15 Non-Ionizing Radiation

"High frequency radiation is sometimes thought to be the cause of cancer, while low frequency radiation is generally assumed to be harmless."

Susan Dean and Barbara Illowsky

electromagnetic radiation

Radiation-protection regulations concern ionizing radiation like α, β, γ radiation and neutrons. Separate regulations concern the handling of X rays and X-ray-generating devices. γ radiation and X rays are electromagnetic waves: they differ from visible light or microwave radiation only by their energy or, equivalently, by their frequency or wavelength. It is only natural to ask to what extent electromagnetic radiation of other frequencies might be dangerous for humans.

Energy and frequency are related in a simple way following the relation discovered by Max Planck:

$$E = h\nu \ , \tag{15.1}$$

where ν is the frequency in hertz (cycles per second), and $h = 6.62 \times 10^{-34}\,\mathrm{W\,s^2}$ is Planck's constant. The frequency itself is related to the wavelength λ by

$$\nu\,\lambda = c \ , \tag{15.2}$$

where c is the velocity of light in vacuum.

Depending on the frequency or energy, electromagnetic radiation has quite different effects. The following Table 15.1 gives some characteristics of frequency ranges along with their commonly used names.

ionizing radiation

non-ionizing radiation

The transitions between the different characteristic ranges are not particularly well defined. To ionize atoms in human tissue an energy of approximately 30 eV is required. Therefore, radiation with frequencies below 10^{16} Hz corresponding to 30 eV are termed non-ionizing. Apart from defining electromagnetic waves by their frequency, wavelength, or energy, they can also be characterized by the associated electromagnetic field. An electromagnetic wave can be described by a transverse electrical and magnetic field, which are both perpendicular to the direction of emission. Electric and magnetic field vectors are also perpendicular to each other.

electric field strength

magnetic field strength

magnetic flux density

The electric field strength E is measured in V/m, the magnetic field strength H in A/m, and the magnetic flux density B in tesla

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classification	**frequency** $\nu[s^{-1}]$	**wavelength** $\lambda[m]$	**energy [eV]**
mains, AC current	≈ 50	$\approx 6 \times 10^6$	$\approx 2 \times 10^{-13}$
long-wave radiation	$\approx 6 \times 10^4$	≈ 5000	$\approx 2.5 \times 10^{-10}$
short-wave radiation	$\approx 3 \times 10^6$	≈ 100	$\approx 1 \times 10^{-8}$
ultrahigh-frequency radiation	$\approx 10^8$	≈ 3	$\approx 4 \times 10^{-7}$
mobile-phone communication	$\approx 3 \times 10^9$	≈ 0.10	$\approx 1 \times 10^{-5}$
microwaves	$\approx 6 \times 10^9$	≈ 0.05	$\approx 2 \times 10^{-5}$
radar	$\approx 3 \times 10^{10}$	≈ 0.01	$\approx 1 \times 10^{-4}$
infrared	$\approx 10^{12}$	$\approx 3 \times 10^{-4}$	$\approx 4 \times 10^{-3}$
visible light	$\approx 6 \times 10^{14}$	$\approx 5 \times 10^{-7}$	≈ 3
UV	$\geq 1.5 \times 10^{15}$	$\leq 2 \times 10^{-7}$	≥ 6
X rays	$\geq 2 \times 10^{17}$	$\leq 1 \times 10^{-9}$	$\geq 10^3$
γ rays	$\geq 2 \times 10^{20}$	$\leq 1 \times 10^{-12}$	$\geq 10^6$

Table 15.1
Characterization of electromagnetic radiation for different frequency ranges

