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See also BRACHYTHERAPY, HIGH DOSAGE RATE; IONIZING RADIATION, BIOLOGICAL EFFECTS OF; NUCLEAR MEDICINE INSTRUMENTATION; RADIOTHERAPY, HEAVY ION.

NEUROSTIMULATION. See SPINAL CORD STIMULATION.

NMR. See NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY.

NONIONIZING RADIATION, BIOLOGICAL EFFECTS OF

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INTRODUCTION

Non-ionizing radiation (NIR) refers to that portion of the electromagnetic (EM) spectrum in which the characteristic wavelength is greater than around 180 nm. Radiation of shorter wavelength than this has sufficient quantum energy (given by hc/λ, with h = Planck's constant, c = wavespeed in vacuo, and λ = wavelength) to remove outer electrons from neutral atoms to cause the atom to become ionized, hence, the term "ionizing radiation." NIR consequently does not have the same intrinsic potential for atomic and molecular alteration or the health effects consequent to this. For this reason, damage to DNA and other biomolecules due specifically to the removal of electrons is difficult to envisage. The main groupings of NIR, with increasing wavelength (and decreasing frequency) are ultraviolet (UVR), visible, infrared (IR), radio frequency (RF), and extremely low frequency (ELF). The RF spectrum can be further divided as shown in Table 1 to include microwaves (MW), millimeter waves (MMW), terahertz radiation (THzR), as well as the conventional divisions for broadcast communications. Although not part of the EM spectrum, UVR is normally considered to be part of NIR, as are static (0 Hz) electric, and magnetic fields. The application of the term "radiation" to the ELF portion is also of little consequence, because the wavelength is several thousand kilometers at 50/60-Hz power frequencies.

NON-IONIZING RADIATION PROTECTION

Guidelines on NIR radiation protection are developed by the International Commission on NIR Protection (ICNIRP). In North America, other bodies have developed standards, such as the IEEE International Committee on Electromagnetic Safety and the American National Standards Institute (ANSI), or guidelines, such as the American Conference of Government Industrial Hygienists (ACGIH). Some jurisdictions have chosen to incorporate these (or related) guidelines into legislation.

The mechanism of interaction of NIR with living tissue varies with the groupings just mentioned. These are summarized below, along with effective protection measures against overexposure.

UVR

UVR exposure from the sun outweighs that from all other sources except for a small group of persons in exceptional circumstances. Solar UVR over-exposure is a worldwide problem, leading to increased skin cancer, and by World Health Organization estimates, up to 3 million people are made blind through cataracts. Burning of the skin is a direct indicator of overexposure, at least in the short term. Solar radiation and other UVR sources can initiate photochemical reactions, such as the breakdown of atmospheric oxygen to form oxygen-free radicals and ozone. UVR also has a role in vitamin D control and production. Of greater relevance to adverse health effects, biomolecules (such as DNA components and proteins) can undergo resonant UVR absorption to give rise to dimers (where two similar molecules join to form a single unit). For example, adjacent thymine bases in DNA can fuse to cause an abnormal form. The cell repair mechanisms can sometimes fail to detect this, leading to mutations. The initial response of the skin to UVR within hours of exposure is reddening (erythema or sunburn) due to increased blood flow and edematous changes. The role of photochemical reactions in erythema is unclear. In addition, the immune response can also be suppressed by UVR, increasing risk of infection. On the other hand, the socially attractive tanning of the skin is caused by UVR-induced increase in melanin pigmentation. Chronic exposure leads to skin aging and increased risk of skin cancer. Non-melanoma skin cancers (NMSC) include basal cell carcinoma (BCC: 80%) and squamous cell carcinoma (SCC). The risk of NMSC varies with annual solar UVR dose to the power of between 2 and 3. Melanoma, which has a poor prognosis due it its ability to metastasize, is related to the amount of sun exposure or sunburn during childhood. Chronic eye exposure leads to increased cataract risk. Certain pharmaceutical and other agents lead to photosensitization, in which absorption of longer wavelength UVR can lead to resonant absorption usually associated with shorter wavelengths. The UVR range is usually divided into UV A, B, and C, as indicated in Table 1. The rationale for this is that (1) biological photoreactions are less important above 315–320 nm, and (2) there is virtually no terrestrial solar radiation below 280–290 nm. The boundaries between the ranges are somewhat imprecise. UVA has less capability to cause erythema (by a factor of around 1000) than UV B, but because UVA radiation is the predominant form of solar radiation, it contributes around one sixth of erythemal dose. A minimum erythemal dose (MED) is the UVR exposure (in joule per centimeter squared), which gives rise to just noticeable reddening in the skin of previously unexposed persons. Overexposure is defined as that which leads to erythema within 3 hours or less in a normal population. MEDs have been determined experimentally for narrow bandwidths in the range 180–400 nm, giving a minimum of 30 $J \cdot m^{-2}$ at 270 nm. A set of values $S\lambda$, which denote the relative effectiveness of UVR to cause erythema at a specific wavelength λ, are then derived. For example, because at 180 nm, 2500 $J \cdot m^{-2}$ is required for the occurrence of erythema compared with 30 $J \cdot m^{-2}$ at 270 nm, S_{180} is 30/2500 or 0.012. As exposures are usually to a range of wavelengths (and mainly in the UVA range), a weighted sum for each wavelength component according to its capacity to cause erythema can be obtained. The standard erythemal dose (SED) is then defined such that 1 SED is 100 $J \cdot m^{-2}$. This measure is independent of skin type, because MED measurements relate to fair-skinned subjects. Most commonly, overexposure is a result of being outdoors without skin protection, but it can also result from artificial sun-tanning

