Chapter 15

NONIONIZING RADIATION

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INTRODUCTION

The electromagnetic (EM) radiation spectrum has been divided into somewhat arbitrary frequency regions (Figure 15-1). The spectral divisions are usually based on the radiation's originating process and the manner in which this radiation interacts with matter. The most useful divisions are between ionizing radiation (X rays, gamma rays, and cosmic rays) and nonionizing radiation (ultraviolet [UV] radiation, visible light radiation, infrared [IR] radiation, and radio-frequency [RF] waves). The division between ionizing and nonionizing radiation is generally accepted to be at wavelengths (λ) around 1 nm, in the far-UV region.

Ionization of matter occurs when an electron that is orbiting a stable atom is expelled. Atoms of all elements can become ionized, but only gamma rays, X rays, alpha particles, and beta particles have enough energy to create ions. Because ions are charged particles, they are chemically more active than their electrically neutral forms. Chemical changes that occur in biological systems may be cumulative and can be detrimental or even fatal.

Another obvious division occurs at wavelengths of approximately 1 mm between the optical and RF radiation regions. These can be further divided into narrower bands ad infinitum. The radiation produced in this portion of the spectrum, however, does not possess energy sufficient to ionize matter. This nonionizing radiation excites atoms by raising their outer electrons to higher orbitals, a process that may store energy, produce heat, or cause chemical reactions (photochemistry). The biological effects of nonionizing EM radiation are caused by thermal stress (the accumulation of heat). When heat is dissipated, the effects do not persist (they are not cumulative). When the thermal stress is extreme, however, persisting injuries such as erythema, cataracts, or burns can occur. These are not minor injuries: for RF radiation, the burn can be internal and life threatening; for laser systems, the injuries occur to the eye.

CHARACTERISTICS OF ELECTROMAGNETIC RADIATION

Two complementary concepts have been used to describe EM radiation: the wave model and the particle model.[1] Certain EM phenomena are easier to conceptualize with the wave model, and others are easier to conceptualize with the particle model. The wave model characterizes EM radiation as *the propagation of energy through transverse oscillations of the electric and magnetic fields*. These EM waves are measured by

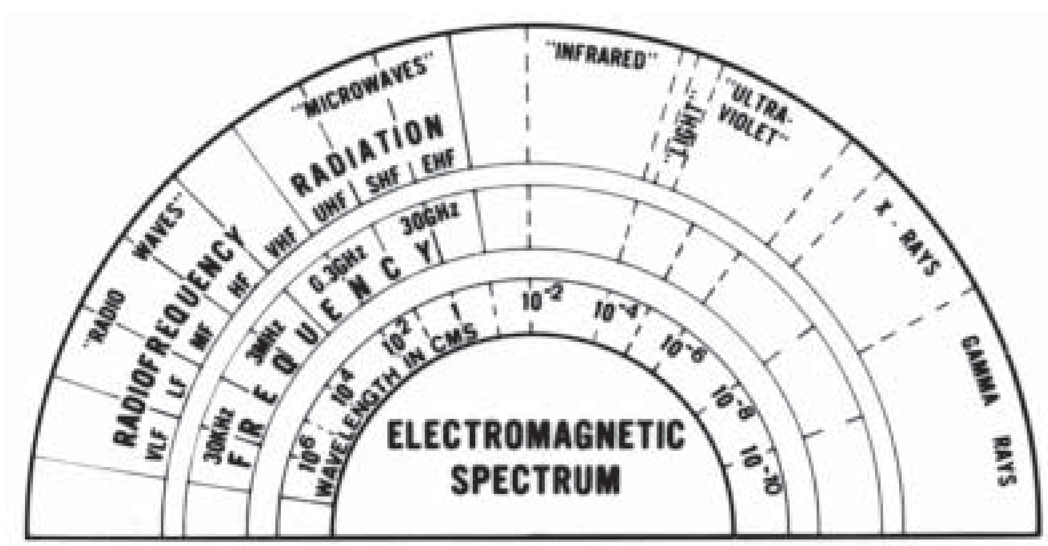

Fig. 15-1. The divisions of the electromagnetic spectrum are arbitrary, overlapping regions on a continuum. The generally accepted divisions are cosmic rays λ < 0.005 Å; gamma rays λ 0.005–1.4 Å; X rays λ 0.1–100 Å; ultraviolet (UV) λ 40–400 nm; visible light λ 400–700 nm; infrared (IR) λ 700 nm–1 mm; microwave (MW) λ 1 mm–1 m; radio-frequency (RF) λ >1 m.

four parameters: frequency, wavelength, polarization, and amplitude (field strength). The *frequency* of a wave is its number of oscillations per second as measured in hertz; the *wavelength* is the distance between successive waves, or the distance between the peaks. *Polarization* is the relative orientation of the EM radiation (horizontal, vertical, or circular). *Amplitude* is the absolute strength of the EM radiation as measured in volts per meter or amperes per meter. Frequency and wavelength are related to each other through wave *velocity* such that

$$c = \lambda \bullet f$$

where *c* represents the wave velocity, λ represents the wavelength, and *f* represents the frequency. The speed will change with different media but will never exceed the speed of light in a vacuum ($3.0 \bullet 10^8$ m/s).[1]

The particle model proposes that EM radiation consists of entities called *photons*, which can possess only discrete amounts of energy (*quanta*). Photons can only exist in motion, which, for them, can only mean moving at the speed of light. Photons can interact with other particles, exchanging energy and momentum through elastic and inelastic collisions.

Higher-frequency EM radiation has higher energy. Planck's constant ($6.62 \bullet 10^{-34}$ J/sec) relates the actual energy value of a quantum to frequency in the equation

$$E = h \bullet f$$

where *E* represents the actual energy value, *h* represents Planck's constant, and *f* represents the frequency.

The particle model is useful in conceptualizing certain phenomena such as scatter, and is also used to describe the phenomenon of *stimulated emission* (a quantum mechanical phenomenon that results in the emission of two photons in the same direction with the same energy and spatial coherence).[1] This is the essence of the *laser* (***l***ight ***a***mplification by ***s***timulated ***e***mission of ***r***adiation), which is a technology, not a type of radiation. However, current usage employs the term laser to refer both to the technology and to the highly collimated beam of nonionizing radiation that it produces.

The terms *energy* and *power* are not synonyms. Energy refers to the ability to do work, whereas power is the ability to do work per unit time.

The characteristics of EM radiation can be categorized as shared properties and distinctive interactions with matter. All types of EM radiation share certain properties that make them alike. However, when EM radiation interacts with matter, the differences become evident. For example, visible light can be absorbed by a thin sheet of black paper, but RF radiation passes through the paper essentially uninhibited.

Physical Properties

All types of EM radiation—ionizing and nonionizing—share the properties of (*a*) divergence, (*b*) interference, (*c*) coherence, and (*d*) polarization, and aside from having differing amounts of energy, they do not differ in their physical properties.

Divergence

The term *divergence* is used to describe how the radiation emitted from a source spreads out. It can be calculated using the formula

$$D = \frac{b - a}{r}$$

where *D* represents divergence, *b* represents the diameter of the beam at the point measured, *a* represents the diameter of the beam at the point of emission, and *r* represents the length of the ray in question (Figure 15-2).

Divergence is related to the diffraction limit, which is the degree to which nonionizing radiation interacts with matter. It is impossible for divergence to be less than the diffraction limit.[2] (With lasers, the divergence is almost equal to the diffraction limit.) Other factors that contribute to divergence include the size of the source, the means of radiation production, the geometry of the emitter's aperture, and the medium of propagation.

Isotropic and collimated radiation emitters exemplify two contrasting concepts. By definition, radiation from an isotropic emitter spreads out uniformly in all directions surrounding the source. The intensity of the radiation decreases with the square of the distance from the source: at triple the distance from the source, the intensity of the radiation decreases by a factor of 9 (Figure 15-3).[3]

Collimated radiation, however, has an asymmetrical or directional spatial pattern. The intensity of the radiation does not decrease with the square of the distance but gradually decreases with distance. Lasers are highly collimated sources of radiation. The light from automobile headlights is somewhat collimated; it has a larger divergence than that from a laser but a smaller divergence than that of an isotropic emitter (such as a tungsten light bulb).

Interference

The principle of *superpositioning* maintains that amplitudes of intersecting waves combine to produce a resultant wave (Figure 15-4). Therefore, the net effect of interference for two waves of the same frequency will be either *constructive* (the amplitude will increase)

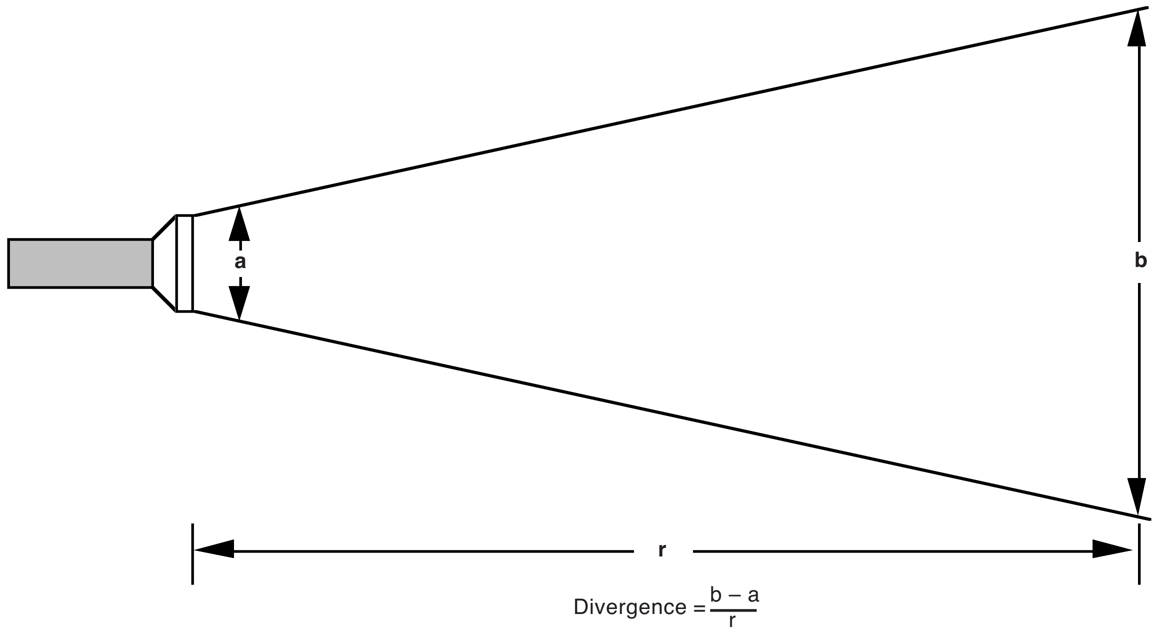

Fig. 15-2. Divergence can be measured as the change in the diameter of the beam divided by the distance of propagation.

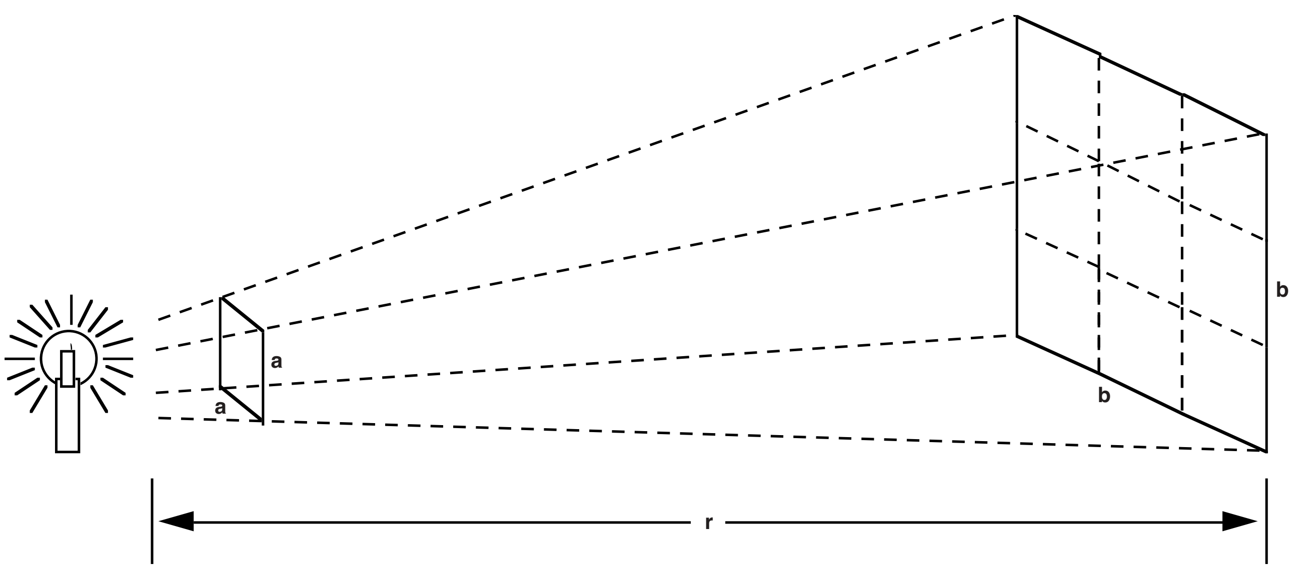

Fig. 15-3. When the distance from an isotropic emitter increases by 3-fold, the light fills a 9-fold greater area. Inversely, the amount of light falling on a given area decreases by ⅑ (the Inverse Square law).

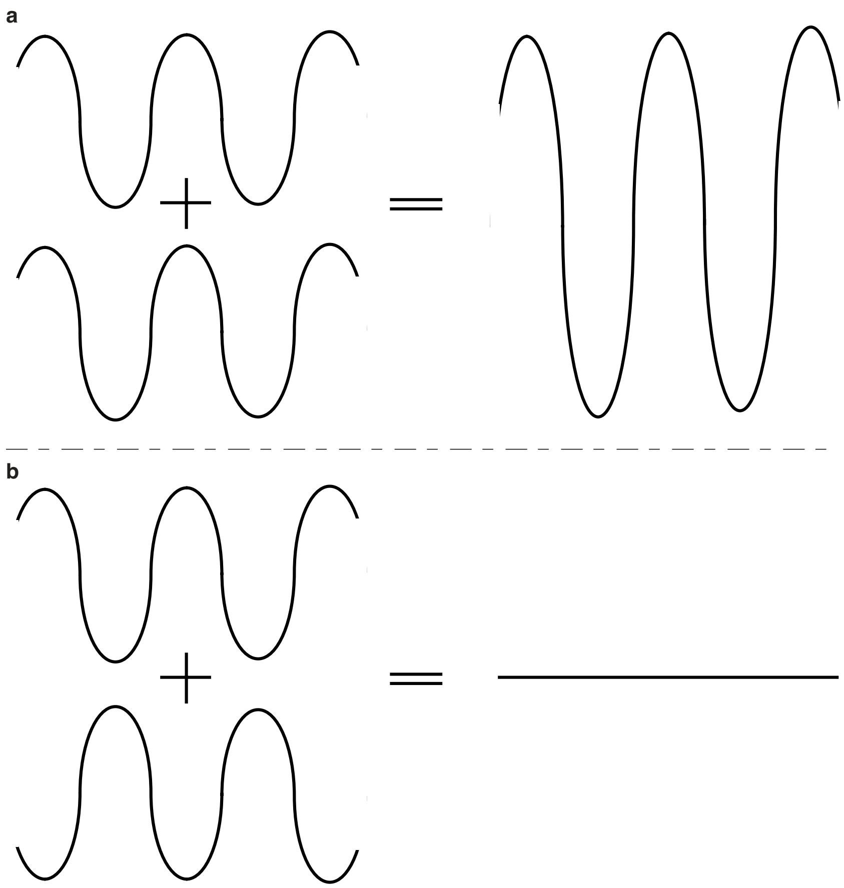

Fig. 15-4. Constructive and destructive interference. (**a**) Two waves that are in phase, in which peaks match with peaks, can be combined to produce a wave the amplitude of which is the sum of the peaks. (**b**) Two waves that are out of phase can nullify each other. Note that these waves are precisely in or out of phase. Waves only slightly out of phase will result in other types of waves.

or *destructive* (the amplitude will decrease). Constructive interference occurs when two waves of equal amplitude are in phase (their crests overlap); the result is a single wave with twice the amplitude. Destructive interference occurs when two waves are out of phase (a peak overlaps a trough) and their energies nullify each other. The interference phenomenon can be illustrated by illuminating two diffraction slits with spatially coherent light. The intersection of the two diffraction patterns produces alternating constructive and destructive interference bands.[1]

Coherence

The coherence of EM radiation implies organization and means literally "sticking together" with respect to phase. As the amplitude of the EM field varies cyclically, likewise so does the wave phase. In addition, EM radiation coherence may be either spatial or temporal; the two differ greatly (Figure 15-5). A temporally coherent radiation source is monochromatic and requires equal amounts of time for the phase peak of the radiation rays to pass. A spatially coherent radiation source emits rays with *like* phases all passing a point at the same time. The term *coherence* usually refers to spatial coherence.[4]