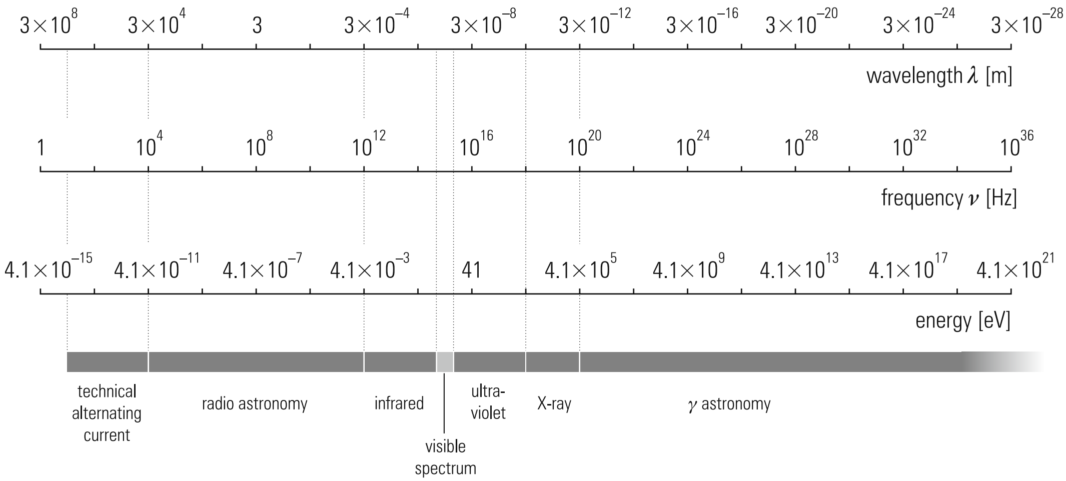

Figure 15.1
Spectrum of the electromagnetic radiation along with fields of typical applications

(1 tesla = $\frac{1\,\mathrm{V\,s}}{\mathrm{m}^2}$). The magnetic flux density B is related to the magnetic field strength by

$$B = \mu\mu_0 H \ , \qquad (15.3)$$

where μ and μ_0 are the relative permeability and the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}\,\mathrm{N/A^2}$),

$$[B] = [\mu_0]\,[H] = \frac{\mathrm{N}}{\mathrm{A}^2}\,\frac{\mathrm{A}}{\mathrm{m}} = \frac{\mathrm{N\,m}}{\mathrm{A\,m}^2} = \frac{\mathrm{V\,A\,s}}{\mathrm{A\,m}^2} = \frac{\mathrm{V\,s}}{\mathrm{m}^2} \ . \qquad (15.4)$$

current density

Electrical fields in conducting material lead to currents, where the current density (in ampere/cm^2) is responsible for possible biological effects.

nervous system
electrocardiogram
electroencephalogram

There are, however, already natural currents in the human body for conduction in the nervous system. The activity of the heart can be measured with an electrocardiogram (ECG), that of the brain with an electroencephalogram (EEG). The associated natural current densities vary between $0.1\,\mu A/cm^2$ and $1\,\mu A/cm^2$. These currents are related to low-frequency fields. Limits for additional low-frequency fields have to be set taking these natural current densities into account.

current density

The current density is related to the electrical voltage and field strength according to Ohm's law:

$$U = \varrho \frac{\ell}{q} I \qquad \text{and} \qquad E = \frac{U}{\ell} = \varrho \frac{I}{q} = \varrho\, j \tag{15.5}$$

(ϱ – specific resistance in Ω m, ℓ – length of the conductor, q – cross section of the conductor, $\frac{I}{q} = j$ – current density).

For the production of current densities of $0.1\,\mu A/cm^2$ in the human body external electrical fields of about $\approx 5\,kV/m$ and magnetic fields of $80\,A/m$ at frequencies of $50\,Hz$ are required. This corresponds to a magnetic induction of

$$B = \mu\mu_0 H = 4\pi \times 10^{-7} \times 80\, \frac{V\,s}{m^2} = 100\,\mu\text{tesla} , \tag{15.6}$$

Earth's magnetic field

which is on the same order of magnitude as the magnetic induction of the Earth's magnetic field. Therefore, it is only natural that limits for permanent exposure to low-frequency electromagnetic AC fields of $5\,kV/m$ and $100\,\mu T$ are proposed.

effects in nerve and muscle cells

Low-frequency electromagnetic fields create effects in nerve and muscle cells. In contrast, high-frequency radiation ($\gg 50\,kHz$) is characterized by its heat production after absorption. Therefore, it makes sense for this frequency range to consider the radiation power per mass unit. For a whole-body exposure, a limit of $\approx 0.1\,W/kg$ is recommended. For partial-body doses higher limits are tolerated[1] (head and body $2\,W/kg$, legs and arms $4\,W/kg$).