Table 1. The Non-ionizing Radiation Spectrum

Name of Range	Frequency Range	Wavelength Range	Common Sources
Ultraviolet	UVC 1.07–3 PHz[a]	100–280 nm	Germicidal lamps, Arc welding
	UVB 0.95–1.07 PHz	280–315 nm	Solar radiation, Arc welding
	UVA 750–950 THz[b]	315–400 nm	Solar radiation, Solarium
Visible	430–750 THz	400–770 nm	Solar radiation, indoor and outdoor illumination
Infrared[c]	Near IR (IR A) 214–430 THz	0.7–1.4 µm	Furnaces
	Mid IR (IR B) 100–214 THz	1.4–3 µm	Night photography
	Far IR (IR C) 0.3–100 THz	3 µm–1 mm	Infrared spectroscopy
Terahertz			
Microwave (including millimeter wave)	Extremely High Freq 30–300 GHz	1 mm–1 cm	Satellite, radar, and remote sensing
	Super High Freq 3–30 GHz	1–10 cm	Speed radar guns, Communications
	Ultra High Freq 1–3 GHz	10–30 cm	Mobile telephony
Radio frequency	Ultra High Freq 0.3–1 GHz	30 cm–1 m	Mobile telephony
	Very High Freq 30–300 MHz	1–10 m	TV, FM Radio Broadcasting
	High Freq 3–30 MHz	10–100 m	Electro-welding equipment
	Medium Freq 0.3–3 MHz	100 m–1 km	AM Radio
	Low Freq 30–300 kHz	1–10 km	Long-wave radio
	Very Low Freq 3–30 kHz	10–100 km	Navigation and time signals
Extremely low frequency	< 3 kHz	> 100 km	Electrical power, Electrotherapy
Static	0 Hz		Geomagnetic field, Magnetic Resonance Imaging systems

[a]PHz = peta-Herz, or 10^{15} Hz
[b]THz = tera-Herz, or 10^{12} Hz
[c]The boundaries between near-, mid-, and far-IR are imprecise, as is the terahertz range indicated.

(in a solarium), proximity to tungsten halogen lamps (without filtering glass covers), proximity to UVR light-boxes in scientific and industrial applications, and certain forms of flame welding, with the main possibility of eye damage in these latter sources. Cases of erythema from fluorescent tubes have been reported in extreme cases of photosensitization. The main forms of protection are wearing appropriate clothing, sunblocks (such as zinc oxide cream), sunscreens (based on photo-absorbers, such as para-amino-benzoic acid and cinnamates), and effective sunglasses. Staying out of the sun where this can be avoided is a good behavioral approach for exposure minimization. The "sun protection factor" (SPF) is effectively the ratio of time of exposure before erythema occurs in protected skin to the corresponding time in unprotected skin. A ratio of at least 30 is recommended for effective protection in recreational and occupational exposure to solar radiation. It is important to ensure that sunglasses have sufficient UVR absorption to protect against cataract. Various forms of clothing protect against UVR exposure to differing degrees, ranging from wet open-weave cotton, which offers an ultraviolet protection factor or UPF (which is analogous to SPF) of only around 3–6, to elastane (Lycra) with UPF values of around 100 (99% absorption). It should be noted that these protection factors are computed as the ratio of effective dose (ED) with and without protection (ED/ED_m). The ED is the sum of solar spectral radiance components weighted according to erythemal effectiveness. Here $ED = \sum E_\lambda S_\lambda \Delta\lambda$, where E_λ is the solar spectral irradiance in watt per centimeter squared per nanometer, S_λ is the relative effectiveness of UVR at wavelength λ causing erythema (as mentioned), and $\Delta\lambda$ is a small bandwidth in nanometers. The units of ED are watt per centimeter squared. ED_m is similar, but it contains a factor T_λ to denote the fractional transmission of the test sunscreen (cream, fabric) at a particular wavelength (i.e., $ED_m = \sum E_\lambda S_\lambda T_\lambda \Delta\lambda$). The Global UV Index (UVI) is a dimensionless quantity in which the ED is summed over the range 250—400 nm and multiplied by 40 m^2W^{-1}. In Darwin, Australia, this ranges from 0 to 3 in the early morning and evening to 14 or more at noon on a clear day. At this UVI, erythema will result in fair skin after 6 minutes. See http://www.icnirp.de/documents/solaruvi.pdf for further information.