Polarization

The *orientation* of the electric and magnetic fields (ie, their polarization) affects the radiation's interaction with matter. Most natural sources of EM radiation do not exhibit a preferred orientation and are therefore unpolarized. However, EM radiation can gain a preferred direction of oscillation by reflection or by transmission through a material. For example, sunglasses with polar-

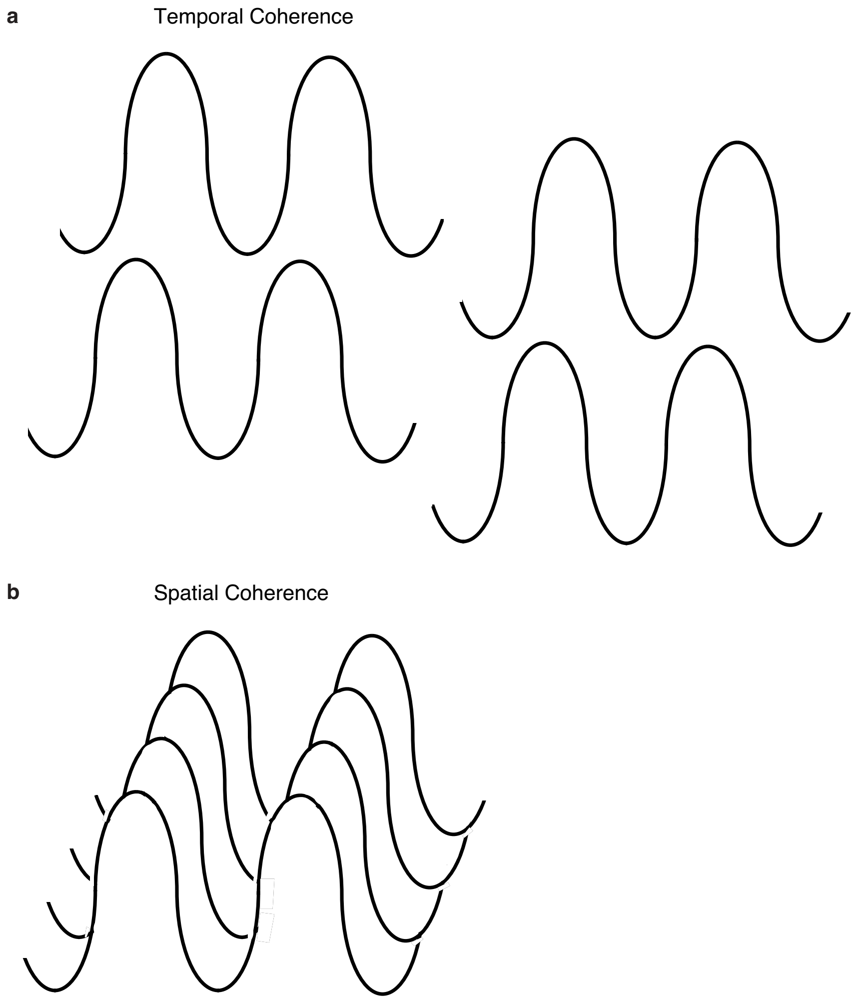

Fig. 15-5. (**a**) Temporally coherent waves have identical wavelengths, but they are not necessarily *in phase* (aligned). (**b**) Spatially coherent waves not only have the same wavelength, they are also all in phase.

izing filters prevent glare by blocking horizontally polarized light that reflects off surfaces such as car hoods.

Polarized radiation is classified according to its structure. *Linear* polarization, both horizontal and vertical, occurs when the electric and magnetic fields oscillate in a constant plane. In comparison, *elliptical* polarization (which includes circular polarization) occurs when the plane of oscillation rotates about the axis of the direction of propagation. Polarization can be modulated and thus can be used to transmit information. Elliptical polarization is commonly encountered in RF radiation work and is also important in the field of optics.[1]

Interactions with Matter

When EM radiation contacts matter, it interacts with the atoms in the medium and behaves in some respects like a particle and in some respects like a wave. The particlelike behaviors include scattering, reflection, and absorption. The wavelike behaviors include reflection, refraction, transmission, diffraction, and absorption. (Note that reflection and absorption are characteristics shared by both particles and waves.) The resulting effect of the radiation on matter depends on numerous factors including the wavelength components of the radiation, the sending medium, the receiving medium, the polarization components of the radiation, and the angle of incidence.

Reflection, Refraction, and Scatter

Reflection depends on the smoothness of the material's surface relative to the wavelength of the radiation. A rough surface will affect both the relative direction and the phase coherency of the reflected wave. Thus, this characteristic determines both the amount of radiation that is reflected back to the first medium and the purity of the information that is preserved in the reflected wave (Figure 15-6). A reflected wave that maintains the geometrical organization of the incident radiation and produces a mirror image of the wave is called a specular reflection.[1]

The speed of EM radiation in any medium depends on (*a*) its wavelength and (*b*) the medium's physical properties, although it always will be slower than its speed in a vacuum (3.0×10^8 m/sec). The medium's index of refraction determines the speed of EM radiation through a specific material. If more than one material is involved in the passage of EM radiation, the propagation direction is subject to bending, which is called refraction. This is exemplified when light passes from a substance with one index of refraction (such as water) into another substance (such as air). Refraction is the property that enables a lens to form images by bending light.[1] When parallel rays of EM radiation from an object converge after passing through a lens, an image of the object is formed at the focal point. Prescription eyeglasses utilize this principle to aid the eye in focusing on an image at the retina rather than in front of or behind it.

However, if the reflection process fails, then the reflecting medium does not preserve the information to produce an image but scatters the radiation in all directions and destroys the image. When radiation passes through the medium, it loses coherence because of scattering. A reflecting medium that fails to produce an image is described as *diffuse*; a medium that loses an image during transmission is described as *translucent*.

The scattering mechanisms depend on the size of the particles composing the medium and the wavelength of the incident radiation.[1] The radiation exhib-

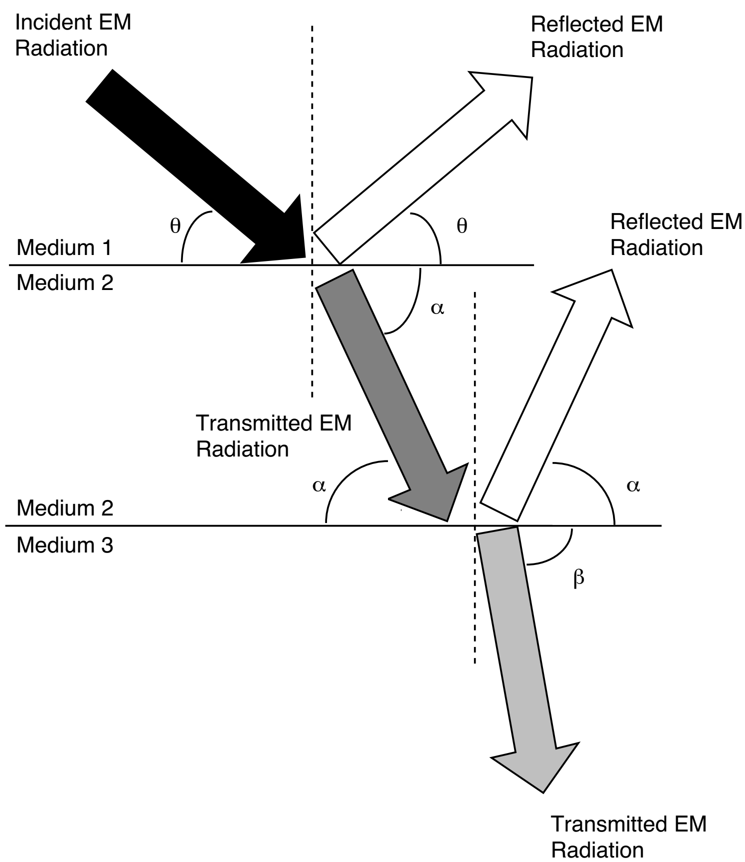

Fig. 15-6. When electromagnetic radiation encounters an interface between media (eg, between air and glass) the incident beam splits into reflected and transmitted beams. The angle of reflection (θ) is equal to the angle of incidence (θ) of the incident beam. The direction of the transmitted beam differs from that of the incident beam, a phenomenon known as refraction. The angle of refraction (α) of the transmitted beam depends on the physical properties of both media at their interface. Likewise, the energy transmitted through Medium 2, or reflected back from Medium 1, depends on both the physical properties of the media at their interface and the angle at which the incident beam strikes Medium 1.

its *Rayleigh scattering*, which is nondirectional when the size of the particles is on the order of the radiation's wavelength.[4] The diffusion by larger particles is called *Mie scattering*, which is not as wavelength-dependent as Rayleigh scattering. This scattering profile is dependent on particle size and can produce forward and backward scattering.

Transmission

The wavelength of the radiation greatly influences transmission and absorption because a given material can be transmissive at one wavelength and absorptive at another. For example, red glass transmits light with wavelengths near 650 nm; it absorbs the complementary color green, which has wavelengths near 550 nm. Transmission of radiation occurs when materials lack the properties necessary for absorption.

Absorption

Absorption is both particlelike and wavelike behavior. When EM radiation interacts with matter, it can be absorbed, transferring the energy of the radiation to the medium. For a particle, this interaction is an inelastic collision. For a wave, the wave energy is transferred from EM wave energy into energy modes in the absorbing medium. The absorption process is divided into categories that correspond to modes of molecular energy storage and include thermal, vibrational, rotational, and electronic modes (Figure 15-7). How energy is absorbed depends on the frequency of the radiation, the intensity of the beam, and the duration of exposure.

Thermal modes of energy storage consist of translational movement modes, in which atoms move horizontally and vertically about their lattice points in a medium, and which is commonly referred to as heat. Thermal absorption is common in the IR and other longer-wavelength spectrums. Vibrational energy modes consist of intramolecular vibrations between component atoms. Rotational energy modes consist of inertial energy stored in the orientation of spinning polarized molecules in local electrical fields that are found within some materials and can be stimulated by RF radiation. Electronic modes consist of the

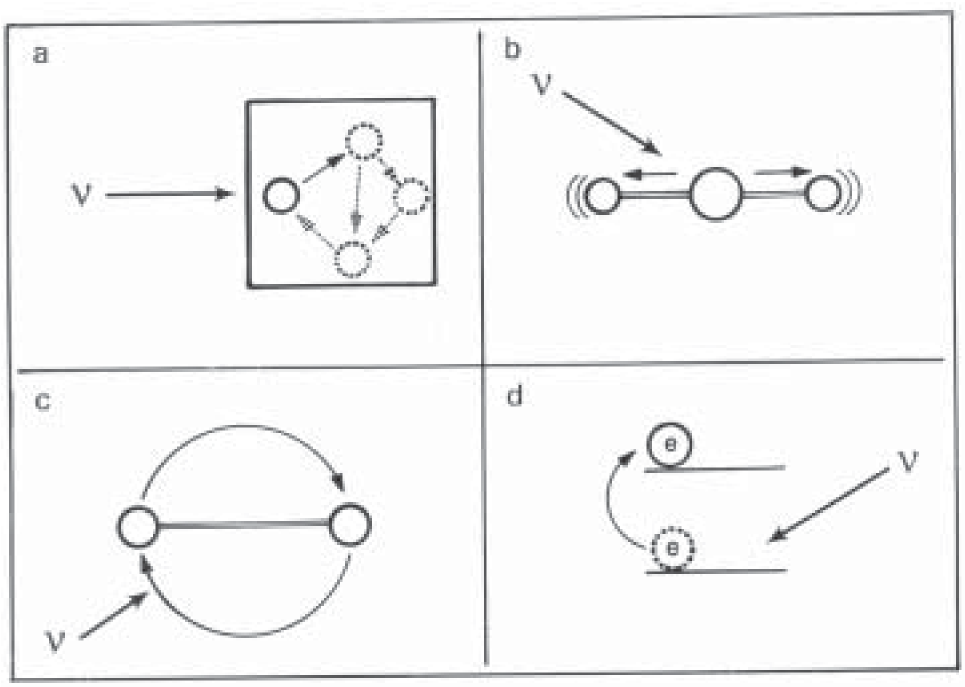

Fig. 15-7. Radiation interacts with matter and its energy is absorbed in several modes; in this drawing, ν represents the incident radiation. (**a**) In the thermal mode, the radiation is absorbed by an atom, which then begins to move about its locus within the molecular lattice of the medium. (**b**) In the vibrational mode, radiation is absorbed and results in vibrations between neighboring atoms within a molecule. (**c**) In the rotational mode, energy is absorbed by polar molecules, which reorient themselves relative to local electric fields within the medium, storing energy. (**d**) In the electronic mode, electromagnetic radiation is absorbed by electrons, raising them to higher orbitals, storing energy that can be reradiated when the electrons return to their original energy state.

different orbital energy states to which electrons can be excited, and these modes can produce new radiation energies as the excited electrons drop back to their original orbitals. Both electronic and vibrational modes can be stimulated by visible light and microwave EM radiation.

The amount of energy that a material will absorb from nonionizing radiation depends on (*a*) the frequency of the radiation, (*b*) the intensity of the beam, and (*c*) the duration of exposure. The most important of these parameters is frequency. Microwaves, IR radiation, and RF radiation can excite translational modes and generate heat. Microwaves are suspected to excite vibrational modes, and RF radiation excites rotational modes.

The intensity of the beam is also a factor in determining how much energy is absorbed. The greater the intensity of the beam, the more energy is available to be transferred. The duration of exposure is another factor. The longer the duration of exposure, the more energy that will be absorbed.

Diffraction

A phenomenon called diffraction allows EM radiation to bend, pass through small apertures, and move around small particles of matter. The smaller the aperture or particle, the more the light rays will bend This bending is quantitatively referred to as the diffraction limit. Because stars are so distant from earth, their light is almost perfectly collimated and the angle of subtense is infinitesimal. However, what we on earth see is actually a star's diffraction patterns, which occur when starlight passes through galactic dust.[1]

RADIO-FREQUENCY RADIATION

In 1864, James Clerk Maxwell proposed mathematically that energy can be transferred by electric and magnetic fields traveling together at a finite speed. It was not until 1886, however, that Heinrich Hertz experimentally proved Maxwell's theory of electromagnetism. To accomplish this, Hertz constructed the first oscillator-transmitter. This consisted of two metal spheres that were each connected to the end of a rod that had a spark gap in the center. The receiving antenna consisted of a loop with a tiny gap cut into it. With this equipment, Hertz conducted experiments that demonstrated the similarity between radio waves and light waves, and the polarization, refraction, and reflection of EM waves. Although Hertz's experiments were performed with relatively short wavelength radiation (50 and 450 megahertz [MHz]), later work in radio was performed at longer wavelengths.[5]

Radio Communication and Radar Technology

Guglielmo Marconi put the theories and experiments of Maxwell, Hertz, and others to practical use. In 1901, Marconi succeeded in establishing coherent wireless communications (using short-wavelength radiation) across the Atlantic Ocean. By 1907, regular commercial wireless service had been established between North America and Europe. Marconi not only predicted and successfully demonstrated radio communication between continents, he also recognized the potentialities of short-wavelength radiation for *radar* (***ra***dio ***d***etecting ***a***nd ***r***anging), the radio detection of objects. However, he was unsuccessful in attracting support for this application. Marconi's suggestions did stimulate some experimental work at the Naval Research Laboratory, which resulted in the first radio detection of a wooden ship in 1922, and the first detection of an aircraft in 1930. By 1932, equipment operating at 33 MHz was capable of detecting the presence of an aircraft at distances of 50 miles. However, target-position information such as range and bearing could not be readily determined.[6]

From Marconi's primitive radar equipment, development efforts continued during the 1930s and 1940s. The U.S. Navy tested the first true radar, the XAF, aboard the battleship *New York* in 1939. This radar operated at 200 MHz with a range of 50 miles. By October of the same year, orders were placed for a manufactured version, the CXAM, and by 1941, 19 of these radars had been installed on major ships of the fleet. The army also conducted research in radar development. During the 1930s, the U.S. Army Signal Corps began efforts to develop radar, which intensified in 1936 when its first radar was tested. In 1938, the army introduced the first operational radar for aiming antiaircraft fire, the SCR-268. This radar was used in conjunction with searchlights because its angular accuracy was poor, although its range accuracy was superior to any optical methods in use at that time. The SCR-268 was the standard fire-control radar until early 1944, when the SCR-584 microwave radar replaced it. The SCR-584 was developed through work conducted at the Radiation Laboratory of the Massachusetts Institute of Technology. In 1939, the U.S. Army developed the SCR-270, a long-range, early-warning radar. This radar detected the first signs of the attack on Pearl Harbor in 1941, but these were ignored until after the bombing began.[7–9]

Microwave Radar

The first efforts to develop radar that could operate at microwave frequencies were initiated in 1936, when two papers were published that discussed replacing conventional transmission lines with waveguide—metal tubing—to operate radar systems at microwave frequencies.[10] Second, a successful cavity magnetron was developed in Great Britain in 1940, and for the first time it was possible to generate substantial amounts of power at microwave frequencies. During that year, prototypes of the cavity magnetron were transported to the United States, and the Radiation Laboratory at the Massachusetts Institute of Technology began research and development efforts in the microwave field. Much of this early work was directed toward the design of airborne microwave radar equipment because the microwave frequencies permit relatively small antenna structures. The term radar was first applied to a specific type of microwave equipment that was used to "see" electronically by means of a transmitted radio wave that reflected from the object that was "seen" (ie, a receiver detected the reflection and translated it to indicate an object's range, azimuth, and elevation). Microwave radar equipment revolutionized the existing very high frequency (VHF) equipment. By using the shorter-wavelength microwave spectrum, the newer radar devices not only could be made smaller but also could have greater range and versatility.[9]

Radar During World War II

The value of radar was not recognized in the civilian sector during the early years of World War II because its development was a successfully guarded secret of war preparation. Radar equipment was installed on battleships, submarines, and in airplanes—often against the wishes of the commanding officers. One of the first and best-known uses of radar in naval warfare occurred off the coast of Greenland in May 1941, in an engagement fought by the German battleship *Bismarck* and the cruiser *Prinz Eugen* against the British battlecruiser *Hood* and the battleship *Prince of Wales*. The commanding officer of the *Hood* preferred an optical rangefinder's readings to that of his newly installed radar ($\lambda = 0.5$ m) because the radar was unable to measure distances with the accuracy required for the main caliber guns to score hits. Nevertheless, the *Hood*'s companion ship, the *Prince of Wales*, did use an air-warning radar and scored three hits on the *Bismarck* after the *Hood* had been sunk.[11] Germany had developed a naval radar in 1939 ($\lambda = 0.8$ m), but it was used primarily for target search and had only limited use for fire control since it could not provide target course and speed for accurate fire-control plot. Therefore (and indicative of the primitive state of radar development), the *Bismarck* did

> ... not use her radar for rangefinding; it was the stereoscopic rangefinders, with their ability to measure accurately great distances in conditions of adequate visibility, that had allowed the quick destruction of the *Hood*.[12]

Although the radar used in the Battle of Britain operated at VHF, it still provided accurate range and tracking data, and the ability to function in spite of fog, clouds, and darkness reduced the threat from Hitler's bombers. The introduction of microwave techniques not only sharpened these abilities, but the reduced size and weight of the equipment and the extended applications of radar made improved radar a decisive factor in winning the war.