heat production of high-frequency radiation

mobile-phone communication
pulsed microwave radiation

In mobile-phone communications peak powers of up to 2 watts are reached. It has to be mentioned, however, that the biological effect of pulsed microwave radiation requires further research. The proposed limits in radiation-protection regulations for non-ionizing radiation depend on the assumption that the biological effect of microwave radiation for high frequencies can be characterized by its heating effect on tissue. Particular care must be taken for the brain and the eyes where one has to consider that the human body has poor heat-conducting properties. The limits are defined for the heat power

radiation-protection limits

[1] ICNIRP – International Commission on Non-Ionizing Radiation Protection

per unit area. As an example, some limits which are recommended in the European Union are compiled in the following table:

radiation source	**frequency range**	**maximum allowed power per square meter**
ultrashort wave	88–108 MHz	$2\,W/m^2$
VHF	174–216 MHz	$2\,W/m^2$
UHF	470–890 MHz	$2–4\,W/m^2$
D network	890–960 MHz	$4.5\,W/m^2$
E network	1710–1880 MHz	$9\,W/m^2$
UMTS	$\approx$ 2 GHz	$10\,W/m^2$
microwave ovens	2.45 GHz	$10\,W/m^2$

For comparison: the radiation power of the Sun in the visible range at the edge of the atmosphere is about $1400\,W/m^2$. This radiation power is attenuated in the atmosphere to different extents in different weather conditions. Under a cloudy sky, about $100\,W/m^2$ can be measured at sea level.

solar ultraviolet radiation

In the ultraviolet range, the heating of the skin becomes particularly important. For the spectral range between 315 and 400 nm, a limit for the eyes of $10\,W/m^2$ is recommended corresponding to an area energy density of $10\,kJ/m^2$ for an exposure time of 1000 s. For a solar radiation power in clear weather conditions corresponding to $300\,W/m^2$, an assumed exposure time of 1000 seconds and an exposed area of the skin of $0.5\,m^2$, one obtains an absorbed energy of

$$E = \frac{300\,W}{m^2} \times 0.5\,m^2 \times 1000\,s = 150\,kJ \ , \tag{15.7}$$

reddening of the skin

which already leads to a reddening of the skin for people with sensitive skin. This is due to the fact that the radiation is absorbed at low skin depths and transformed into heat.

15.1 Supplementary Information

Example 1

radiation cancer

ultraviolet radiation

Also non-ionizing radiation can cause skin cancer. An example for this is ultraviolet radiation, which is present in the spectrum of sunlight. The ultraviolet spectrum is subdivided into three ranges:

- UVA wavelength 400–315 nm energy 3.1–3.9 eV
- UVB wavelength 315–280 nm energy 3.9–4.4 eV
- UVC wavelength 280–100 nm energy 4.4–12.4 eV

tanning of the skin

pigmentation

The main effect of absorption of low-frequency or low-energy UV radiation is heating of the tissue. UVA radiation results in tanning the skin: the maximum effect is obtained at a wavelength of 340 nm. The threshold value for pigmentation is around $10\,\mathrm{W\,s/cm^2}$. If the dose of UVA, or more commonly UVB, is too high, sunburn results. Sunburn is not only created by the thermal effect of radiation. UV radiation also induces photochemical reactions in the skin which for high intensities can lead to the release of cellular poison.

UVC radiation is already energetic enough for quantum effects to occur. Depending on the absorbed energy, rotational or vibrational levels of electrons can be excited. For the highest energies, ionization processes can even occur. The required ionization energy depends on the type of atom. The biologically relevant atoms like carbon, oxygen, and nitrogen are only ionized for wavelengths below 100 nm, however. As well as ionization, the breaking of molecular bonds can occur. Atoms and molecules affected in this way tend to interact more intensively with the tissue leading to possible biological hazards.

grassing

In the early days this effect was taken advantage of for grassing. The ultraviolet radiation from the Sun produces hydrogen peroxide from the water using the oxygen of the air. The peroxide destroys the colorant embedded in the laundry thereby whitening the clothes. The exposure of plastic materials to UV radiation frequently also causes brittleness.

sunburn

inflammations of the cornea, keratitis

cataract

skin cancer

Apart from tanning and sunburn (erythema) also inflammations of the cornea (keratitis) and cataract of the eye may occur. Also damages with substantial latency which depend on the integrated radiation dose have been observed. The late effects mainly concern skin cancer (malignant melanoma) which shows up only after a certain delay. Already an excess of UVB radiation might lead to a formation