It is estimated that significant reductions in the incidence of both malignant and benign forms of skin cancer could be achieved by the enforcement of protective measures, particularly in occupational settings involving fair-skinned people in outdoor work in tropical or subtropical regions. Occupational exposures in Australia have recently been measured (1), and UVR safety has been reviewed in several publications (see Reference (2), for example). Indicative exposure limits are given in Table 2. It should be emphasized that for brevity many details are omitted from this table. For full details of limits pertaining to a particular geographical region, local radiation protection authorities should be consulted. The ICNIRP guidelines are readily accessible via downloads from http://www.icnirp.de. These represent reviewed publications originally appearing in *Health Physics*.

Visible Radiation

This is the region of NIR to which the retinal pigments of the eye are sensitive, so understandably, eye injury is the main concern in overexposure. There are two forms of hazard: photochemical and thermal. In addition, if the eye lens has been surgically removed (aphakia), there is an enhanced risk of damage. Photochemical damage becomes more likely with shorter wavelengths and is sometimes referred to as the "blue light hazard." The type of photochemical reaction is bleaching of the visual pigments, leading to temporary loss of vision. Thermal injury can result in permanent impairment of vision, especially if the foveal region, used for fine focus, is involved. Thresholds for these forms of injury have been determined in the wavelength range 400–1400 nm (thus including near infrared, see below) and an assessment of whether these are exceeded, for a particular source takes into consideration the spectral characteristics of the source. For exposures shorter than a few hours, the total radiance should be below 10^6 $W \cdot m^{-2} \cdot sr^{-1}$, where sr refers to a unit solid angle tended by the source. Lasers represent the sources most likely to cause injury, and because these emit a small number of discrete wavelengths, this assessment can be straightforward. Eye injury is minimized by the blink reflex, but laser wavelengths outside the visible range are less easy to control, because their paths are difficult to track, especially from incidental reflections. Lasers are classified according to the luminous power, their visibility, and their effective aperture, as described further in a separate entry on LASERS. High-power lasers are used in machining, welding, and engraving of a variety of materials, including plastics, metals, and fabrics. They also provide the source of beams in communications and photonics research laboratories. During normal operation, a combination of administrative and engineering controls provide adequate protection for workers. On the other hand, high-power lasers used in "light show" entertainment have sometimes given rise to unintentional beams directed at members of the public. The unrestricted distribution of laser pointers, with a capacity of causing eye damage, has also been a concern in several jurisdictions. Apart from laser sources, welding flames represent the next most common form of visible light hazard ("welder's flash"). Hazard can be minimized by the use of appropriate goggles. Recently, high-powered light-emitting diode (LED) sources have been evaluated by the ICNIRP for their potential for visible light hazard, particularly those emitting blue light. Although injury is unlikely, the power density of these devices continues to increase as technology develops.

IR

The major sources of IR radiation that are of concern are furnaces and some high-powered non-visible laser devices (femtosecond lasers). Here there is an increased possibility of local thermal injury, but because there is poor penetration of the lens of the eye, the possibility of retinal damage is reduced compared with the visible range. The IR range is divided into three ranges as shown in Table 1. Above 1–2 μm, water is a strong absorber of IR. Whereas guidelines for optical radiation extend up to 1.4 μm (near

Table 2. Approximate Exposure Limits for NIR: Exact Limits Vary Between Countries and In Some Cases Between Different Contexts of Exposure