Until 1942, allied airborne antisubmarine radar, operating at a frequency of approximately 200 MHz, had neutralized the effectiveness of German submarines in the North Atlantic. At that time, many German submarines were equipped with listening receivers operating at the radar frequency. A German submarine with a directional antenna could now determine the direction of allied antisubmarine aircraft and estimate their range from the strength of the signal received. The effectiveness of allied antisubmarine aircraft decreased greatly because German submarines, warned of impending attack, dived before the aircraft were positioned to drop depth charges. However, allied aircraft countered the effect of the submarines' listening receivers by using an attenuator inserted between the radar transmitter and the transmitting antenna. During the final phase of attack, the radar operator would adjust the attenuator to reduce the radiated signal level. The operator of the listening receiver in the submarine would then note a decrease in the signal strength and conclude that the aircraft was moving away, when in fact the aircraft was approaching for attack.

When the allied forces introduced microwave radar, the German forces mistakenly believed that some sort of IR equipment operating on heat from the submarine had replaced the VHF radar. Because the German military made no attempt to develop microwave listening receivers, allied antisubmarine operations increased in effectiveness. By 1943, microwave equipment operating at a wavelength of approximately 10 cm replaced most of the VHF airborne radar. Germany's Grand Admiral Karl Dönitz said, "The enemy has rendered the U-boat war ineffective … through his superiority … in the modern battle weapon-detection (radar)."[7]

During the next 2 years, new types of radar were developed including airborne-targeting radar and ground-controlled approach (GCA) radar equipment. The airborne-targeting radar allowed airborne bombers to accurately locate targets on the ground in overcast conditions. GCA equipment permitted ground operators to direct an aircraft to a safe landing under zero visibility conditions. Neither of these two technologies had been practicable before the advent of microwave radar: the required antenna directivity was not possible using small VHF antennas.

Since World War II, microwave equipment has been used for various types of communication systems such as microwave relay installations that handle telegraph, telephone, or television signals. The wide microwave band affords significant data-handling capacity, offers great antenna directivity, and requires relatively low-power transmitting equipment.[13]

Physical Parameters That Determine Energy Transfer

RF energy is typically transferred to the body through conduction, coupling, and absorption mechanisms, which are dependent on both the length of the RF wavelength and the body's distance from the radiating source. Distances from the source in wavelengths and their corresponding mechanisms are

- 0 λ = *conduction* (contact),
- 0–0.2 λ = *coupling* (direct transfer of a charge), and
- > 0.2 λ = *absorption* (conversion to internal heat at frequencies > 1,000 MHz).

Conduction

Conduction occurs when the body makes contact with an RF source (eg, when an individual touches an antenna element or an exposed transmission line). The detrimental effects usually associated with conducted energy are electrical shock and burn. At frequencies above 100 kilohertz (kHz), most of the energy delivered through contact with an RF source will be absorbed within a few millimeters of the RF current's travel through the tissue. In this case, the specific absorption rates (SARs) involved may be significant if a small volume of tissue absorbs a large amount of energy.

Even if the induced current from RF conduction is not sufficient to create a thermal injury, it can stimulate the nervous system and cause a response similar to that invoked by an electrical shock. The individual may jerk involuntarily or reflexively, and the resulting movement could cause an injury to the victim or to someone nearby.[14]

The exposure limits (ELs) to control RF shocks and burns are intended to limit induced RF-current flow through the body for frequencies less than 100 MHz.[15] From 100 kHz to 100 MHz, the standard limits the RF current through each foot, and at the contact point to 100 mÅ. The current through both feet is limited to 200 mÅ. This limit is conservative, so even if this current enters the body through the smallest area of tissue, such as a fingertip, it would not be great enough to produce RF shock or burn. The RF current limits change with frequency below 100 kHz (ie, they decrease from 100 mA at 100 kHz to a lower limit of < 3 mA at 3 kHz). This decreased current limit is primarily due to the increased depth that RF current penetrates the body. At frequencies lower than approximately 3 kHz, the penetration is sufficient to interact with the CNS and other electrically sensitive organs such as the heart. At these frequencies, the biological effects associated with RF current flow in the body are clearly discernible and the physiological effects are well understood. They include (in addition to shock and thermal injury) electronarcosis, ventricular fibrillation, and involuntary movement. However, allegations of low-level effects have been made regarding the frequency region lower than 3 kHz, with the largest cluster of questions presently centered at the 60 Hz power-line frequency.[15–17]

Coupling

An individual can be exposed to the stored energy fields—at frequencies lower than 1,000 MHz—that are present close to element antennas or transmission lines. The body will absorb this energy through capacitive or inductive *coupling*, which is the direct transfer of a charge from one conductor (an antenna) to another (the body). Physical contact with the source need not occur, but inductive coupling can occur only if the second conductor is within 0.1 to 0.2 λ of the antenna or transmission line. At distances greater than 0.1 to 0.2 λ from the source, the radiation fields dominate. The actual exposure levels and SARs for coupled fields are difficult to predict and measure. Therefore, most cases of suspected RF radiation overexposure due to coupling must be investigated using dosimetric measurements on tissue-equivalent models.[18]

The type of energy-transfer mechanism involved in a suspected overexposure does not affect the resulting biological effects. Likewise, the exposure standards designed to prevent thermal insult will remain constant throughout the low-frequency region, with this exception: when a conducting object, such as the human body, is placed in an RF radiation field, the object will absorb 3- to 5-fold more RF energy due to coupling if the field is at the object's *resonant* frequency. Resonance occurs when an object's dimensions approximate one-half the wavelength of the incident energy. The human body standing in a vertically polarized field is resonant in the frequency band between 30 to 100 MHz. For example, a person 175 cm in height would be resonant at 85 MHz, where 175 cm is 0.5 λ. This resonance exists because the body attracts the RF current by acting as an antenna that appears to have an increased cross-sectional area. As body size decreases, the frequency for resonance increases (Figure 15-8).

The permissible exposure level (PEL) in the resonant frequency region for humans (30–300 MHz) is reduced 10% from the PEL in the nonresonant region. The SAR still remains 0.4 W / kg and the effects are still thermally induced. Only the PEL, which is derived from the SAR, changes.[19]

Absorption

The body will absorb RF radiation when it is located more than 0.2 λ away from the radiation source. Absorption is the principal mechanism of energy transfer for frequencies greater than 1,000 MHz. At lower frequencies, RF energy transfer occurs through a combination of radiation conduction, coupling, and absorption.

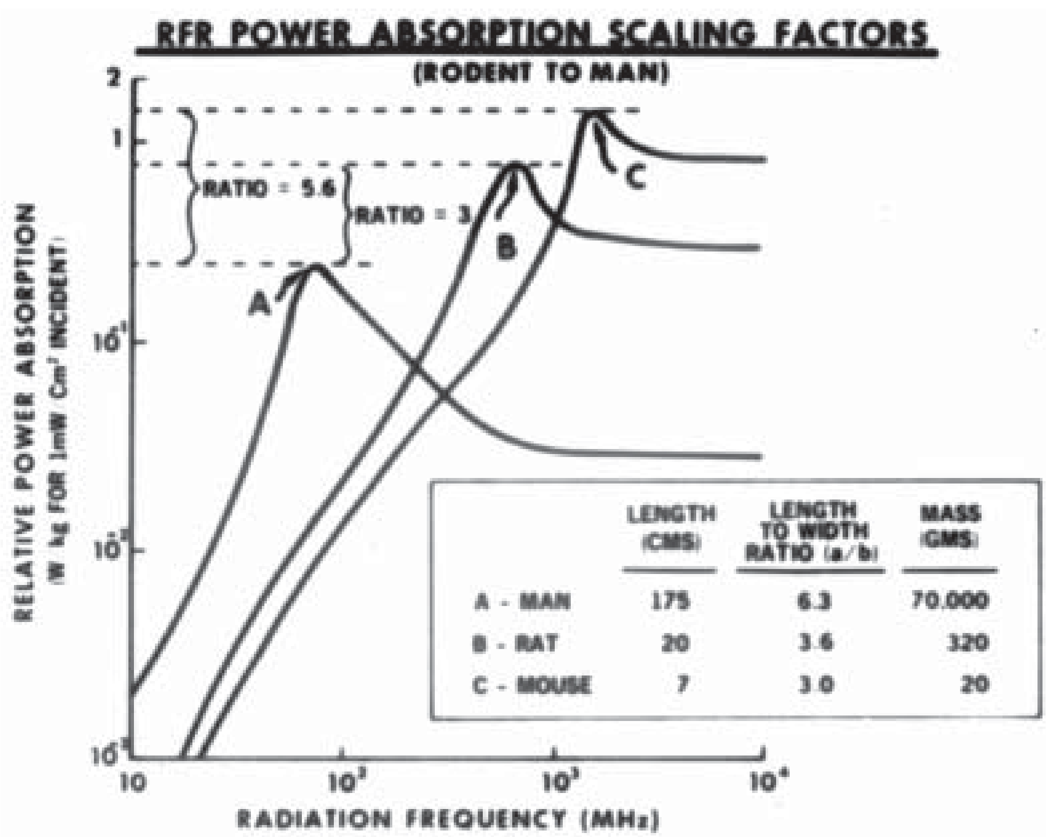

Fig. 15-8. The power absorption rate is related to the complex absorbing and scattering properties of the organism. The rate of absorption for mice, rats, and humans is associated with the length and mass of the animal such that the maximum absorption rate occurs at different frequencies. The absorption rate is independent of the intensity of the incident field and is a critical parameter for establishing exposure limits in humans. For humans, the maximum absorption rate occurs around 70 MHz. Reprinted with permission from DeLorge JO. Disruption of behavior in mammals of three different sizes exposed to microwaves: Extrapolation to larger mammals. In: Stuchly SS, ed. *Symposium on Electromagnetic Fields in Biological System.* Edmonton, Canada: International Microwave Power Institute; 1979: 215–228.

The PEL at frequencies greater than 1,000 MHz is based on a whole-body SAR of 0.4 W/kg. This SAR corresponds to absorbing 100% of the RF radiation energy incident on the body and equates to a measured power density of 10 mW/cm^2. For energy absorption at frequencies greater than 1,000 MHz, the biological effects are induced thermally.

The SAR threshold for thermal damage, even to the lens of the eye, is considered to be much greater than 4.0 W/kg. This SAR corresponds to absorbing 100% of the RF radiation energy incident on the body and equates to a power density of 100 mW/cm^2.

Direct Biological Effects

The absorption of energy is the key mechanism by which EM radiation affects living cells. Energy is transformed from electric and magnetic fields of radiation into one or more types of energy modes in the target material. When translational modes are excited, the ambient cell temperature rises due to the heat generated by these modes. If the temperature rise is sufficient, proteins denature and a burn results. In the case of lasers, the energy beam may be so intense that extreme heating can occur almost instantaneously, resulting in a superheated ionized gas (plasma). A secondary, mechanical effect of this ionized gas is a shock wave that is created as the gas expands. This shock wave and associated cavitation has been used surgically to disrupt certain fragile tissues such as the posterior capsule in the lens.

Depositing RF radiation energy into the body increases its overall thermal load. The thermoregulatory system responds to the increased thermal load by transfer of energy to the surrounding environment through convection, evaporation of body water, and radiation (primarily IR). When the RF radiation causes localized heating of certain organs, such as the eyes, prolonged exposure to this thermal stress can directly damage that organ. However, short duration exposure to RF-induced thermal load will usually not cause damage and the heat will be dissipated. For this reason, RF radiation exposure is not cumulative, unlike ionizing radiation exposure. The biological effects of RF radiation are thoroughly treated in textbooks such as *CRC Handbook of Biological Effects of Electromagnetic Fields*.[20,21]

Burns caused by exposure to nonionizing radiation exposure are different from conventional and electrical burns in that contiguous tissues are not necessarily affected: which tissue will be affected depends on the frequency of the incident EM radiation. For example, microwaves excite thermal modes in water molecules, and tissues with high water content such as skin and muscle are affected more severely than tissues with low water content such as fat. Therefore, microwave-induced burns tend to damage skin and muscle preferentially, and (relatively) spare the subcutaneous fat layer that separates these two structures. In addition, tissue interfaces such as organ capsules and fascial planes tend to be more susceptible to microwave damage.

Burns induced by nonionizing radiation also differ from electrical burns. For example, charring is minimal with electrical burns and is usually localized only to the site of entry. *Nuclear streaming* (the cellular nuclei align along the direction of current flow) is characteristic of electrical burns,[22] but is not a characteristic of radiation burns.

The lens of the eye is recognized as the most sensitive site for thermal damage. Studies on rabbits show that cataracts can be induced after repeated exposure to RF radiation in the FM frequency band (Figure 15-9).[23] However, the cataract-producing phenomenon could not be reproduced in a primate model; it may be a species-specific phenomenon. The nonionizing radiation absorption characteristics of the human eye are shown in Figure 15-10. (Although whether cataracts are induced in humans by chronic exposure to RF radiation remains an issue of debate, near-instantaneous cataract formation can be induced thermally by acute exposure to UV lasers with $\lambda = 365$ nm. UV lasers can also induce cataracts by a photochemical process, but this can take as long as 24 hours after exposure.[24] Laser injuries are discussed later in this chapter.)

EM radiation exciting electronic energy modes can cause significant biological effects by making photochemical reactions occur. Atoms do not need to be ionized to react chemically. Covalent chemical bonds can form when outer-shell electrons are excited to higher-energy states. For example, UV radiation creates thiamine dimers in skin tissue, a process that is associated with solar keratosis, premature aging, and skin cancer. Because sunlight contains UV radiation, sun exposure is a risk factor for skin cancer.