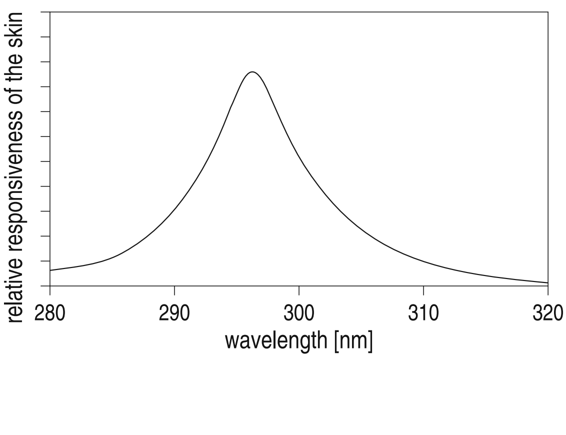

Figure 15.2
Relative responsiveness of the skin for UV radiation in the wavelength range from 280 nm to 320 nm (≈ UVB) (Canadian Centre for Occupational Health and Safety)

of precursors of cancer, the so-called solar keratoderma. Also basal cell carcinoma may emerge. This type of cancer is the most common and least lethal form of all cancers. An early treatment is important and usually effective. In contrast, high-frequency UV radiation favors the formation of malignant melanoma. In this case an early detection of the skin cancer is essential since malignant melanoma have the tendency to form metastases. Skin cancers are the fastest growing type of tumors in most countries with intense sunshine.

basal cell carcinoma

The negative effect of UV, particularly UVC, on biology can also be useful. With intense UVC radiation microorganisms, and especially bacteria, can be killed. Therefore, this type of radiation is suited for disinfection, in particular, for transparent media like water and air.

disinfection

Threshold values for the eyes, related to inflammations of the cornea and cataracts, are around $5\,\mathrm{W\,s/cm^2}$ for a wavelength of 315 nm. Limits for ultraviolet whole-body irradiations as well as those for inflammations of the eye depend strongly on the wavelength of the radiation. For the tanning effect of UVA radiation a safe limit is about $10^4\,\mathrm{W\,s/m^2}$ for an 8-hour day. For the dangerous UVC radiation (around 280 nm) the limit per day is considerably lower at $30\,\mathrm{W\,s/m^2}$. These energy area doses correspond to radiation powers in the respective wavelength range of $0.35\,\mathrm{W/m^2}$ (for 315 nm) and $1\,\mathrm{mW/m^2}$ (for 280 nm).

Example 2

Laser

Of particular importance are the radiation-protection regulations for Lasers (= Light Amplification by Stimulated Emission of Radiation). The biological effect of laser radiation is related to its extremely high power density. Because of the production mechanism, a laser beam is highly collimated. Laser beams are frequently used for alignment and laser-optical experiments. With laser beams very small holes can be burnt, tissue and material can be cut, and lasers can even induce fusion in a hydrogen plasma. The proposed limits for lasers show a rather complicated time and wavelength dependence. In particular, the eyes are potentially at risk when working with laser radiation. A commercial laser pointer emits mostly in the wavelength range between 630–680 nm (red). It has an output power of less than 1 mW and a beam cross section of about $2\times 2\,\mathrm{mm^2}$. Even this leads already to radiation power densities of $< 25\,\mathrm{mW/cm^2}$, corresponding to a maximum exposure of $250\,\mathrm{J/m^2}$ for an exposure time of one second.

extremely high power density

laser pointer

In addition to red lasers, green lasers are now available, which have higher power and better visibility. In the handling of laser beams, one must be aware of reflecting surfaces, as even reflections can be harmful.

femtosecond laser

Particular care has to be taken for lasers in the pulsed mode. At present there are femtosecond lasers which produce high-power laser pulses of 10^{-15} s duration.

hazard categories

Because of the large number of applications and laser variants, lasers are subdivided into different classes according to their potential hazard:

class 1: High security class. With such a type of laser it is impossible to exceed the allowed limits.

class 2: Laser of low radiation power in the optical range. For continuous-wave lasers the power limit is 1 mW. 'Red' laser pointers belong to this class 2.

class 3: Optical laser with powers > 1 mW. A direct view into the laser beam is dangerous. Diffuse reflexes of unfocused lasers of this class, however, are not dangerous.

high-power laser

class 4: High-power lasers for which diffuse reflexes are also hazardous.

CW laser

Limits for continuous-wave lasers (CW lasers) in the micrometer range (> 1400 nm) are $100\,\mathrm{mW/cm^2}$, and for nanosecond-pulse lasers the intensity limit is $< 10^{10}\,\mathrm{mW/cm^2}$. In the visible range the limits are $1\,\mathrm{mW/cm^2}$ (CW) or $5 \times 10^5\,\mathrm{mW/cm^2}$ for nanosecond pulses.

safety goggles

Scientists and technicians handling lasers have to wear safety goggles which are adapted for the relevant wavelength range. These goggles absorb laser beams reliably. However, the disadvantage is that in adjusting laser-beam equipment it is impossible to see the laser beam when wearing these safety goggles.