Name of Range	Indication of Level Above Which Intervention Is Recommended	Biohazard Forming Basis of Protection	References to *Health Physics* Publications
Ultraviolet	U-shaped over wavelength range: 180 nm–2.5 kJ·m^{-2}; 270 nm–30 J·m^{-2} (minimum); 400 nm–1 MJ·m^{-2}	Skin reddening due to burn (erythema), also prevention of cataract	Vol 71, p 978 (1996) Vol 84, pp 119–127 (2004)
Visible	Depends on viewing position and spectral content of source	Retinal thermal or photochemical damage	Vol 73, pp 539–554 (1997)
Lasers (includes above and below)	Depends on wavelength, exposure duration, and size of aperture. For long exposures (> 100 s), limits are of the order of 1 W·m^{-2}	Retinal (esp. foveal) damage: photochemical or thermal Also skin.	Vol 71, pp 804–819 (1996) Vol. 79, pp 431–440 (2000)
Infrared	100 W·m^{-2} for long exposure*	Thermal injury to lens and cornea	Vol 73, pp 539–554 (1997)
Terahertz	Not well defined		
Microwave (including millimeter wave)	6–300 GHz: 50 W·m^{-2} (time averaged) 50 kW·m^{-2} peak[a] 10 mJ·kg^{-1} within 50 μs interval[a]	Rise in tissue temperature sufficient to cause protein denaturation Microwave hearing	Vol. 74, pp 494–522 (1998) As above
Radio frequency	0.1–6,000 MHz: 0.4 W·kg^{-1} for whole-body exposure; 10 W·kg^{-1} for 10 g mass (head and torso)[a]. 3–10,000 kHz: f/100 (f in Hertz) mA·m^{-2} in head and torso[a]	Rise in tissue temperature sufficient to cause protein denaturation Shocks or burns due to induced current or contact current	As above As above
Extremely low frequency	Tissue induced field: 18 mV·m^{-1} for f, 20 Hz; 18(f/20) mV·m^{-1} for f between 20 & 800 Hz (IEEE)[b], 10 mA·m^{-2} for range 4–1,000 Hz (ICNIRP)	Magnetophosphenes, micro-shock	As above
Static	0.2 T time weighted average[a], 2 T ceiling, 5 T limbs	Magnetophosphenes associated with movement	Vol 66, pp 100–106 (1994)

[a] These basic restrictions are for occupational exposures: Divide by 5 to get general public limits.

[b] These basic restrictions are for "controlled environment" (i.e., occupational) exposures: Divide by 3 to get general public limits.

infrared), there is some disagreement on the appropriate levels beyond that. Levels of incident radiation above 100 W·m^{-2} are considered as posing an unacceptable thermal hazard. Those at risk of overexposure include foundry workers and welders. Recently, advances have extended telecommunications frequencies into the "terahertz gap," the region between 0.3 and 3 THz, which has been unexploited by technological applications. The health effects are currently unknown, but they are expected to be similar to those of the contiguous frequency ranges. However, there is a current discontinuity between IR and RF standards or guidelines for a 1 mm wavelength (0.3 THz).

RF

Common sources of high-power RF emissions include welding equipment and induction heaters used in industrial drying processes. Radio, TV, and telecommunications transmitters can involve high broadcast powers (400 kW or more for commercial TV stations). There are two types of potential hazard: thermal injury in the range 100 kHz–300 GHz and neural stimulation due to induced currents or contact with metallic surfaces at frequencies below 10 MHz. At 300 GHz, the effective wavelength in tissue is less than 1 mm, so very little will penetrate below the skin. On the other hand, at 80 MHz, the wavelength is comparable with the long axis of the human body, so absorption is enhanced. Protective measures in terms of incident RF power density (W/cm^{-2}) are thus strictest in the range 10–400 MHz. The basic restriction above 100 kHz is on the rate of energy absorption by tissue (specific absorption rate, or SAR, in W/g of tissue). SAR is related to the RF electric field induced in tissue (E_i V·m^{-1}) such that

$$SAR = \sigma E_i / \rho$$

where σ is local conductivity in S/m and ρ is tissue density in kg/cm^3. In unperfused insulated tissue, SAR is related to the rate of rise of temperature dT/dt via

$$SAR = k \cdot dT/dt$$

where k is the specific heat of tissue, 3480 J·kg^{-1}·K^{-1} approximately.

This basic restriction is limited to values for whole-body or localized exposures such that normal thermoregulation would not be compromised, with a 10-fold safety margin. Although there is some variation between standards in place throughout the world, many countries employ a distinction between occupationally exposed persons ("aware users") and the general public, for whom an extra five-fold level of protection is provided. The ICNIRP value for whole-body SAR for the general public is 0.08 W·kg^{-1}, with higher values of 2 W·kg^{-1} in the head and trunk and 4 W·kg^{-1} in the limbs, averaged over 10 g of tissue. The power density of incident plane-wave radiation (in watt per centimeter squared), which would give rise to these levels of SAR (for far-field exposures), has been computed by mathematical modeling and animal studies in a conservative manner, such that if these reference levels are complied with, the basic restrictions will be met. As, for free space, the power density S is related to the electric and magnetic field values (E and H, respectively) by $S = E^2/377 = H^2 0.377$, compliance testing can be accomplished by measuring E-field values alone. Reference levels at particular frequencies can be found by reference to the ICNIRP guideline as indicated in Table 2.