Low-Level Effects of Electromagnetic Radiation

Controversy surrounds the possibility that EM radiation at frequencies between 300 kHz and 300 gigahertz (GHz) may cause harmful biological changes in the absence of demonstrable thermal effects.[25] Thermal effects can affect all body tissue and are induced by measurable temperature increases in the affected tissue. These thermal effects occur at levels at least 10-fold greater than the officially mandated PELs. RF environments in the U.S. Army are relatively safe, but

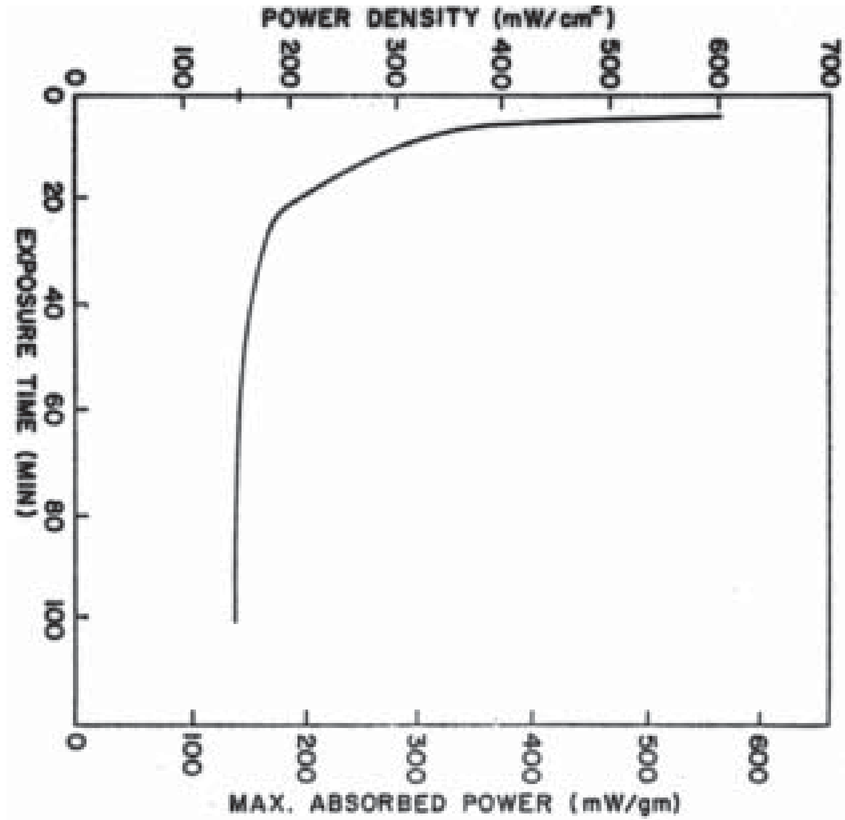

Fig. 15-9. Using 2450 MHz of radio-frequency radiation, the minimum power density required to induce a cataract in the eye of the rabbit is greater than 100 mW/cm^2 (the specific absorption rate is 4.0 W/kg). Reprinted with permission from Guy AW, et al. Effects of 2450 MHz radiation on the rabbit eye. *IEEE Transactions on Microwave Theory and Techniques*. T-MTT, 1975:23(6):495. © 1975 IEEE.

medical officers must realize that the effects can range from nuisance, to minor discomfort, to serious injury, to death. Serious effects such as extensive burns are obvious, but low-level effects may not be so clear cut.

Effects of low-level RF radiation, actual or alleged, involve temperature increases that are (*a*) too small to measure, (*b*) transient, or (*c*) are too localized to distinguish.[26] The significance of these effects on health is a subject much debated among scientists, public health officials, and various special-interest groups. The most common allegations of low-level effects encountered today involve frequencies lower than 3 kHz (the present lower limit of U.S. Army exposure standards). Low-level effects have also been alleged at frequencies above approximately 3 kHz. This includes low-level effects linked to use of video display terminals.[27]

Although thermal effects are the basis for current RF radiation exposure standards, scientific investigations during the 1980s have focused on effects of low-level exposure. Cancer, birth defects, behavioral changes, and other detrimental effects have been investigated using low-level RF energy below the current PELs. These investigations include epidemiological studies, animal studies, and other research efforts. No conclusive evidence substantiates claims of low-level RF radiation effects.[1]

Indirect Biological Effects

RF radiation indirectly poses a threat to health through electromagnetic interference (EMI) with electronic devices by disrupting their normal operation. EMI affects medical personnel by causing interference with sensitive healthcare devices (such as electrocardiograph equipment, operating-room monitors, or cardiac pacemakers), and affects military personnel by causing electronic weapons platforms (such as helicopters) to fail. Currently, the U.S. Army Medical Department (AMEDD) is only addressing concerns associated with the interference of medical devices, specifically from those EMI sources that the Department of Defense (DoD) produces and operates. This concern justifies the ongoing evaluation of the biological effects associated with the RF energy that these

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Fig. 15-10. (**a**) Microwave (MW) and gamma ray radiation can penetrate the human eye with some absorption in all tissues. (**b**) Far ultraviolet (UV) and far infrared (IR) do not penetrate the eye at all. (**c**) Near UV penetrates into the anterior portion of the eye, where it can damage the lens and posterior capsule. (**d**) Visible and near IR are focused by the lens onto the retina, where they can cause retinal damage. Adapted with permission from Sliney DH, Wolbarsht ML. *Safety with Lasers & Other Optical Sources*. New York: Plenum; 1980.

systems produce. These evaluations determine system characteristics such as *rise time* (the time required for the RF pulse to reach peak intensity), modulation, duration, and peak amplitude of the RF radiation.

Most manufacturers carefully design sensitive healthcare devices (that are intended to be used in a fixed setting such as a hospital) to operate satisfactorily in conventional RF environments. The U.S. Army Environmental Hygiene Agency (USAEHA) is tasked to study EMI problems with healthcare devices at army hospitals. The USAEHA maintains special measuring equipment capable of detecting the very low EMI threat levels. Typical EMI threat levels may be 7 to 10 orders of magnitude below the PEL associated with direct biological effects.

Implantable electronic devices such as cardiac pacemakers may be subject to EMI-related failure in certain RF radiation environments, such as near electromagnetic pulse (EMP) generators. Most implanted pacemakers provide a stimulating pulse to the heart only when the heart's own pacemaker fails to do so. The implanted pacemaker monitors the biological pacemaker, but the artificial pacemaker is sometimes susceptible to EMI. Fortunately, the device's shielding and the surrounding tissue act to reduce the threat of EMI.

During 1987 to 1989, a citizens group protested the use of an EMP generator that supposedly posed an EMI threat to implanted cardiac pacemakers.[28] The army and other military services used this generator to test the susceptibility of electronic weapons platforms to the effects of EMP. A thorough study of the alleged threat was conducted in response to the protest. The results showed that EMPs can indeed interact with modern, implanted cardiac pacemakers. Individuals who work close to the EMP source (EMI test personnel) are at risk and require radiation protection controls; however, the EMP levels actually encountered by the general public will not produce EMI interactions.

Presently, although the army's RF environments pose no known uncontrolled EMI threats to pacemakers or similar medical devices, pacemaker wearers are denied access to controlled areas that might pose an undetermined threat. Such devices and sources of EMI are continually evaluated through the U.S. Army Radiation Protection Control Program.[29–31]

Radio-Frequency Radiation Protection

Every installation or activity commander is responsible for ensuring that nonionizing radiation controls are implemented. The radiation protection officer (RPO), who is designated by the commander, usually manages the entire Radiation Protection Program including nonionizing radiation controls. Each installation also maintains a radiation control committee, which meets periodically to advise the commander on radiation hazards and methods for controlling them.

Radiation Controls

The PELs for RF radiation have changed dramatically over the past three decades. Until the mid-1960s, the maximum PEL for both the military and private industry was 10 mW/cm^2 regardless of the exposure duration. However, the increasing power output levels of new radar and other RF radiation sources, as well as certain tactical requirements of the military, made compliance difficult. Therefore, the military adopted new criteria that permitted higher exposure levels for determined lengths of time. Levels of exposure greater than 10 mW/cm^2 were permitted if the average exposure over a 6-minute period did not exceed 10 mW/cm^2. In 1974, the U.S. Army and the C-95.1 Committee of the American National Standards Institute (ANSI) adopted new standards that related the exposure level to the duration and were more frequency specific. ANSI Standard C95.1-1974 recommended a limit of 10 mW/cm^2 for frequencies lower than 10 MHz. Like the previous standard, ANSI Standard C95.1-1974 permitted exposure above the ELs, provided the average level did not exceed these limits for longer than 6 minutes. The U.S. Army further refined the standards in 1981 for frequencies lower than 10 MHz: a PEL of 66 mW/cm^2 averaged over a 6-minute period.

The DoD adopted the army's current PELs in April 1987, based on the recommendations of ANSI C95.1-1982 Standards Committee.[32] These standards encompass the frequency range 10 kHz to 300 GHz. They state that personnel should not be exposed to RF radiation fields that would cause a whole-body SAR of 0.4 W/kg. The threshold for biological effects is 4.0 W/kg. Thus, these control standards are based on levels of direct biological threats.

Derived equivalent PELs that correspond to exposures of 0.4 W/kg—which were determined theoretically and experimentally—were also specified in the 1987 standard for power density and levels of electric and magnetic field strength. They are further divided into areas restricted and nonrestricted for human occupancy to correspond to a whole-body SAR of 0.4 W/kg. These derived equivalent PELs are valid only under the conditions for which they were designed to be applicable.

Many RF radiation sources—most radars and some communications systems—can radiate bursts of energy rather than continuous energy. The pulses can contain power-density levels far in excess of the PEL. But the PEL is based on an average exposure over a 6-minute period. Therefore, it is possible to derive an equivalent average power density using the formula

$$Pd = \frac{6 \cdot PEL}{t}$$

where *Pd* represents the power density level under consideration and *t* represents the exposure duration measured in minutes. It is this derived PEL that is compared to the standard, not the maximum power density contained in a single pulse.

A new ANSI Standard C.95.1 was approved by the Institute of Electrical and Electronic Engineers (IEEE) in 1992. This new standard maintains the use of 0.4 W/kg SAR for calculating PELs, but adds limits for RF shock and burn. This standard will likely be adopted by the DoD in the near future. The DoD has considerable input to this standard-setting committee and has consistently adopted its recommendations. The limits are self-imposed by consensus agreement with the findings of the IEEE in the absence of federal regulations.

Attenuation of the Beam

The direction of maximum radiation of some RF radiation sources can be changed by physically turning the antenna or electronically steering the beam. A person standing near one of these systems would experience the maximum power density for only a fraction of the total time the system is transmitting. Again, a time-weighting factor can be used to derive the equivalent power-density level for comparison with the standard. However, regardless of the weighting factor, no individual should be exposed to an average power density level that exceeds the PEL by 5-fold (as averaged over 6 min). This is calculated by treating the scanning system as if it were radiating a fixed beam.

Threat Analysis and Evaluation

The evaluation of the exposure potential associated with RF radiation sources generally has several steps. First, the USAEHA determines if the system is capable of emitting field-intensity levels that exceed the PELs. Next, the USAEHA investigates the engineering controls that have been incorporated into the system to reduce the potential for exposure. Then, the degree of threat is determined by measuring the actual field intensities to which personnel may be exposed. To this end, the USAEHA is required to evaluate new RF radiation sources both to ascertain each system's threat and to recommend appropriate engineering modifications or system controls.

Emission of Radio-Frequency Radiation

Minimally, RF radiation emission requires (*a*) a generator or source, (*b*) a means to direct or guide the radiation, and (*c*) an antenna. Most practical systems for transmitting and receiving information require additional components that are relevant to the waveform, but this discussion will be limited to these three components of all RF emitters.

The Generator

RF radiation sources, or generators, convert electrical power into RF radiation using appropriate technologies such as oscillators or magnetrons. The radiation requirements of the system determine the type of generator or RF radiation source used. Some of the parameters are the power-output requirements, efficiency, size, bandwidth, frequency, and the modulation requirements. An oscillator is the most basic RF radiation source and consists of a tuned resonant circuit that is usually equipped with amplification stages and positive-feedback circuits. This basic RF radiation generator is often used as the input to other high-power amplifiers.[33] These amplifiers, such as the klystron and traveling wave tube, increase the power of an oscillator's output. Both amplifiers use a similar technique—injecting a beam of electrons into a vacuum tube—and use the input from the oscillator to alternately accelerate and decelerate the beam at the desired frequency. The oscillating beam of electrons is extracted via an electrical conductor.[34]

In comparison, a magnetron is a vacuum tube with resonant cavities. Its static magnetic field bends the electron beam from the cathode to the anode. The bent electron beam passes the resonant cavities and induces an alternating current at the desired frequency for radiation. These generators do not require an oscillating source or amplifier.[34]

The Transmission Line

Once RF radiation has been generated and information has been imparted to the signal through modulation stages, the next task is to guide the energy from the generator to an antenna. This can be accomplished with waveguide, coaxial cable, or wires. Waveguide is a long, hollow conductor, the dimensions of which can be designed to accommodate the transmission of any frequency. However, waveguide is impractical at frequencies lower than a few hundred MHz, and is usually used at frequencies of 3 GHz and higher. Coaxial cable, like that used for cable television, will transmit frequencies up to 3 GHz before significant transmission losses make it impractical. A colinear pair of wires will usually suffice for RF radiation up to 100 MHz.[35]

The Antenna

The final phase in transmitting RF radiation from a system is the *antenna*, a device used to make an efficient transition from a guided to a radiated wave. The complex design of an antenna, which has been the subject of many textbooks, will be influenced by such requirements as size, weight, frequency range, power output, directivity, propagation technique (such as troposcatter, line-of-sight, or ground wave), polarization, and electrical impedance.[3]

These requirements explain the wide variety of antenna designs available for different functions. In many respects, the characteristics of the antenna are the most important aspect of radiation hazard evaluation. The antenna will determine the direction and range of the radiation. A parabolic reflector antenna has the advantage of propagating RF radiation over long distances, but to achieve this, the energy is contained in a limited region. A monopole antenna will radiate equally in azimuth, but the RF radiation has a shorter range.

Military Applications

It should be understood that many military uses of RF radiation are not associated with weapon systems. For example, the military uses RF radiation for communication; target detection; imaging; electronic countermeasures; therapeutic medical diathermy; industrial heating, drying, and hardening of metals; and food preparation.

Radio communication is used to transmit voices and data between distant locations; radar technology is used to detect targets on the ground or in the air. The military also uses RF radiation sources offensively, as electronic countermeasures to interfere with hostile communication or detection devices. Although the military is experimenting with high-power sources as potential weapons, the main applications continue to be information gathering and broadcasting. Much of the hardware discussed below is known by a descriptive code, from which the user can determine the installation, type of equipment, and its purpose. For the most part, these codes will be used to identify the equipment and weapons systems.

Information Gathering

Ground-surveillance radar, lower-power radio, and air-defense radar are the most significant information-gathering uses of RF radiation.[36] Others, not discussed further in this chapter, include

- mine-detection devices;
- avionics radios and weather radars (which are also used in broadcasting);
- ground-mapping radars;
- navigational aids, transponders, and altimeters;
- missile tracking and guidance systems;
- object classification and identification;
- security systems and motion detectors;
- mortar source location;
- projectile tracking; and
- personnel location.

Ground Surveillance Radar. The AN/FPN-40 is a ground-control approach radar system that is used to assist aircraft landings when weather conditions and visibility are poor. It comprises an antenna group, a receiver-transmitter group, a control-indicator group, and a power-supply group. The AN/FPN-40 transmitter is able to produce average power of 180 W in a frequency range of 9.0 to 9.16 GHz. The PEL, which has the force of law and is established by the Occupational Health and Safety Administration (OSHA) for soldiers and civilian employees at this frequency range, is 10 mW/cm^2 for continuous exposure.

Two antennas can be used to obtain both azimuth and elevation information on aircraft positions. This information is obtained through the scanning or surveillance operation mode, or through the precision operation mode. In the scanning or surveillance operation mode, the system uses the azimuth antenna to search the horizon for aircraft. In this scanning mode, personnel around the system will not be exposed to RF radiation in excess of the PEL because the RF radiation can only be experienced for a fraction of the total time it is radiating. In the precision-operation mode, the system uses both antennas to provide accurate azimuth and elevation information during the final approach of aircraft attempting to land. In this mode, personnel located within 28 m may almost continuously experience the main beam from either antenna. Therefore, in the precision mode, a 28-m exclusion zone is observed immediately in front of the antennas.

Low-Power Radio. SINCGARS-V is a new family of VHF-FM (very high frequency-frequency modulation) radios for tactical communications designed for simple, quick operation using a push-button tuner. It is capable of voice, frequency shift key, or digital data communications. The frequency range is 30 to 88 MHz, with a nominal output power of 5 W and a maximum output power of 50 W when equipped with a power amplifier. The antennas used with these systems are typical low-gain element models such as a monopole whip, the same type used with citizens band (CB) radios. Physical contact with the antenna when it is equipped with a power amplifier may cause an RF radiation shock. Without the amplifier, the system is not subject to control procedures for RF radiation protection.

Air-Defense Radar. The purpose of the Hawk air-defense system is to acquire and engage hostile targets in the air. To this end, the system is equipped with several radars. Details of system performance and parameters are classified.

The pulsed acquisition radar (PAR) is one of the Hawk radars. The PAR provides information on the range and azimuth direction of acquired objects such as airplanes. Range information is obtained by transmitting pulses of RF radiation and measuring the time for one pulse to return or echo back to the PAR. The azimuth direction is known by observing the direction from which the echo is received.

The antenna is mechanically scanned in azimuth through 360 degrees. In this scanning mode, the RF radiation levels do not exceed the PEL for continuous exposure due to the short duration of exposure that personnel would experience during each rotation. However, the RF radiation levels in front of the system will exceed the PEL to a range of 17 m when the system is operated with the mechanical scan disabled for maintenance. More importantly, soldiers who perform these maintenance operations must never place themselves between the feed horn and the reflector of the antenna; extremely high levels of RF radiation are present at the feed horn.

Stabilotron and thyratron amplifier tubes generate high-power RF radiation. These tubes can produce X rays, which must be shielded to preclude exposing soldiers who are working in the vicinity of these devices.

Broadcasting

In addition to high-power radio and satellite communications terminals, other broadcasting uses of RF radiation include electronic countermeasures, directed energy, avionic radios, and weather radars.