Example 3

mobile phone

antennas for mobile-phone communication

heating effect

SAR value

The discussion about possible dangers from the use of mobile phones has become quite widespread. Antennas for mobile-phone communications work at rather high frequencies, which depend on the network (900 MHz, 1800 MHz, or even 2 GHz for Universal Mobile Telecommunications System (UMTS)). The power from these antennas is not emitted continuously but in pulses with a frequency of 217 Hz. The photon energies are in the range of 5 μeV well below values which could lead to the breakup of molecular bonds or to ionizations. Therefore, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has recommended a limit for the emitted power based only on the effect of heating the tissue. The heat generated in the head during the use of mobile phones is of particular importance. The limit is at 2 W/kg. Exposures are characterized by the so-called SAR value (specific absorption rate), which judges on the biological effectiveness of non-ionizing radiation. For an exposure time of 30 minutes the 2 W/kg limit corresponds to an energy deposition of 3600 J/kg. Such a high non-hazardous value demonstrates the increased sensitivity of human tissue against ionizing radiation, for which only 4 J/kg gives a mortality of 50%.

By special precautions the exposure to microwave radiation can be reduced. It is better to use an areal antenna instead of a stub or helix antenna[2]. Also a metallic foil between head and antenna is advantageous. Further possibilities exist to decrease the power, like the optimization of the geometrical emission characteristic by appropriate electronic circuitry. Mobile phones with separate microphone and loudspeaker are also preferable. It has to be mentioned that children are much more sensitive to mobile-phone radiation because their nervous system is still developing.

areal antenna

helix antenna

Currently it is a matter of debate whether the limitation of mobile-phone radiation solely on its effect of heating of the tissue makes sense or can be justified. Even though it is known that electromagnetic fields have an effect on the nervous system and the cell membranes, there are still no solid scientific results which demonstrate that electrosmog effects might result in biological damage other than heating. However, it is conceivable that for certain frequencies resonance effects might show up. For UMTS frequencies (2 GHz), the resonance length is on the order of the dimensions of the head ($\lambda = 15$ cm). It has, however, to be mentioned that the electromagnetic skin depth at these high frequencies is only a few cm.[3]

heating effect

UMTS frequencies

"I no longer suffer from cold ears, since I use my mobile phone in winter time!"

[2] A helical antenna is an antenna consisting of a conducting wire wound in the form of a helix. In an areal antenna the linear arrangement of a stub antenna is replaced by a two-dimensional one, i.e., the conducting wire is spread over a surface. Areal antennas are mounted on a ground plane shielding the user of the mobile phone considerably against possible exposures.

[3] High-frequency electromagnetic radiation is attenuated in matter according to

$$I = I_0 \, e^{-x/\delta} \, , \tag{15.8}$$

where δ is a characteristic skin depth.

δ depends on the material properties as

$$\delta = \sqrt{\frac{2\varrho}{\omega\mu_0}} \, , \tag{15.9}$$

where ϱ is the specific resistance, ω the angular frequency ($2\pi \times$ frequency), and μ_0 the absolute magnetic permeability ($4\pi \times 10^{-7}$ N/A^2). For tissue typical penetration depths of about 3 cm for frequencies of 2 GHz are obtained.

Summary

From the point of view of physics non-ionizing radiation is not fundamentally different from short-wave, X-ray, and gamma radiation. For frequencies below 10^{16} hertz, electromagnetic radiation is non-ionizing, but biological processes in the human body are also influenced by non-ionizing radiation. Low-frequency radiation (alternating current, 50 Hz) affects humans via its electric and magnetic fields. High-frequency radiation (GHz range) leads to heating of the tissue. Ultraviolet light can lead to a burning of the skin and even to skin cancer because this radiation is completely absorbed at very shallow depths of the tissue. Particular care has to be taken with collimated laser beams which are characterized by very high power density.

15.2 Problems

Problem 1 Show that an external AC field ($\approx$ 50 Hz) of 5 kV/m is necessary to create a current density of $\approx 0.1\,\mu\text{A/cm}^2$ in the human body.

Problem 2 Estimate the electric and magnetic field strengths underneath a high-tension cable (220 kV, 1000 A current, height 30 m).

Problem 3 Low-voltage halogen lamps produce strong magnetic fields over a large area. Compare the magnetic field of a 12-V cable supplying a halogen lamp of 100 W at a distance of 1 m with the corresponding magnetic field caused by a conventional bulb operated at 220 volt.