Induced current density restrictions are imposed at 10 MHz and below. Above this frequency, it is considered that the fields vary too quickly to produce neural stimulation. Again, there is a safety factor of 10 between occupational levels and the level at which mild stimulatory effects can be noted in 1% of the population. This ranges from 100 A·m^{-2} at 10 MHz to 10 mA·m^{-2} at 4 Hz–1 kHz, in the ICNIRP guidelines. This will be discussed further in the ELF section.

At frequencies between 0.2 and 6 GHz, a phenomenon of "microwave hearing," due to thermoelastic expansion of brain tissue in response to pulsed radiation, occurs. Additional restrictions are in place in the ICNIRP guidelines to prevent this from occurring.

Overexposure to RF radiation, leading to serious burns, is usually due to the failure of control measures, such as guards on RF seam welding apparatus or work on RF antennas mistakenly thought to be nonoperational.

The safety of communications equipment, including mobile telephony handsets and base stations, is a major community concern. There is little substantive evidence of harm from long-term exposure at so-called "non-thermal" levels, but because there are many young users of handsets, many countries have endorsed a precautionary approach, encouraging use only for necessity. The scientific evidence for the possibility of "non-thermal" effects has been reviewed in the United Kingdom by the Independent Expert Group on Mobile Phones (IEGMP) (3) and by other bodies. The IEGMP concluded that although "the balance of evidence to date suggests that (low levels of RF radiation) do not cause adverse health effects" that "gaps in knowledge are sufficient to justify a precautionary approach." Some national standards (for example, Australia and New Zealand) incorporate a "precautionary" clause; that is, exposures incidental to service delivery should be minimized (but taking other relevant factors into consideration). The limiting of mobile phone use by children was recommended by the IEGMP (3), but the Health Council of the Netherlands sees no convincing scientific argument to support this (4).

ELF and Static

The range of frequencies (0–3 kHz) includes power transmission and distribution systems (50/60 Hz) as well as transportation systems (0, 16.7, 50, and 60 Hz), surveillance systems, and screen-based visual display units. Here the main potential hazard from exposure to fields (rather than direct contact with conductors) seems to be from inappropriate neural stimulation due to induced current (as in the case of RF, above). Consequently, treating ELF as a special case may seem out of place, but because the ELF range is precisely that of biogenic currents due the operation of nerves and muscles, its separate treatment is justified. The susceptibility of cells to the influence of exogenous currents is related to the time constants for the operation of cell membrane channels, which are typically of the order of milliseconds. At lower frequencies, cell membranes tend to adapt to imposed electrical changes, so restrictions need to be strictest in the range 10–1000 Hz. In humans, the retina of the eye represents a complex network of interacting nerve-cells, giving rise to sensations of pinpoints of light when stimulated by external electric and magnetic fields (EMFs). As this gives a guide to the levels at which stimulatory effects could become an annoyance, or could possibly be interpreted as a stressor, a basic restriction for occupational exposure of 10 mA·m^{-2} (which corresponds to an induced field of around 100 mV·m^{-1}) has been adopted by the ICNIRP for the range 4–1000 Hz. This restriction rises above and below this range. In particular, at 0 Hz (static fields), levels are restricted to 40 mA·m^{-2}. Levels for the general public are less by a factor of 5. Reference levels for magnetic fields are derived from these basic restrictions by considering the body to be simple geometric objects, but more advanced modeling yields similar results. For sinusoidally varying fields, the reference magnetic fields can be derived from basic restrictions via the formulas

$$B = E/(\pi f r) \quad \text{or} \quad B = J/(\sigma \pi f r)$$

where E refers to the basic restriction in terms of induced tissue electric field (in volt per meter), J is the basic restriction in induced current density (A/cm^2), f is the frequency in Hertz, σ is the tissue conductivity (S/m), and r is the radial distance from the center of symmetry (in the same direction as the external magnetic field B).

