever be occupationally exposed to levels comparable to the exposure limits.

CONCLUSION

Research based on epidemiological studies, experimental biology, volunteer studies and dosimetry are being pursued actively. These areas of science play an essential role in identifying possible health effects and in providing information on appropriate exposure guideline levels. A most recent review of the scientific data relating to possible adverse health effects of exposure to electromagnetic fields in the frequency range 0-300 GHz is another milestone [19].

ACKNOWLEDGEMENT

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USEFUL WEB SITES

FDA on mobile phones
www.fda.gov/cdrh/phones/index.html

Federal Communications Commission (FCC) RF Safety Program
www.fcc.gov/oet/rfsafety

IEEE Engineering in Medicine and Biology Society Committee on Man and Radiation (COMAR)
http://ewh.ieee.org/soc/embs/comar/

Independent Expert Group on Mobile Phones
www.iegmp.org.uk/

International Commission on Non-Ionizing Radiation Protection (ICNIRP)
www.icnirp.de/

Medical College of Wisconsin. Electromagnetic Fields and Human Health.
http://www.mcw.edu/gcrc/cop/cell-phone-health-FAQ/toc.html

National Radiological Protection Board (NRPB)
www.nrpb.org.uk

World Health Organization (WHO)
www.who.int/peh-emf/

Appendix 1. Relevant mechanisms of interaction, adverse effects, biologically effective physical quantities and reference levels used in different parts of the optical spectrum. (ICNIRP 2002 [20])

Part of optical spectrum	Relevant mechanisms of interaction	Adverse effect	Biologically effective physical quantity	Exposure, reference level
Ultraviolet radiation UVA, UVB, UVC (180 to 400 nm).	Photochemical alterations of biologically active molecules such as DNA, lipids, and proteins.	Acute erythema, keratitis, conjunctivitis, cataracts, photoretinitis, accelerated skin aging, skin cancers.	Fluence and action spectrum weighted radiant exposure.	Radiant exposure at skin or cornea. exposure irradiance
Visible radiation (380 to 600 nm).	Photochemical alterations of biological molecules in the retina.	Photoretinitis ("blue-light hazard").	Retinal radiant exposure weighted by action spectrum.	Radiance and exposure duration.
Visible and near-infrared radiation (IRA) (400 to 1,400 nm).	Thermal activation or inactivation. Photocoagulation.	Thermal injury: skin burns and retinal burns. Thermal denaturation of proteins, tissue coagulation/necrosis.	Irradiance, radiant exposure and absorbing volume (spot size) at tissue site.	Radiance and duration.
Middle (IRB) and far-infrared radiation (IRC) (3 µm to 1mm).	Thermal activation or inactivation. Coagulation.	Thermal injury: skin and cornea1 burns, cataracts. Thermal denaturation of proteins. Tissue coagulation/necrosis.	Irradiance, radiant exposure and absorbing volume (spot size) at tissue site.	Radiant exposure and at skin or cornea.
Laser radiation (180 nm to 1 mm).	Photochemical, photothermal, photoacoustic, exposure duration <100 µs. Photoablative exposure duration < 100 ns. Bubble or plasma formation (change of phase). Non-linear optical effects.	Tissue damage. Skin burns. Ocular burns. Tissue vaporization.	Radiant exposure and irradiance.	Radiant exposure and irradiance at skin or cornea; exposure duration.

Appendix 2. Relevant mechanisms of interaction, adverse effects, biologically effective physical quantities and reference levels used in different parts of the electromagnetic field spectrum. (ICNIRP 2002 [20])

Part of NIR spectrum	Relevant mechanism of interaction	Adverse effect	Biologically effective physical quantity	Exposure, reference level
Static electric fields.	Surface electric charges.	Annoyance of surface effects, shock.	External electric field strength.	Electric field strength.
Static magnetic fields.	Induction of electric fields in moving fluids and tissues.	Effects on the cardiovascular and central nervous system.	External magnetic flux density.	Magnetic flux density.
Time-varying electric fields (up to 10 MHz).	Surface electric charges. Induction of electric fields and currents.	Annoyance of surface effects, electric shock and burn. Stimulation of nerve and muscle cells; effects on nervous system functions.	External electric field strength. Tissue electric field strength or current density.	Electric field strength. Electric field strength.
Time-varying magnetic fields (up to 10 MHz).	Induction of electric fields and currents.	Stimulation of nerve and muscle cells; effects on nervous system functions.	Tissue electric field strength or current density.	Magnetic flux density.
Electromagnetic fields (100 kHz to 300 GHz).	Induction of electric fields and currents; absorption of energy within the body. > 10 GHz: Surface absorption of energy. Pulses < 30 ps, 300 MHz to 6 GHz, thermo-acoustic wave propagation.	Excessive heating, electric shock and burn. Excessive surface heating. Annoyance from microwave hearing effect.	Specific energy absorption rate. Power density. Specific energy absorption.	Electric field strength; magnetic field strength; Power density. Peak power density