High-Power Radio. The AN/GRC-106 is a high-frequency (HF), single-sideband (SSB) radio set used primarily as a mobile link in a communications network. It may also be used in fixed and semifixed applications. The AN/GRC-106 has an amplitude modulation (AM) mode to make it compatible with standard AM radio sets. It is now being used as the basic radio set with all the newer radio teletype (RATT) configurations.

The RF power (400 W in the frequency range of 2–3 MHz) is fed to an element antenna. The RF radiation levels from this system will not exceed the PEL beyond 1.5 m from the antenna. More importantly, however, an RF shock or burn can be induced if an individual makes physical contact with the antenna while it is transmitting.

Satellite Communication Terminals. The AN/TSC-93 satellite communications (SATCOM) terminal contains receiver and transmitter equipment for voice, data, and teletypewriter communications via geosynchronous orbit satellites. The system is transportable for field operation with all but the antenna components contained in a standard military vehicle. The antenna is a transportable, high-gain, aperture model that is set up next to the vehicle.

The nominal power output is 500 W in the frequency range of 7 to 8 GHz, but typically this system is operated at a much lower power output (< 100 W). The maximum power density in the main beam of the antenna will exceed the PEL to a range of 110 m from the antenna when transmitting at full power. In normal operation, the antenna is set up on high ground, away from elevated structures and is directed toward the sky to acquire a satellite. This procedure will preclude overexposing personnel on the ground in the vicinity of the system.

Exposure Incidents

The severity of an alleged personnel overexposure to RF radiation determines the extent of the medical and technical investigations. When overexposure to RF radiation is suspected, the local medical department activity must examine the person involved and complete a *Special Telegraphic Report of Selected Condition* (Requirement Control Symbol [RCS] MED-16 [R4]), which is to be transmitted to the Office of The Surgeon General (OTSG), Preventive Medicine Division. This medical evaluation initiates a technical evaluation to analyze the following RF radiation parameters and incident data:

- operating frequency,
- antenna gain,
- average output power of the transmitter,
- transmission losses between the transmitter and the antenna,
- distance from the antenna to the location of the alleged overexposure, and
- duration of the exposure.

Another consideration that may influence the evaluation is the calibration of the measuring instrumentation. The state of the art of measuring technology does not permit measurements more accurate than ± 20%. Therefore, it is often necessary to calculate the measurement tolerance by calibrating the instrumentation. To maintain consistency, calibrations should be traceable to National Institutes of Science and Technology standards.

The initial technical evaluation permits the investigator to determine the maximum possible exposure level the individual could have encountered. However, an incident is not classified as an overexposure solely because the exposure level exceeded the PEL. For example, the power density may be averaged over a 6-minute period to determine if the exposure level exceeds the PEL by a factor of 5. A factor 10 for safety is integrated into the PEL. Army regulations do not allow actual exposures of more than 5-fold greater than the PEL over 6 minutes.

If the initial technical evaluation indicates that the person could have been exposed to RF radiation exceeding the PEL by a factor of 5, then (*a*) medical personnel will administer a complete medical evaluation but the only manifestation of overexposure that the evaluation will diagnose is thermal injury; (*b*) the USAEHA will conduct an investigation; and (*c*) an investigation report, which includes the following components, will be published: on-site interviews, evaluation of the radiation source, measurements at the incident cite (or at a similar site using the same equipment), consideration of other evidence to establish the extent of the overexposure, and recommendations for improving deficiencies in the Radiation Protection Program.

The following incidents of alleged exposures were selected to demonstrate the investigation process from start to finish. Most exposure investigations do not proceed beyond the initial phase: determining if an overexposure could possibly have occurred. Usually investigations find that the field intensity was not *excessive* (5-fold greater than the PEL) or the duration of exposure was too short. In the first case study described below, an overexposure was determined not to have occurred, but this fact could only be determined after full investigation. In the second case study, an overexposure to RF radiation did occur and was investigated fully by the USAEHA. Interestingly, in the first case, RF radiation exposure was alleged to be responsible for an actual injury, whereas in the second case, no discernible injury was found.

Case Study 1

One RF radiation exposure incident involved a soldier working near a high power illuminator radar (HIPIR) unit that was tracking aircraft (Figure 15-11). The soldier was dismantling a tent 35 to 40 m from the HIPIR when he reported feeling localized heating on his back. As the soldier turned around to discern the heat source, he noticed the HIPIR directed toward him. Immediately, he entered a nearby equipment shelter, which put the HIPIR out of sight (thus making the soldier feel safe). The soldier soon began to notice sunburnlike reddening on the backs of his arms and on his upper back.

Although the soldier's commanding officers did not direct him to a medical facility, he later visited the installation hospital for treatment of the burned areas and the general uncomfortable feeling he was experiencing. The burned areas, described as superficial burns, were 1 cm^2 on the arm and 3 cm^2 on the upper back. There was no generalized erythema. All vital signs were normal and the soldier was released after being treated with Silvadine ointment (a 1% suspension of silver sulfadiazine in a hydrophilic base). The hospital created a MED-16 report of the occupational injury because RF radiation was a possible cause. (AR 40-400, Patient Administration, requires this report.)

[The actual medical records, which would have told exactly what physical signs were present, were not available for this case report. Medical officers might ask (a) if the burns were first, second, or third degree, or (b) if localized, rather than generalized, erythema were present. The use of Silvadine suggests that bullae characteristic of second-degree burns were present, but if so, the lack of erythema would be most unusual.—Eds.]

In addition to the initial medical examinations, the OTSG

Fig. 15-11. The high-power illuminator radar (HIPIR) is an acquisition radar of the Hawk air-defense system.

requested that the USAEHA conduct an investigation of the circumstances surrounding the incident. This investigation, which was performed within several weeks of the incident included (a) a determination of the actual RF radiation levels to which the soldier may have been exposed, (b) the duration of any RF radiation exposure, and (c) the possible biological effects resulting from an RF radiation exposure. The initial evaluation was conducted via telephone interviews. The preliminary findings indicated that the maximum RF radiation levels that the soldier may have experienced were between 110 and 150 mW/cm^2. However, the actual exposure duration could not be determined. Because the RF radiation levels exceeded the PEL by more than 5-fold, the USAEHA initiated a full investigation of the incident, including a visit to the incident location to obtain the actual power-density measurements.

The investigation team who were dispatched to the incident site consisted of medical and engineering personnel. The team conducted extensive interviews with personnel associated with the operation of the HIPIR at the time of the incident, the soldier who allegedly was injured by radiation from the HIPIR, personnel who were working with the soldier at the time of the incident, and hospital personnel who examined the soldier. These interviews attempted to create an overall picture of the events surrounding the incident.

In addition, the team engineers conducted measurements of the actual RF radiation levels at 35 to 40 m from the HIPIR source. Figure 15-12 shows the relative positions of the HIPIR and the tent. The measured values agreed with those the initial evaluation predicted. The team also determined that the HIPIR was in a tracking mode at the time of the incident. When a HIPIR loses its target, the radar will coast (continue in the same direction with the same velocity) in an attempt to reacquire the target. If the HIPIR does not reacquire the target within a few seconds, the radar will return to its primary target (the direction is preset by the operator), which, in this instance, was away from the tent. It is likely that the soldier was exposed to the main beam of the HIPIR during this coasting function.

The investigation team determined that no RF radiation overexposure had occurred. The PEL in the frequency range of the HIPIR is 10 mW/cm^2 when averaged over 6 minutes. The duration of the exposure could not have exceeded a few seconds. Therefore, the soldier was not exposed to RF radiation in excess of the PEL. The burn may have been caused by another heat source such as the sun. The sensation of heat from the RF energy may have exacerbated the soldier's injury, but did not cause it. Nevertheless, unauthorized personnel will not be permitted within the RF radiation control range established for the HIPIR.

The soldier continued to report fatigue and chest pains. A series of examinations including liver function tests, blood counts, pulmonary function tests, and ophthalmic examinations were conducted over the next 6 months. All these examinations found no abnormalities. Later examinations included an electroencephalogram (EEG) and a computed tomography (CT) scan. These examinations also found no abnormalities. The attending internist recommended regular neurological evaluations, which also found no abnormalities.

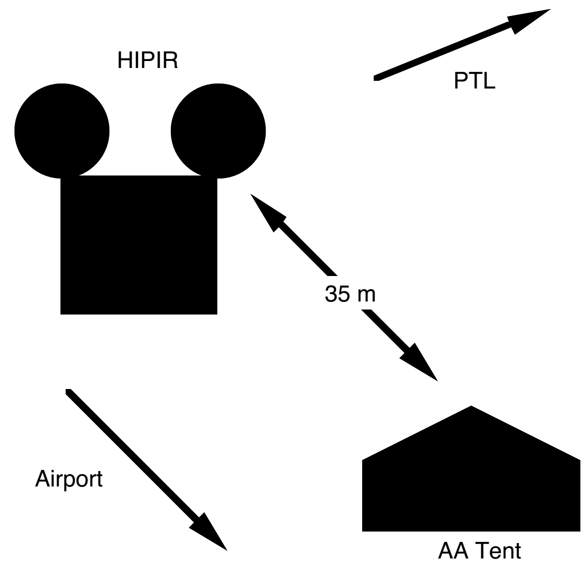

Fig. 15-12. During a training exercise, the operators of the high-power illuminator radar (HIPIR) were tracking aircraft near a local airport. The air assault (AA) tent was located between the airport and the HIPIR. After the radar had attempted to reacquire an aircraft that had descended below the line of sight, it automatically returned to its preassigned primary target line (PTL), away from the tent.

Case Study 2

Another RF radiation exposure incident involved two soldiers performing maintenance operations on a HIPIR. They were attempting to determine why the antenna's arc-detector crystal—located inside the transmitter housing—repeatedly burned out. While the radar was transmitting, the two soldiers removed the transmitter housing cover and visually examined the inside. After having examined the inside for 10 minutes, they noticed that a rigid waveguide was positioned incorrectly. They shut off the radar to remove the antenna pedestal head assembly. Upon further inspection after removing the assembly, they found the source of the repeated crystal burnout: a section of flexible waveguide that transfers high-power RF radiation to the antenna had been severed (Figure 15-13).

Within hours of discovering the severed waveguide, the two soldiers independently reported nausea and general malaise, and they reported the incident to the RPO. The RPO used an RF radiation meter to attempt to determine the actual power-density levels to which the soldiers may have been exposed. The measured levels exceeded the

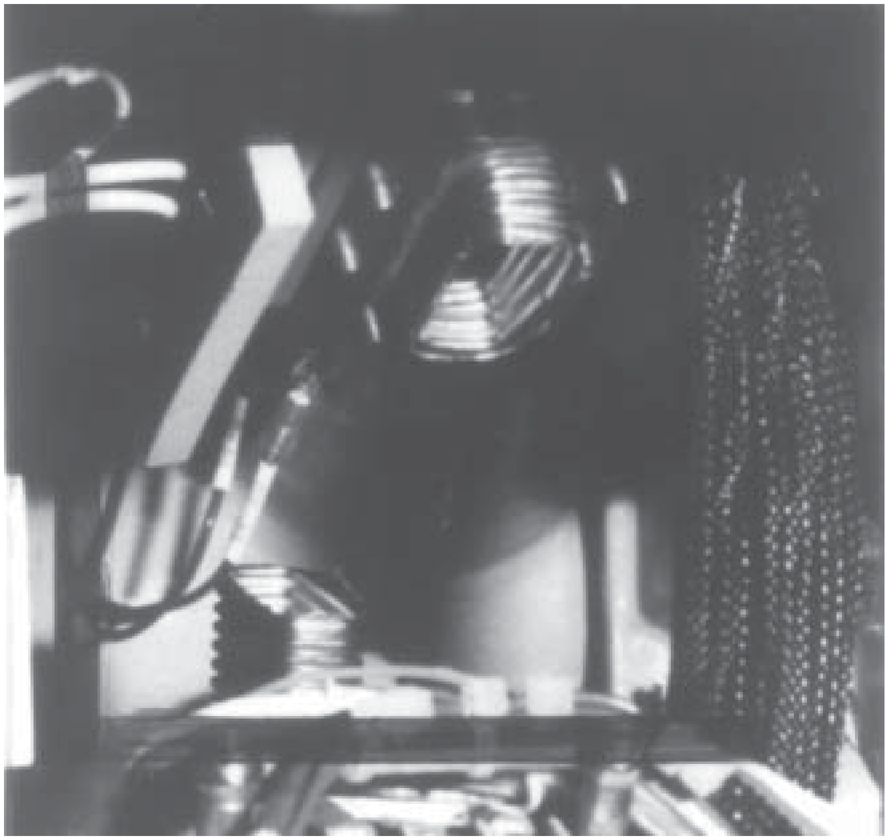

Fig. 15-13. There is no visible indication that RF radiation is being emitted by severed or cracked waveguide.

100 mW/cm^2 limit of the meter, and therefore the RPO requested the services of the USAEHA.

On the day after the incident, before the USAEHA investigation team arrived, the soldiers received ophthalmic examinations. The examinations included tests for visual acuity, a slitlamp evaluation of the crystalline lens, ophthalmoscopy, and an intraocular pressure test. The examinations revealed no abnormalities in either of the soldiers' eyes. The soldiers also reported that their initial nausea had subsided.

The USAEHA medical and engineering investigation team conducted an investigation. They interviewed the two soldiers, the RPO, and medical personnel at the installation. In addition, they measured the actual power-density levels in the regions where the soldiers were troubleshooting. The RF radiation levels ranged from 50 mW/cm^2 to 250 mW/cm^2. Assuming that at least the minimum exposure level was experienced for a maximum of 10 minutes, there is no question that the soldiers were exposed to RF radiation more than 5-fold greater than the PEL (10 mW/cm^2).

The primary recommendation of the investigation team was to test the HIPIR to determine why the flexible waveguide section had broken. (This was apparently not the first time the waveguide had broken in this manner.) The investigation team also recommended that maintenance personnel should always perform visual inspections around the transmitter housing with the power to the transmitter turned off.

The Radio-Frequency Radiation Protection Program

The installation or activity RPO is responsible for assuring that a comprehensive Nonionizing Radiation Protection Program (NRPP) is implemented in accordance with U.S. Army regulations. The NRPP for each installation or activity should include the specific systems, environments, and controls involved at the installation or activity. Most programs contain elements in common, including (*a*) inventories of RF radiation sources, (*b*) engineering controls, (*c*) administrative controls, (*d*) training programs, and (*e*) emergency procedures. No personal protective equipment (PPE) is used by DoD for RF radiation.[37]

Inventories of Radio-Frequency Radiation Sources

The installation RPO and the activities that operate the RF radiation sources must maintain inventories of all RF radiation sources (with their corresponding threat classifications). From these inventories, the RPO can recommend appropriate engineering and administrative controls to curb exposure.

Engineering Controls

Any device or method that modifies the design, construction, or operation of the system to prevent undesired radiation is considered to be an engineering control. This includes safety interlocks that are incorporated into a system to prevent its operation under less-than-optimum conditions. Engineering controls restrict radiation levels and radiation zones through methods such as warning sirens, flashing warning lights, built-in dummy loads, azimuth- and elevation-limiting switches, couplers, and attenuators.

Administrative Controls

Physical barriers (such as fences, warning signs, lights, or alarms) that identify the radiation-control area at its perimeters and access routes are administrative controls. They are used to preclude individuals from RF radiation exposure. Administrative controls rely on the individual to ensure his or her own radiation protection. Standing operating procedures (SOPs) are developed to inform those who use the system about RF control procedures. Warning signs are placed around the device to further remind users of the potential for exposure.

Training Programs

The personnel who should receive radiation safety training include all those responsible for operating, maintaining, or repairing RF radiation sources that are capable of emitting levels at or exceeding the PEL. This training should be conducted when an individual is first employed and annually thereafter. The RPO should maintain a record containing a brief outline of the instructions for each training session and a list of individuals who received the training. Training sessions should include instruction concerning

- exposure potential associated with specific pieces of equipment,
- biological effects associated with overexposure to power density levels exceeding the PEL,
- proper use of protective equipment and devices such as barriers, signs, and lights,
- accident-reporting procedures,
- routine radiation-safety surveys, and
- procedures for maintaining an operational log for recording radiation-safety-related events (such as radiation-zone violations or overrides of warning signs or safety interlocks).

Emergency Procedures

Specific individuals—designated in writing—will be notified in the event of an emergency (such as equipment malfunctions or alleged overexposures) that involves RF radiation levels that possibly exceed the PEL. A list of those to be notified should be posted in control areas. The individual so designated will report the circumstances of the emergency to the installation or activity RPO, who will determine if an RF radiation exposure 5-fold greater than the PEL has occurred. If the exposure did exceed the PEL by 5-fold, the OTSG will request that the USAEHA conduct an on-site investigation.

The OTSG will also ensure that potentially exposed individuals receive an appropriate medical evaluation within 24 hours of the incident, and will develop and transmit an RCS-MED-16 report.[38] At a minimum, this examination will include an ocular examination, which consists of the following:

(1) Ocular history, with emphasis on previous eye injury or disease and medication use (especially any photosensitizing medications).