Electric field reference levels are derived more from considerations of avoiding "microshocks," which may occur, for example, if an arm with finger extended is raised in an intense electric field. Details of these reference levels can be found (for the ICNIRP limits) at http://www.icnirp.de. As it is possible to exceed the electric field reference levels in electrical switchyard work, special precautions need to be taken. Exceeding magnetic field reference levels is rare. Some government and other organizations have advocated a much more prudent approach to limiting exposure, particularly to the general public. This comes from some dozen or so well-conducted

epidemiological studies linking exposure of children to a time-weighted average magnetic field of 0.4 μT or more, to an approximate doubling of leukemia incidence. The possibility of low-level health effects of ELF has been the topic of research for nearly three decades. As there is no agreed mechanism for how elevated leukemia rates could be brought about, nor is there adequate evidence from long-term animal studies, there is doubt that magnetic fields are the causative agent. Nevertheless, time-varying ELF magnetic fields (but not electric fields, nor static fields) have been categorized by the International Agency for Research in Cancer (IARC) as a "possible carcinogen" (category 2B) (5). Essentially, the U.S.-government funded EMF-RAPID (Electric and Magnetic Field Research and Public Information Dissemination) program, whose Working Group reported in 1998 (6), came to a similar conclusion. The final report of the NIEHS Director (7), on the other hand, concluded that "the scientific evidence suggesting that ELF-EMF pose any health risk is weak" but also acknowledged that "exposure cannot be recognized as entirely safe because of weak scientific evidence that exposure may pose a leukemia hazard." The report also advocated "educating both the public and regulated community on means aimed at reducing exposures." There is intense debate on how a policy of prudence should actually be interpreted, because approximately 1% of homes would be in the "over 0.4 μT" category (8,9) (this percentage varies widely between and even within countries). Several moderate cost engineering measures can be employed to reduce field levels from transmission lines, and electric power companies often employ these in new installations.

PERCEIVED ELECTRO-SENSITIVITY

Several persons claim debilitating symptoms associated with proximity to electrical installations or appliances or in association with the use of mobile (cell) phones. Despite several well-conducted, independent, "provocation studies," in which sufferers have been subjected to energized and not energized sources in random order, no association between exposure status and occurrence of symptoms has been established. A recent Dutch study of psychological sequelae of mobile phone use implied that the overall baseline responses in a group of "electro-sensitives" differed from a similarly sized group of "normals," but that the changes associated with mobile phone use were similar in both groups.

ULTRASOUND

Few processes and devices outside of clinical medicine involve the possibility of human exposure to ultrasound if normal protective guarding measures are in place. Airborne ultrasound is used in surveying instruments and in a variety of drilling, mixing, and emulsification industrial processes. Ultrasonic descalers are used in dentistry and to clean jewelry. Reports of injury are rare. For industrial applications, the frequency range of 20–100 kHz is covered by ICNIRP limits and is based on the pressure amplitude of the ultrasound in air (these are of the order of 110 dB, referenced to 2×10^{-5} Pa). In clinical applications, ultrasonic energy is usually delivered across the skin via coupling gel and is in the frequency range 1–25 MHz. Diagnostic ultrasound is designed to prevent tissue temperature rising above 41 °C for sustained periods (10,11). Effectively, beam intensities are capped at 1000 W·m^{-2} (spatial peak, temporal average), except for short periods of insonation. Higher intensities are possible if the energy density is below 500 kJ·m^{-2}. This gives a large margin below established hazardous effects. Therapeutic ultrasound exposure is usually limited by patients reporting excessive heat, but use on patients with limited sensation is of concern. Intensities of 10 kW·m^{-2} are common in therapeutic applications. Tissue damage occurs above 10 MW·m^{-2}.

SERIOUS INJURY FROM NIR

From above, it would appear that NIR is fairly innocuous. It should be stressed, however, that high-power devices, if inappropriately used or modified, can cause serious injury. UVC is routinely used as in germicidal devices, and the micro-cavitation produced by intense ultrasound beams is used to disrupt tissue. Laser skin burns occasionally occur in research laboratories. Severe injury and fatalities have resulted from surgical uses of lasers in which gas embolisms have become ignited within body cavities. Early unshielded microwave ovens were associated with severe kidney damage. Cases of severe burns are still too common in small businesses using RF heat sealers, often due to the removal of guards. Serious burns result from an accidental or ill-advised approach to broadcast antennas and other communications equipment (12). In addition to burns, severe chronic neurological deficits can also result from overexposure to RF currents (13).

ACHIEVING ADEQUATE PROTECTION AGAINST NIR

Opinion is divided about the need to control NIR exposure by legislation. Communications equipment manufacturers have to comply with rigid requirements related to health guidelines and standards, and many countries have the power to prosecute in instances where equipment is tampered with or altered such that the guidelines would be exceeded. Codes of practice often have provisions for marking "no go" areas where levels could be exceeded, with appropriate signage. In terms of the potential for preventing debilitating illness or early death, the link between solar UVR and skin cancer and cataract represents the area where intervention is most warranted. It is estimated that adequate sun protection could perhaps save tens of lives per million of population per annum with over $5M pa per million in savings in health costs. The costs of ensuring employers of outdoor workers and the workers themselves complying with measures of UVR exposure reduction are hard to estimate, but they are likely to be high. Whereas compliance with a limit of 30 J·m^{-2} equivalent (or MED) is achievable in relation to artificial sources, this level can be exceeded in less than an hour's exposure to intense solar

radiation around noon in low latitudes. Employers can be required to educate their workforce to use appropriate measures to reduce the risk of becoming sunburnt, but it is virtually impossible to eliminate this from actually occurring. It would seem unreasonable to require employers to be responsible for an overexposure to a familiar and essential source of energy to which we have all been exposed since the dawn of time.

As several forms of NIR carry with them an uncertainty of possible harm in the long term, several national radiation protection authorities have espoused the "Precautionary Principle." This entails taking measures to reduce exposure, even where exposures are well within levels set by scientific evaluation of the available research. It is recognized that reducing exposure might itself introduce new hazards or increase other hazards (such as being unable to use a cell-phone in an emergency because of extra power restrictions), so an evaluation of the need to be "Precautionary" with respect to NIR should be in the wider context of overall risk management. In general, the introduction of arbitrary extra margins of safety, in order to appease public outcry, is not warranted.

USES OF NIR IN MEDICAL DIAGNOSIS AND THERAPY

UVR

The UVR-induced photochemical reactions form the basis of an effective treatment of the disease psoriasis, which is marked by widespread red itchy scales on the skin. This is caused by an accelerated cell cycle and DNA synthesis in skin cells. The drug psoralen is preferentially taken up by these dividing cells, which on subsequent exposure to UVA radiation, leads to binding with DNA and subsequent inhibition of synthesis and cell division. A normal course of treatment consists of 25 monthly visits to a clinic, with 8-methoxypsoralen taken orally, followed 2 h later by a UVR exposure of 10–100 kJ·m^{-2} per visit. This is usually delivered via a bank of 48 or so high-intensity fluorescent tubes.

A second use of UVR in biological and clinical analysis and research is in the identification of biomarkers through fluorescence. One technique involves placing electrophoretic gels over a UVR lightbox to localize the fluorescent regions. As mentioned, the possibility of overexposure in those who perform multiple observations is a matter of concern.

Lasers

The high intensity of laser radiation, particularly if it is pulsed, provides a means of tissue ablation, carbonization, coagulation, and desiccation. High-intensity short pulses produce photomechanical disruptions of tissue. At longer pulse lengths (~ 1 s), thermal and photochemical processes become more important. Excimer (= excited dimer) laser radiation has proved to be useful in the surgical treatment of defects in vision. This technique, radial keratotomy or keratectomy, reshapes the corneal surface to alter the effective focal length of the eye and thus do away with the need for spectacles or contact lenses. Laser ablation is also useful in the treatment of ocular melanoma, Barratt's

esophagus, removal of "port wine" stains on the skin, and (using an optical fiber delivery system in a cardiac catheter) the removal of atheromatous plaque in coronary arteries. A second property of intense laser light, that of photo-activation, is exploited in a range of treatments known as photodynamic therapy (PDT). In this, several compounds are known to be preferentially taken up by tumor tissue but also have the property of resonant absorption of light to produce free radicals, such as singlet oxygen and oxygen radical, which ultimately lead to endothelial cell membrane damage, blood supply shutdown, and hence necrosis of tumor tissue. These photosensitizing compounds are injected, or in some cases taken by mouth. Intense laser light (of 600–770 nm wavelength) is then directed at the tumor to produce this photo-activation. Energy thresholds are of the order of 1 MJ·m^{-2}. Although used mainly on superficial tumors (depth less than 6 mm), optical fiber delivery into deeper tissue (such as the breast) has also been trialled. As the tumor tissue becomes fluorescent on uptake of these compounds, diagnostic techniques (photodynamic diagnosis or PDD) are based on a similar principle. Suitable compounds are related to hemoglobin (hematoporphyrin derivative or HpD), rhodamine, amino levulinic acid, bacteriochlorins, and phthalocyanines. The herb St John's Wort also yields hypericins that have similar properties. The ability to use scanning optics in association with optical fibers has provided ways of making microscopic endoscopy possible.

Incoherent sources of blue light are used in the treatment of neonatal jaundice (hyperbilirubinemia). Bilirubin is decomposed during the exposure of the neonate to fluorescent tubes (filtered to remove wavelengths shorter than 380 nm).