(2) Distance visual acuity (with correction) in each eye. If the corrected distance visual acuity is poorer than 20/20 in either eye, a refraction will be performed to obtain the best corrected acuity.

(3) Amsler grid or similar pattern will be used to test macular function for distortions and scotomas.

(4) A slitlamp examination of the lens and cornea and an ophthalmoscopic examination of the fundus, both with a rapidly acting, short-duration mydriatic (eg, tropicamide) unless the use of a dilating agent is contraindicated by medical history and/or professional judgement. The following, as a minimum, are to be recorded:

- (*a*) Presence or absence of opacities in the media.
- (*b*) Sharpness of the outline of the optic nerve head.
- (*c*) Cup to disk ratio.
- (*d*) Ratio of the size of the retinal arteries to retinal veins.
- (*e*) Presence or absence of a well-defined macula.
- (*f*) Presence or absence of a foveal reflex.
- (*g*) Any retinal abnormality, however small or subtle.
- (*h*) A color fundus photograph (the preferred method) that includes the optic nerve head and macula may be used in place of (*b*) through (*g*) above.[39]

LASERS

Laser technology developed in a sequence that integrated the findings of both theoretical and experimental investigators. When he stated his theory of the hydrogen atom in 1913, Niels Bohr first proposed his contentions that atoms could (*a*) exist in discrete energy states and (*b*) radiate light of well-defined frequencies in transitions between these energy states. In 1917, during the course of a theoretical investigation of blackbody radiation, Albert Einstein showed that a third process, stimulated emission of radiation, was necessary to account for the observed form of the blackbody's radiation spectrum.

The field of electronics and the extension of available sources of radiation in the RF region developed steadily during the first half of the 20th century. In the visible and IR regions, however, no similar extension occurred until 1958, when knowledge and technologies began to proliferate (Exhibit 15-1).

The current inventory of fielded laser systems in the United States military consists primarily of three types of lasers: (1) ruby, (2) neodymium:yttrium aluminum garnet (Nd:YAG), and (3) gallium arsenide (GaAs). Prototypes of military laser rangefinders were developed during the 1960s: a ruby laser mounted on the M551A1 Sheridan vehicle was fielded in the early 1970s, followed shortly by another type of ruby laser rangefinder that was fielded on the M60A2 missile-firing tank. During the 1980s, the Nd:YAG laser rangefinders and target designators were fielded in infantry, armor, artillery, and aviation units. The third type of laser system—the direct-fire simulator, which uses the luminescent diodes of GaAs—was fielded during the early 1980s. These were developed to provide more realistic training in the use of direct-fire weapons.

EXHIBIT 15-1

PROLIFERATION OF LASER TECHNOLOGY

Townes and Schawlow showed the feasibility of operating a maser (***m***icrowave ***a***mplification by ***s***timulated ***e***mission of ***r***adiation) in the optical or near-IR region in 1958.

Schawlow proposed the use of ruby as a laser material in 1960.

Maiman reported the first operating laser using ruby as the medium in 1960.

Javan, Bennett, and Herriott successfully demonstrated an operational, continuous gas laser in 1961.

Keyes and Quist discovered highly efficient luminescent diodes of gallium arsenide (GaAs) in 1962.

Specific Properties of Lasers

Lasers are sources of nonionizing radiation that can operate in the IR, visible, and UV regions of the EM radiation spectrum. Laser technology utilizes three basic components: a lasing medium, a pumping system, and a resonant optical cavity. Although only these three components are necessary for lasing action, other components such as lenses, shutters, and mirrors can be added to the system to change the output.

The fundamental physical process in the lasing medium is the stimulated emission of photons (discrete bundles or particles of energy), which requires that (*a*) the particles of the medium be in an energetic state and capable of photonic emission, and (*b*) the emission must be stimulated (a photon interacts with an atom, triggering an energy-state collapse, which allows another photon to be released) (Figure 15-14). Stimulated emission differs from spontaneous emission, which permits the particle to collapse to a lower

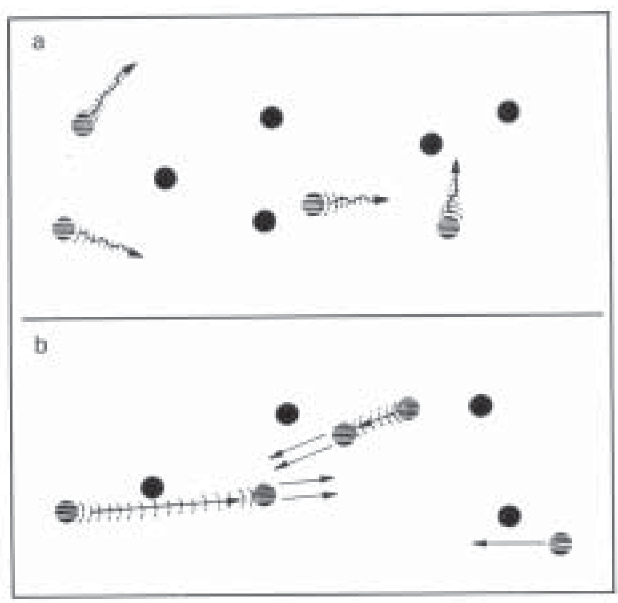

Fig. 15-14. (**a**) Spontaneous emission occurs when an excited system drops to a lower energy state and emits a photon. This process occurs by itself and the departing photon has no preferred direction. (**b**) Stimulated emission occurs after collision with a photon. The two emitted photons leave in exactly the same direction and with the same energy.

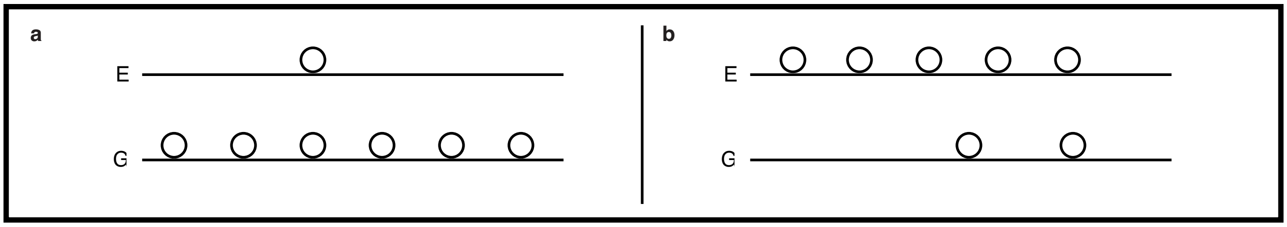

Fig. 15-15. (**a**) A normal electronic population distribution, where the ground state *G* is the most populous. (**b**) An electronic population inversion occurs when the excited state *E* becomes more populous than the ground state.

energy and emit a photon, but in a random direction. Laser operation requires that each of the photons resulting from stimulated emission amplify the radiation by stimulating two other photons, and so forth. This amplification depends on the preexistence of a condition called *population inversion* (more electrons exist in the excited than in the lower-energy state) (Figure 15-15).[40]

When matter absorbs energy, population inversion can be encouraged by special techniques such as *pumping*.[41] Several different systems are available. *Optical* pumping uses a strong source of light, such as a xenon flashtube or another laser (usually of a shorter wavelength). *Electron-collision* pumping is accomplished by passing an electric current through the lasing medium. *Chemical-reaction* pumping is based on the energy release that occurs during the formation and breakdown of chemical bonds.

A mirror at each end of the lasing medium forms a resonant optical cavity, which permits a beam of light to be reflected from one mirror to the other (Figure 15-16).[41] Lasers are designed so that as this light passes through the lasing medium many times, the number of emitted photons (stimulated emission) is amplified with each passage. One of these mirrors is only partially reflective, thus allowing part of the beam to leave the optical cavity. This is the laser beam.

The requirements for the construction of a laser are few and the means of achieving these requirements are numerous.[42] Many materials can act as laser media provided a proper stimulation system and a means of gain exist. The lasing medium can be composed of organic or inorganic materials in any of the four phases of matter (gas, liquid, solid, or plasma). It can be pumped into higher energy states through electrical discharge, flashlamp discharge, chemical reaction,

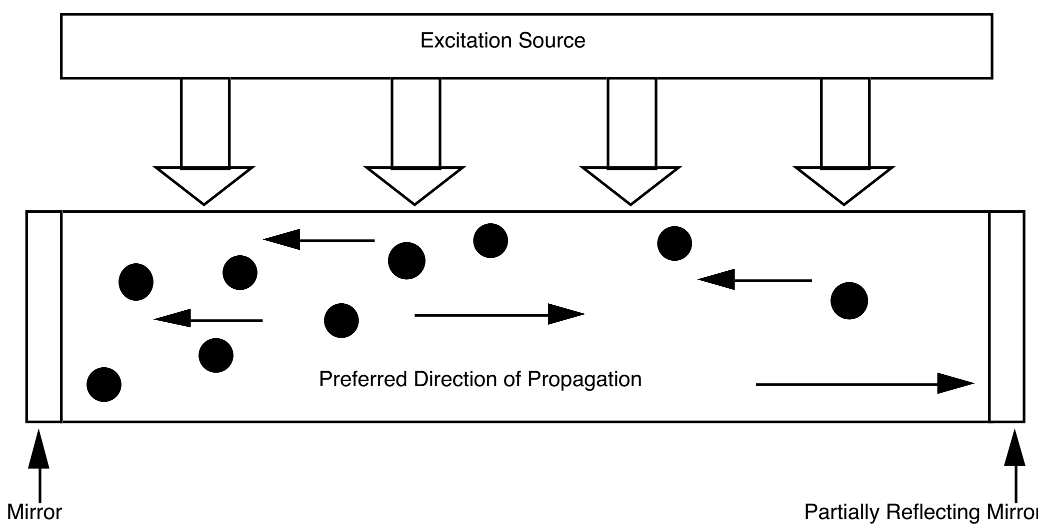

Fig. 15-16. The basic components of a common laser include a lasing medium (or cavity) with a preferred direction of propagation, an excitation source to create a population inversion, and mirrors to amplify the laser beam.

electron injection, and RF stimulation. Laser emission in some systems is fixed at certain wavelengths, while the output from other systems is tunable.

Direct Biological Effects

The biological effects associated with exposure to the laser-optical region of the EM radiation spectrum involve the skin and the retina, lens, cornea, and conjunctiva of the eye. The mechanism of injury for most effects is either photochemical or thermal; some authorities believe that these injury mechanisms are not understood fully.[42,43] Thermal effects predominate from the long-wavelength-end of the visible region, toward the microwave end of the spectrum. Photochemical effects usually predominate in the UV and short-wavelength-light region, where photon energies are greatest. (See Chapter 8, Conserving Vision, for additional discussion of laser injuries to the eye.)

Because the nature and degree of injuries vary with wavelength, it is useful to consider the effects in the seven optical spectral bands that the International Commission on Illumination (*Commission Internationale de l'Eclairage*, CIE) has adopted (Figure 15-17). *Actinic* UV radiation (UV-C [100–280 nm] and UV-B [280–315 nm], which produce photochemical changes) characteristically produces erythema and photokeratitis (welder's flash). UV-A can also produce these effects, but to a far lesser extent. Unless the exposed individual is also being treated with photosensitizers, which make him or her more sensitive to UV-A, exposure to UV-A (eg, from UV-A black lights such as those used in industry) seldom produces an adverse effect. The recent identification of the injurious wavelengths (the *action spectrum*) associated with UV cataracts concluded that only radiation of 295 to 325 nm was effective in producing a temporary or permanent lenticular opacity for acute exposures.[44]

Although lasers exist that can produce thermal effects on the skin, *currently fielded military lasers are not powerful enough to produce any thermal effects on skin*. Effects on the eye are the greatest concern when per-

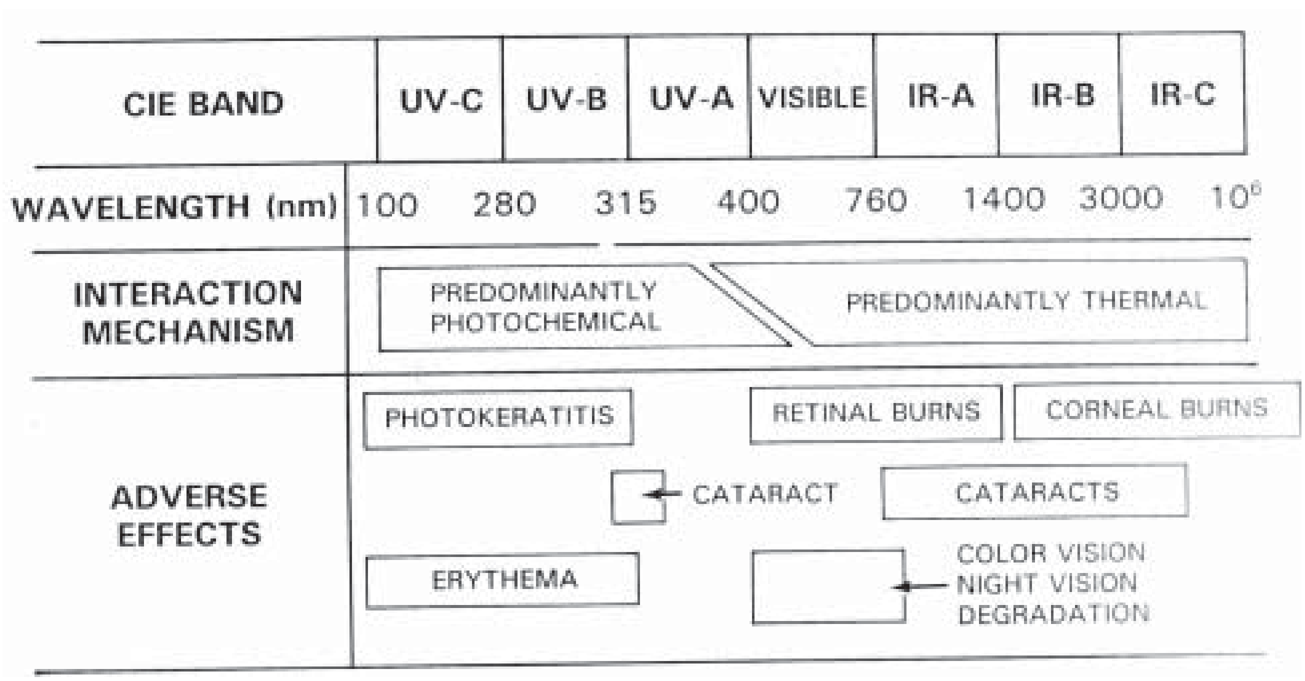

Fig. 15-17. International Commission on Illumination (*Commission Internationale de l'Eclairage*, CIE) spectral bands with their corresponding adverse effects. The direct biological effects of optical radiations are frequency dependent. In the visible and infrared (IR) regions, the interaction mechanism is primarily thermal. In the ultraviolet (UV) region, the interaction mechanism is predominately photochemical, although thermal injury is also present. The biological effects for IR radiation are corneal burns and cataracts. The biological effects for visible radiation are retinal burns, cataracts, and degradation of color or night vision. The biological effects for UV radiation are photokeratitis, cataracts, and erythema. UV-A and UV-B also cause skin cancer.

forming a hazard analysis. There is an obvious interest in defining the sites of principal absorption. Another consideration is not only how much energy is absorbed in tissue, but also its relative biological effectiveness once absorbed. This is particularly important *outside* the spectral region where thermal effects predominate, at wavelengths shorter than approximately 400 nm.

Mechanisms of Injury

Distinguishing the category of injury mechanism is of paramount importance in proposing ELs or maximum permissible exposures (MPEs) for personnel and in predicting the potential long-term, delayed, or chronic effects of exposure. One property that aids in understanding the differences between injury-mechanism categories is *reciprocity* (the product of irradiance, or exposure rate, and the time necessary to produce an effect), which is constant over a wide range of exposure durations. Exposure reciprocity is assumed to hold for up to 8 hours (one workday) and there appears to be very little (although measurable) additivity for multiple exposures if carried over one day.

Photochemical Injury. UV effects and blue-light retinal injury are considered to be photochemical in origin. Photochemical processes involve breaking or forming molecular bonds, or both, and result from the stimulation of electronic energy modes. The property of reciprocity is important in understanding photochemical processes: they obey the reciprocity rule for exposure duration from microseconds to hours. For example, 20 mJ/cm^2 of UV radiation produces the same degree of erythema whether it is delivered as 20 kW/cm^2 for 1 µsec, or as 20 µW/cm^2 for 1,000 seconds, provided the same wavelengths are employed. Exposure guidelines such as the American Conference of Governmental Industrial Hygienists' (ACGIH's) Threshold Limit Values (TLVs) or MPE for eye or skin exposure to UV radiation are therefore expressed as *radiant exposure durations*.

Thermal Injury. Reciprocity does not hold for thermal injury; therefore, it is always necessary to specify the exposure duration when studying a thermal injury. For thermal injury of the skin or eye from a pulsed source, it is the duration of the pulse that determines the threshold irradiance, TLV, or MPE for a given wavelength and effect. The rate-process nature of thermal injury suggests that for exposure durations of less than approximately 10 to 100 µsec, the rate of delivery of thermal energy to the tissue plays only a minor role because heat conduction cannot occur in so short a time.

Even the ELs established for lasers tend to reflect this fact. For example, for ultrashort laser exposures of picoseconds, the biological effect is nonlinear and does not appear to be thermal. For the body to sustain thermal injury, exposure to a higher-intensity laser (J/cm^2) for a duration greater than 100 µsec is required because the body's blood flow and heat conduction away from the exposed site tend to provide some protection. Thus, if thermal injury has not occurred within a few seconds, it is unlikely to occur because a minimal critical temperature (perhaps 45°C) would not be reached through further exposure.

Laser beams may be capable of forming shock waves within tissue. The shock wave is believed to result from the rapid expansion of a plasma, which has been caused by the near-instantaneous heating of a tiny volume of tissue to approximately 10,000°F. Lasers are used in this manner to perform posterior capsulotomies in the treatment of cataracts, and to pulverize gallstones during laparoscopic surgery. Perhaps the clicking or popping sound anecdotally reported by humans who have inadvertently gazed into a laser's beam can be attributed to such a shock wave.[45,46]

Comment on Injury Processes

The entire injury process is better understood when the distinction between injury categories is established. Until recently, the thermal-injury mechanism was thought to be associated with the retinal injury that is sustained when individuals view bright light sources such as the sun. Researchers were puzzled that the calculated retinal temperature rise for an individual who stares at the sun was only 2° to 3°C for a 2-mm pupillary diameter. Laboratory studies of thermal retinal injury also showed that a 10° to 20°C temperature elevation in the 160-µm solar image was required to produce retinal thermal injury within a few seconds. At this duration, short-wavelength light proved to be far more damaging than longer wavelengths, and reciprocity was maintained over a period of hours. Research concluded that the actual mechanism of retinal injury was photochemical, not thermal.[47]

The discovery of the blue-light retinal-injury process and the theory of photochemical injury answered unexplained questions about solar retinitis (eclipse blindness). Researchers had not understood why individuals who gazed at the sun for 2 to 3 minutes during a solar eclipse at midday developed eclipse scotoma, but individuals who gazed for several minutes at the sun while it was low in the sky—and lacking blue light—did not even sustain solar retinitis.[47]

The exact chromophores and details of the injury mechanisms for UV erythema and keratitis also remain largely unknown. However, UV erythema and keratitis, like retinal injury, are apparently multistaged because the manifestations of injury are delayed from several hours to 2 days.

Both UV radiation and blue light are most intense at noon. The solar spectral irradiance at 300 nm drops 10-fold by 1500 hours (Standard Time, not Daylight Saving Time). For this reason, an exposed individual does not receive enough UV-B to develop photokeratitis when the sun is near its zenith, but at the same time the skin is more directly exposed to solar UV-B and the individual may sustain erythema solare.

Indirect Biological Effects

Many laser systems used in both research and development and industry contain or are associated with other potential ancillary sources of adverse biological effects such as chemical burns, loss of hearing, exposure to airborne contaminants, and electric shock.[48] These sources include chemical reactants and byproducts, target-generated contaminants, cryogenic fluids, dyes and solvents, ionizing radiation, noise, and high voltage. Consensus standards (such as those from the ACGIH, local and state agencies, and the Occupational Safety and Health Administration) govern many of these sources to limit exposure to contaminants associated with laser operation (Table 15-1).

Current laser systems used in the military for aiming weapons are not expected to pose any ancillary hazards to the operators. However, a potential for exposure to lethal voltages or other harmful radiation hazards might exist when protective covers are removed for service or maintenance. Safety precautions

TABLE 15-1

REPRESENTATIVE CONTAMINANTS ASSOCIATED WITH LASER OPERATIONS

Contaminant	Probable Source	OSHA Allowable TWA	OSHA Ceiling Value
Asbestos	Target backstop	0.2 F*/cc	—
Beryllium	Firebrick target	0.002 mg/m^3	0.025 mg/m^3
Cadmium oxide fume	Metal target	0.1 mg/m^3	0.3 mg/m^3 (0.05 mg/m^3)
Carbon monoxide	Laser gas	5 ppm	200 ppm
Carbon dioxide	Active laser medium	10,000 ppm	30,000 ppm†
Chromium metal	Metal targets	1.0 mg/m^3 (0.5 mg/m^3)	—
Cobalt, metal fume, and dust	Metal targets	0.05 mg/m^3	—
Copper fume	Metal targets	0.1 mg/m (0.2 mg/m^3)	—
Fluorine	HF chemical laser	0.1 ppm	(2 ppm)†
Hydrogen fluoride	Active medium of laser	3 ppm	6 ppm† (3 ppm)
Iron oxide fume	Metal targets	10 mg/m^3 (5 mg/m^3)	—
Manganese fume	Metal targets	1 mg/m^3 (1 mg/m^3)	3 mg/m^3†
Nickel and insoluble compounds	Metal targets	1 mg/m^3 (0.05 mg/m^3)	1 mg/m^3†
Nitrogen dioxide	GDL‡ discharge	(3 ppm)	1 ppm† (5 ppm)†
Ozone	Target & Marx generators	0.1 ppm	0.3 ppm† (0.1 ppm)
Sulfur dioxide	Laser exhaust	2 ppm (2 ppm)	5 ppm† (5 ppm)†
Sulfur hexafluoride	Saturable absorber	1,000 ppm	—
Uranium (soluble/insoluble)	Target	0.05/0.2 mg/m^3 (0.2 mg/m^3)	0.6 mg/m^3† (0.6 mg/m^3)†
Vanadium fume	Target	0.05 mg/m^3 (0.05 mg/m^3)	—
Zinc oxide fume	Target	5 mg/m^3 (5 mg/m^3)	10 mg/m^3† (10 mg/m^3)†

Values in parentheses denote level recommended by ACGIH
*Fibers > 5 µm in length
†Short-term exposure limits
‡Ground designator laser

are provided in the appropriate technical manuals.

Many chemical fuels and exhaust products are associated with the operation of some laser systems (Exhibit 15-2). For example, the use of high-energy hydrogen fluoride or deuterium fluoride chemical lasers can cause atmospheric discharges of helium, oxides of nitrogen and sulfur, and several fluorinated compounds (including hydrogen fluoride or deuterium fluoride, which are corrosive and environmentally toxic). Normal ventilation techniques, such as dilution and local exhaust, and other engineering and administrative controls for industrial hygiene can reduce the concentrations of chemical reactants and their byproducts.

The *target* of a laser operation can itself generate airborne contaminants during laser material processing, beam termination, and interactions with metal surfaces (such as arc welding). The ACGIH has recommended limits for welding fumes to provide protection from arc-welding contaminants. Control of airborne contaminants can also be achieved through local and dilution exhaust ventilation, and other engineering and administrative controls.

Cryogenic fluids such as liquid nitrogen and others are utilized to cool some lasers and many high-sensitivity photodetectors. When cryogenic fluids evaporate, they displace breathable oxygen and thus should be used only in areas of good ventilation. Another safety hazard associated with the use of cryogenic fluids is the possibility of explosion from ice collecting on a valve or a connector. Both protective clothing and face shields should be used when handling large quantities of liquid nitrogen. Those using gas canisters and cryogenic Dewar flasks are required to follow numerous safety procedures (which are beyond the scope of this chapter) to prevent serious accidents.

Organic dyes and solvents are often used as lasing media. Solvents usually compose 99% of the dye solution by weight and are commonly flammable and toxic by inhalation or percutaneous absorption. Control measures for dyes and solvents include exhaust ventilation and proper storage and handling of flammable chemicals.

Ionizing radiation —X rays—are generated from some high-voltage power tubes and electron-beam lasers. This ionizing radiation can be controlled through proper monitoring and shielding procedures. Manufacturers can successfully shield lasers to prevent X-radiation leakage, provided that the lasers are operated with the shields in place.

Noise levels that exceed the acceptable standards are generated by certain high-energy lasers and transversely excited atmospheric pressure lasers, although most lasers operate silently. However, these hazardous noise levels occur only near the laser or its target, where personnel are not permitted. Other safety considerations thus obviate the need for noise-control measures.

Lethal voltage levels often are generated inside the laser-system enclosure. Personnel can be exposed to these voltages if the system covers are removed or if the electrical interlocks are defeated. Standard electrical safety precautions can reduce the risk of electrocution.

EXHIBIT 15-2

LASER FUELS AND EXHAUSTS

Carbon monoxide
Methane
Sulfur dioxide
Sulfur hexafluoride; other sulfur compounds
Nitrogen
Helium
Fluorine
Lithium
Carbon disulfide
Hydrofluoric acid
Hydrogen
Carbon dioxide
Various fluorides
Nitrogen oxides

Military Applications

Using light for long-range, line-of-sight communication is not new. Paul Revere received a coded message in light before his ride in 1775. Morse code utilizing light was widely used during World War II. Current military uses of laser systems (both hand-held and mounted on vehicles or aircraft) include rangefinding or distance measurement, tactical target designation, and simulation of ballistic characteristics for training purposes. Lasers can also be used as part of fire-control systems and in conjunction with night-vision and IR-sensing technologies.

Rangefinders

Rangefinder laser devices emit a single pulse or series of pulses toward a target. A counter is activated when the pulse is emitted. When the light contacts the target, a diffuse reflector, it is scattered in all directions. Optical sensors receive the light reflected back to the rangefinder and deactivate the counter. Thus, the distance from the rangefinder to the target can be calculated from the time of travel between the laser and target and the speed of light using the formula

$$r = \frac{c \cdot t}{2}$$

where *r* represent the range in meters, *c* represents the speed of light (3×10^8 m / sec), and *t* represents time in seconds for the pulse of light to travel the round trip, which is why it is necessary to divide by 2.

The military frequently uses Nd:YAG as a rangefinding and designating laser medium. The wavelength of this laser is 1,064 nm, in the near-IR region of the spectrum. Both the hand-held AN / GVS-5 rangefinder and the vehicular-mounted AN / VVG-3 rangefinder on the M1 tank employ a single pulse of Nd:YAG. The AH-1F Cobra helicopter employs a multiple pulse of Nd:YAG in its Laser Augmented Airborne Tow (LAAT) rangefinding system. Although the Nd:YAG laser is used frequently, it is not used exclusively in military laser systems. For example, the M60A3 tank employs the AN / VVG-2, which is a single-pulse ruby laser rangefinder that operates in the visible region of the spectrum at 694.3 nm.

Tactical Target Designators

Laser systems accomplish tactical target designation by emitting a series of pulses toward a diffuse reflection target, which scatters the light. Programmed optical sensors respond to the particular code of pulses that the designator emits and direct munitions toward the target. Several laser systems for tactical target designation also have rangefinding capability (such as the G / VLLD [ground / vehicle laser locator designator]), but others are capable only of tactical target designation (such as the hand-held AN / PAQ-1 [portable, invisible radiation, special purpose]).

Directed Fire Simulator

Lasers are used extensively in military training to simulate ballistic characteristics of live-fire weapons. The most frequently used laser training system is the Multiple Integrated Laser Engagement System (MILES), which uses laser diode technology. In most cases, the diode used is GaAs, which operates in the 905-nm region of the spectrum. The laser diode is programmed to emit a code of pulses to simulate a particular weapons system. The sensors attached to the target (such as a tank, aircraft, or personnel) receive the code of laser pulses and interpret the code as a *kill* or a *near miss*. A near miss will signal the target as being engaged, and a kill will shut down the MILES.

New Applications

The military also uses lasers in conjunction with night vision and IR-sensing technology. For example, diode lasers operating in the near-IR region can illuminate a target to enhance its signature, thus making the target more visible through a night-vision or IR-sensing device. Similarly, low-power gas lasers, usually composed of helium and neon (He-Ne) and operating at 632.8 nm, are used in association with small-caliber arms for sighting targets.

Other new applications of lasers include relatively safe, low-powered lasers that are being developed for guided optical communication systems or fiber optic networks, and short-to-medium range or line-of-sight communicators.

Likewise, technology is being developed to use the laser as an optical countermeasure: a high-power laser with a rather large beam divergence can be focused on a target to overwhelm the target's biological (the eyes) or electronic optical sensors that are being used in conjunction with its fire-control system. Also, with the development of technology, very high power lasers will be used in directed energy warfare to engage targets as a direct-fire weapon. The laser will transfer EM energy to a target and cause the target, or one of its critical components, to overheat and malfunction.

Four types of high-energy laser technologies are potentially suitable for weapons applications: the gas dynamic laser, the electric-discharge laser, the chemical laser, and the free-electron laser. However, each of these systems has significant limitations regarding military utility; therefore, no high-energy laser system has been fielded.

Laser Protection Standards

Until 1973, when the first ANSI Standard (Z136.1) pertaining to lasers was published, only general standards for the use of lasers existed. This standard laid the groundwork for a multitude of laser standards, including standards pertaining to laser use in industry and the military, performance standards, and environmental and international laws. Today, ANSI Standard Z136.1[49] is updated triennially. Additional ANSI standards encompass other laser uses: ANSI Standard Z136.2[50] for fiber optics systems, and ANSI Standard

TABLE 15-2

U.S. ARMY GUIDANCE PERTAINING TO LASER USE

Regulation	Title	Purpose
AR 40-5	*Preventive Medicine*	Describes the radiation control program
AR 40-46	*Control of Health Hazards from Lasers and High Intensity Optical Sources*	Establishes U.S. Army policies, procedures, and standards for protection of personnel from the hazards of optical radiation
AR 385-63	*Policies and Procedures for Firing Ammunition for Training, Target Practice, and Combat*	Provides procedures for operating lasers outdoors on a U.S. Army range
AMC Reg 385-29	*Laser Safety*	Defines the use of lasers at U.S. Army Materiel Command installations
TB MED 524	*Control of Hazards to Health from Laser Radiation*	Provides exposure limits and guidance, and establishes responsibilities for personnel protection from radiation; applies to active U.S. Army, U.S. Army National Guard, U.S. Army Reserve, and Corps of Engineers facilities

Z136.3[51] for medical lasers. ANSI Standard Z136.4 concerning laser measurement is also being developed. Although the U.S. Navy uses ANSI Standard Z136.1 directly, the U.S. Air Force maintains its own standard (Air Force Occupational Safety and Health [AFOSH] Standard 161-10)[52] and the U.S. Army maintains several regulations and technical bulletins pertaining to laser use (Table 15-2).

Title 21, Code of Federal Regulations, Part 1040, dictates the performance standards for all laser devices manufactured after 1976, but some exemptions have been made for the military.[53] Soon after this regulation was promulgated, the DoD obtained an exemption for tactical laser systems, outdoor training lasers, and lasers that were classified in the interest of national defense. In addition, alternate design criteria were developed for the army, navy, and air force, and were published in Military Standard (MIL-STD) 1425A.[54] MIL-STD-882C addresses safeguards from other, related potential hazards.[55]

Even certain environmental laws affect the use of lasers and laser facilities. Congress created the *National Environmental Policy Act of 1969* to establish national policy to protect the environment and to minimize adverse environmental consequences of federal actions.[56] Certain provisions of the act are incorporated into other federal regulations including the *National Historic Preservation Act of 1966*[57] and the *Endangered Species Act of 1973*.[58] Army Regulation 200-2 contains U.S. Army policy pertaining to these matters.[59] Because lasers can be used outdoors on a range, the effect of laser radiation on endangered species and other wildlife must be considered.

Lasers are also a subject of concern on the international and national scenes. The United States is a part of the North Atlantic Treaty Organization, which maintains a standardization agreement on laser radiation, *Standardization Agreement* (STANAG) 3606.[60] New York and Texas have also set state restrictions for laser use.

Official standards do not yet address the use of high-intensity optical sources other than lasers. Safety guidelines for these sources are provided in the ACGIH publication, *Threshold Limit Values and Biological Exposure Indices*.[61] This document provides guidelines for the use of intense visible sources, which can produce retinal thermal injury; sources of intense blue light, which can produce retinal photochemical injury; and IR radiation, which can adversely affect the lens. These guidelines will probably provide a basis for future army standards regarding these sources.