IR

Infrared reflectivity from the skin and from layers immediately below the skin varies with skin temperature. Thermography has been used to identify regions of enhanced or reduced peripheral blood flow, occurring, for example, in mammary tumors. The high false-positive rate has inhibited its use in mass screening for this disease. On the other hand, breast imaging using time-of-flight IR transmission methods shows promise. Blood oxygen saturation is easily measured noninvasively via the ratio of reflectances at two wavelengths, 650 and 805 nm (the wavelengths showing greatest and least sensitivity to the degree of saturation, respectively). This forms the basis of the pulse oximeter, which clips on the finger and gives an indication of pulse rate in addition to oxygen saturation. Laser Doppler blood flow meters give an indication of capillary blood flow via the autocorrelation of reflected light signals. Wavelengths of 780 nm are selected because of the good depth of penetration of skin.

IR spectroscopy has a wide range of industrial and research applications, because of specific molecular stretching, bending, and rotational modes of energy absorption.

Terahertz

Several medical applications have been proposed for terahertz radiation, arising out of differential reflection from

cancerous/normal skin and from its relatively good transmission through bones and teeth. Its use in biosensing is also being investigated.

RF

The tissue heating and consequent protein denaturation has been used in catheter-tip devices for ablating accessory conduction pathways in the atria of the heart, giving rise to arrhythmias. The use of focused RF in cancer hyperthermia treatment has been used in conjunction with conventional radiotherapy to improve the hit rate of the latter, most likely due to the increased available oxygen via thermally induced blood flow increase. Increased blood perfusion is also thought to underlie the use of RF diathermy in physiotherapy, although this has now been almost entirely replaced by therapeutic ultrasonic diathermy (see below). RF exposures are part of magnetic resonance imaging (MRI), where some care has to be taken to avoid "hot spots" during investigation. SARs can exceed $2\,W{\cdot}kg^{-1}$ at frequencies in the region of 100 MHz. If we can extend the term "radiation" to include the direct application of RF currents, then electrical impedance tomography (EIT) should be included. In this technique, current of approximately 50 kHz is applied via a ring of electrodes to the torso or head, essentially to identify differential conductivity values in different organs and thus track shifts in fluid content, post-trauma, for example.

ELF

In clinical diagnosis, nerve conduction and muscular function studies are performed by examining responses to electrical stimulation (by single pulses or trains of pulses of the order of a few milliseconds in duration) of particular groups of nerve fibers. Electrical stimulation of specific regions of the body are also reported to give rise to beneficial effects. For example, or transcutaneous electrical nerve stimulation (TENS) is of some efficacy in controlling pain by raising the threshold for pain perception. Interferential therapy, which consists of a combined exposure of regions of the skin to low currents at two narrowly separated frequencies (for example, 4 kHz and 3.7 kHz) are claimed to be useful for a range of muscular and joint pain conditions and for circulatory disorders, but the mode of interaction is unclear. The currents are of the order of 50 mA, and the tissue is reportedly performing a demodulation of the 4 kHz carrier to produce a TENS-like deep current of a few hundred Hertz. Similarly, pulsed magnetic fields (PEMFs) are claimed to be effective in speeding healing in bone fractures, despite the small magnitude of induced currents. On the other hand, electroconvulsive therapy (ECT), in which pulses of current of several milliamperes are passed through the head, cause general nerve activation. This therapy is of proven value in cases of severe depression, but the origin of this benefit is an enigma. Transcranial magnetic stimulation (TMS) can be used both in diagnosis by eliciting specific responses and in therapeutic mode, in a manner analogous to ECT. However, the therapeutic efficacy of TMS still awaits clarification.

Static

The application of permanent magnets to painful joints is claimed to have beneficial effects, but the evidence for efficacy is equivocal. It has been suggested that the Lorentz-type forces on flowing electrolytes (such as blood) produce electric fields and currents. However, at typical blood flow velocities of $0.1\,m{\cdot}s^{-1}$, a 1 mT magnet will only induce $0.1\,mV{\cdot}m^{-1}$, which is well below levels shown in Table 2.

Ultrasound

The use of ultrasound in the range 1–25 MHz in diagnosis originates from the wavelength (and, hence, resolution) being of the order of a few millimeters. Acoustic mismatch between tissue layers gives radar-type echoes that form the basis of 2D and 3D imaging. The Doppler shift due to flowing fluid forms the basis of its use in blood flow measurements. Differential absorption provides a means for tissue characterization. In therapeutic ultrasound, the warmth is produced by adiabatic expansion and contraction within the tissue, to a depth of several centimeters. At higher intensities, cavitation and mechanical movement of organelles can occur.

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