Exposure Limits

PELs are not used in the field of laser technology. The terms used are ELs or MPEs. The ELs for laser sources, like those for RF radiation sources, are based on the biological damage level.[48] (These values should be used as guides in the context of exposure. They are based on the best available information from experimental studies.) The interior of the eye is transparent, to a varying extent, to wavelengths between 400 and 1,400 nm. The visual response of the eye is wavelength dependent. The amount of incoming optical energy that is first transmitted through the anterior portions

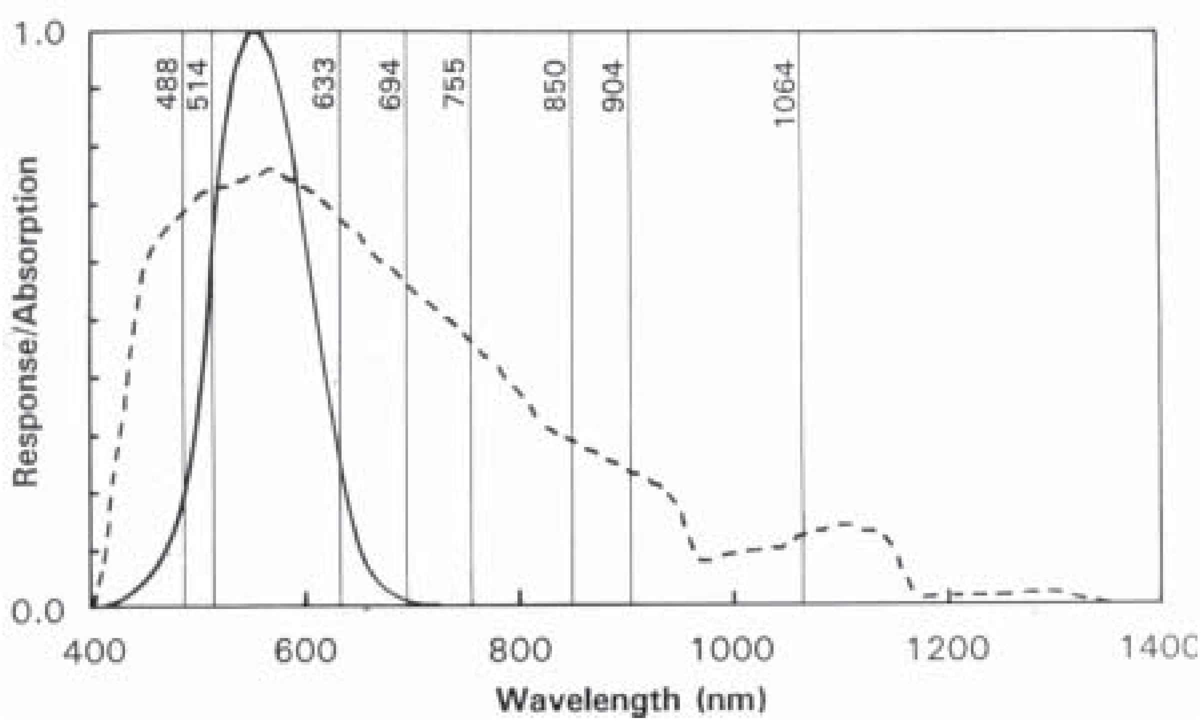

Fig. 15-18. The eye's absorption of nonionizing radiation depends on the wavelength of the incident radiation. Human visual response is limited to wavelengths of approximately 400 to 700 nm, but the retinal pigment epithelium (RPE) absorbs from wavelengths 400 to 1,400 nm. Although we may not be able to see the laser, the eye still responds and focuses the energy.

of the eye and then absorbed by the retinal pigment epithelium (RPE) is also wavelength dependent (Figure 15-18). Separate ELs have been established for all wavelengths. The cornea and lens of the eye concentrate the energy of a laser beam 100,000-fold greater than the unfocused energy; therefore, extremely small amounts of optical energy can injure the retina.

Because pulsed lasers operate at pulse widths of less than one nanosecond to several seconds, the ELs depend on the pulse width, repetition, and expected duration of exposure. An individual might be exposed to a visible laser for 0.25 seconds, until the natural aversion response to light causes the exposed individual to turn away. In comparison, exposure to invisible wavelengths can last 10 seconds or longer, before the individual becomes aware that he or she is being exposed. This is because invisible wavelengths do not invoke the natural aversion response to light.

Laser-control standards keep exposure levels low enough to preclude any known risk, even repeated exposures day after day. The radiant exposure that causes a minimum injury, such as a visible lesion on the retina, cornea, or unprotected skin, is generally 10- to 50-fold higher than the established ELs.[62]

Threat Analysis and Evaluation

An analysis of the hazards that laser systems pose must (*a*) verify that the engineering controls that have been incorporated into the system comply with the control standards, (*b*) determine the requirements for eye protection, and (*c*) determine the nominal ocular hazard distances (NOHDs) for both the unaided eye and the eye that is aided by magnifying optics. The NOHD is the distance required for the beam to expand to the point where the EL is not exceeded. The NOHDs for military designator lasers extend 10 to 20 km for unaided viewing and 40 to 50 km for optically aided viewing; the NOHD for military rangefinders is generally 5 to 10 km. However, these lasers are known to cause various levels of eye injury at shorter distances. The ruby laser rangefinder exceeds the hemorrhage level within 100 m (Figure 15-19), and can inflict a retinal lesion within 1,100 m if the victim is standing directly in the beam. A laser designator can inflict a retinal lesion within 5 km, but again, the victim must be standing directly in the beam to sustain this injury, and, in the judgment of USAEHA's Laser Branch, the probability that this will occur is

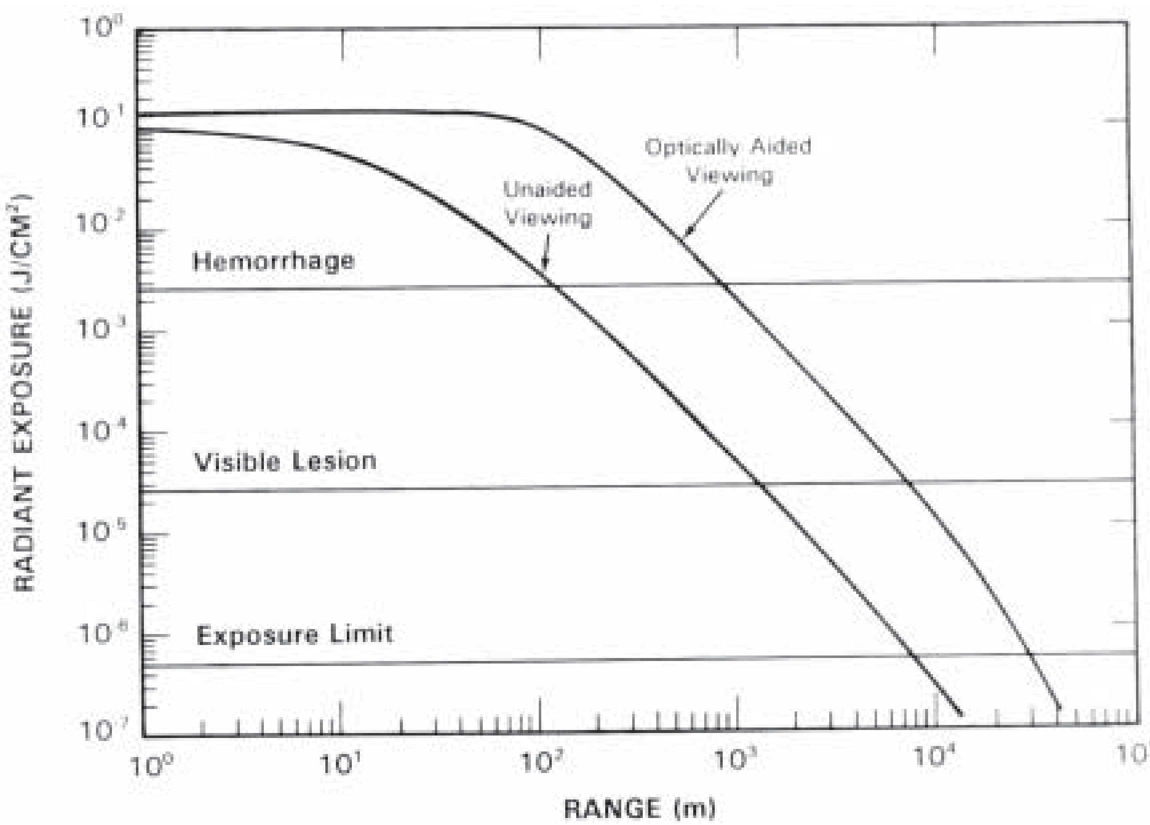

Fig. 15-19. The concentration of ruby laser light is plotted as a function of distance from the laser (range). The graph predicts that a retinal hemorrhage would occur at a distance less than 100 m, a visible lesion would occur at a distance less than 1,100 m, and that the exposure limit would be exceeded at a distance less than 8,000 m.

very small. An optical viewing system can extend these distances by magnifying the power of the system.

Laser and Optical Radiation Exposure Incidents

Unlike RF radiation exposures, few incidents of laser and optical radiation exposures have been reported since 1981, when the USAEHA began investigating them. Eight incidents were formally investigated from 1981 through 1987, although approximately 16 were known to have occurred. From 1988 to 1992, one additional laser incident occurred, and in 1988, a formal procedure was established for the investigation of laser and RF radiation exposure incidents (USAEHA Regulation 40-13).[63] This procedure may involve a formal investigation followed by an official report, but only when directed by the OTSG.

The following four case studies of laser and optical radiation exposures have been selected to illustrate the range of incidents that the USAEHA investigates. The first two concern two of the three serious retinal injuries that have occurred since 1981 (the third, which occurred in 1984 at Fort Bragg, North Carolina, involved the AN/PAQ-1 and was similar to these two). (See Figures 8-17 and 8-18 in Chapter 8, Conserving Vision, for other laser injuries.) The third and fourth case studies describe incidents where the reported ocular effects were inconsistent with the potential laser exposure.

Case Study 1

On 3 March 1987 a civilian employee at Aberdeen Proving Ground, Maryland, was adjusting a Nd:YAG-pumped dye laser when he reported seeing a single orange flash. The laser was operating at a wavelength of 620 nm with a pulse-repetition frequency of 10 Hz. The individual was not wearing laser eye protection at the time because it inhibited his view, and viewing the beam is essential for performing adjustments.

During the eye examination that was conducted after the exposure, the individual reported seeing a central reddish scotoma approximately 2 feet in radius in his right eye when observing a large object 20 feet away. The examination showed visual acuity of 20/x [not measurable] for the right eye, and 20/20 for the left eye. A funduscopic examination showed a macular hemorrhage approximately 1.5 disc diameters wide in the right eye and a normal left eye. Retinal photographs were taken on the day of the injury and on followup eye examinations (Figure 15-20).

The examinations and investigation hold that the individual probably received a total intraocular exposure of approximately 550 µJ, which is 3,000-fold greater than the occupational exposure limit of 0.19 µJ. The injury was consistent with the exposure parameters. The individual did regain 20/20 vision in the injured eye, but continues to experience a slight visual degradation in his visual field when using the affected eye for monocular vision.

Case Study 2

On 18 July 1989 a U.S. Army soldier stationed in the Federal Republic of Germany reported two laser exposures induced by an MX-9838 AN/GVS-5 laser IR observation set. The soldier claimed that he was exposed to the direct beam at 10 to 12 inches from the source. With each exposure, the soldier reported seeing a whitish flash, hearing a click, and then immediately seeing a dark spot in his visual field. Later, he reported seeing what appeared to be dark jellyfish tendrils in his field of view, which appeared red in high-level ambient illumination.

Because the GVS-5 is a single-shot laser rangefinder, a maximum of one injury is expected per exposure. The retinal examination, however, showed four separate lesions in and around the macula. The ophthalmologist, who examined the soldier the day following the injury, discovered the right eye to demonstrate poor visual acuity (20/400), and the left eye to demonstrate 20/20 visual acuity (Figure 15-21). Although the ophthalmologist found the left eye to be normal, the right eye had sustained multiple macular and perimacular laser burns with edema, subretinal hemorrhages, rupture of the internal limiting membrane, and vitreal hemorrhage.

The eye examination and the USAEHA investigation concluded that the maximum intraocular exposure for each pulse could be 15 mJ at 1,064 nm, if the exposed eye collected all the radiant energy emitted. The occupational exposure limit for a pulse less than 50 µs at 1,064 nm is 1.9 µJ. The potential exposure was therefore approximately 8,000-fold greater than this limit. Although the severity of the injuries was consistent with the exposure, the number of injuries was not consistent with the incident as reported.

Case Study 3

On 4 October 1984 an individual at Jefferson Proving Ground, Indiana, reported being exposed to a helium-neon laser for 1 to 2 minutes. The individual reported seeing a dark afterimage in a uniform circle, approximately the size of a golfball. The afterimage gradually disappeared, and it had completely disappeared within 1 hour after the alleged exposure.

The individual had two eye examinations after the alleged incident. An examination performed 6 hours after the incident showed visual acuity of 20/30 for the right eye, and 20/20 for the left eye. The individual reported no visual disturbances. Six days later, a followup examination demonstrated 20/20 visual acuity in both eyes. Neither of the two examinations revealed any ophthalmoscopically visible retinal changes.

Like the eye examination, the USAEHA investigation of the incident failed to prove that an overexposure had occurred. The investigation showed that at the time of the alleged exposure, the individual was located approximately 8.1 m from the transmitter. The laser was rigidly mounted and the direct beam's height was too far above the ground to expose the individual's eyes. If the individual had been exposed to the direct beam at this distance, he would have received a corneal irradiance of 170 µW/cm^2. Approximately 1 minute of exposure to 170 µW/cm^2 is permitted, and similarly, 8 hours of exposure is permitted for 17 µW/cm^2. The actual exposure was probably approximately 1.7 µW/cm^2, which is far below the 8-hour limit. Therefore, the individual was not exposed beyond the occupational limit, and the persistence of the afterimage was not consistent with the exposure level.

Case Study 4

On 2 July 1986, while inside the turret of an M60A3 tank at Fort Indiantown Gap, Pennsylvania, an individual performed a self test on a ruby laser rangefinder operating at 694.3 nm. Within one-half hour after performing the self test, the individual complained of an irritation in his left eye. Inflammation increased, becoming more intense over the next 4 days. When the individual returned to work after a holiday, he was sent for an examination. The civilian ophthalmologist's examination proved normal, except for a preexisting nevus on the fundus of the left eye, and episcleritis and keratitis of the left eye. The ophthalmologist did not attribute the nevus to laser exposure, but did attribute the episcleritis and keratitis to accidental laser exposure because the individual had been working with lasers at the onset of these conditions.

U.S. Army ophthalmologists examined the individual's eyes and disagreed with the findings of the civilian ophthalmologist. The patient was then flown to Walter Reed Army Medical Center for examination 4 days after the initial eye examination. Army ophthalmologists there agreed with the clinical findings of the civilian ophthalmologist, but were more guarded about attributing the other two findings to laser exposure. Contrary to the civilian ophthalmologist's conclusion, episcleritis is a relatively common inflammation of the anterior segment of the eye and its cause is usually unknown. Similarly, the civilian ophthalmologist's conclusion that a ruby laser induced the keratitis is inconsistent with scientific and clinical evidence that suggests that red light at 694.3 nm cannot damage the cornea unless it is of sufficient intensity to cause catastrophic injury to postcorneal ocular tissue. The onset of the episcleritis and keratitis after the laser self test was coincidental. In addition, radiometric measurements verified that no laser radiation was present inside the turret during the self test.

a b

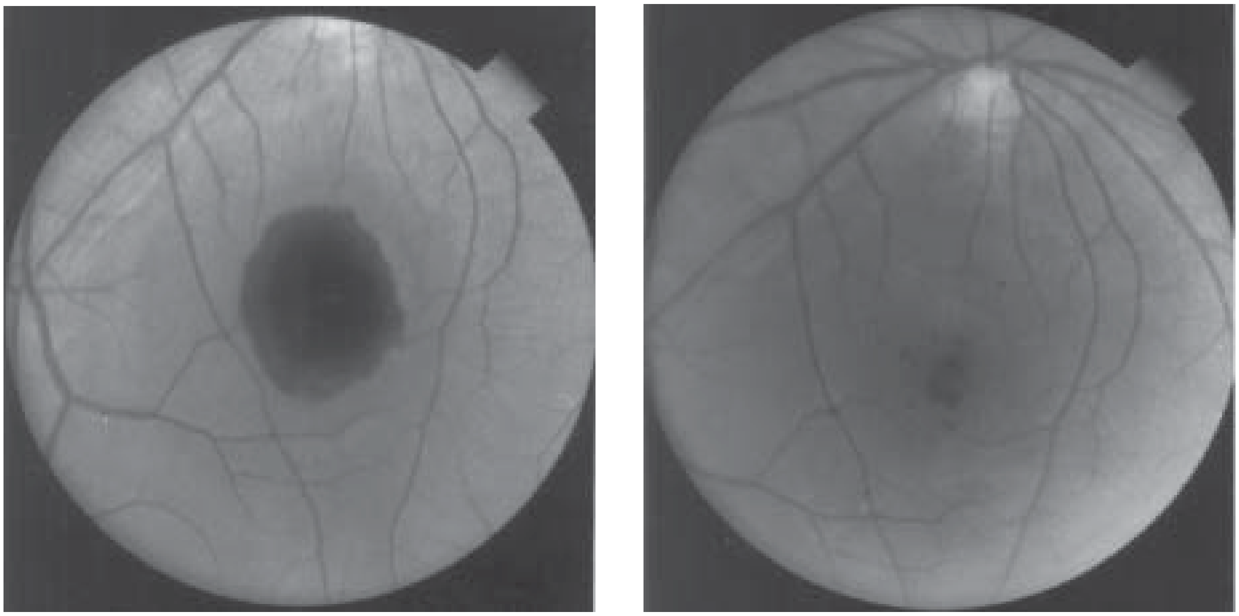

Fig. 15-20. (**a**) The retinal photograph of an accident victim's right eye shows macular hemorrhage. (**b**) The retinal photograph of the patient's right eye, taken 3 months after the accident, shows recovery to 20/20 vision.

a b

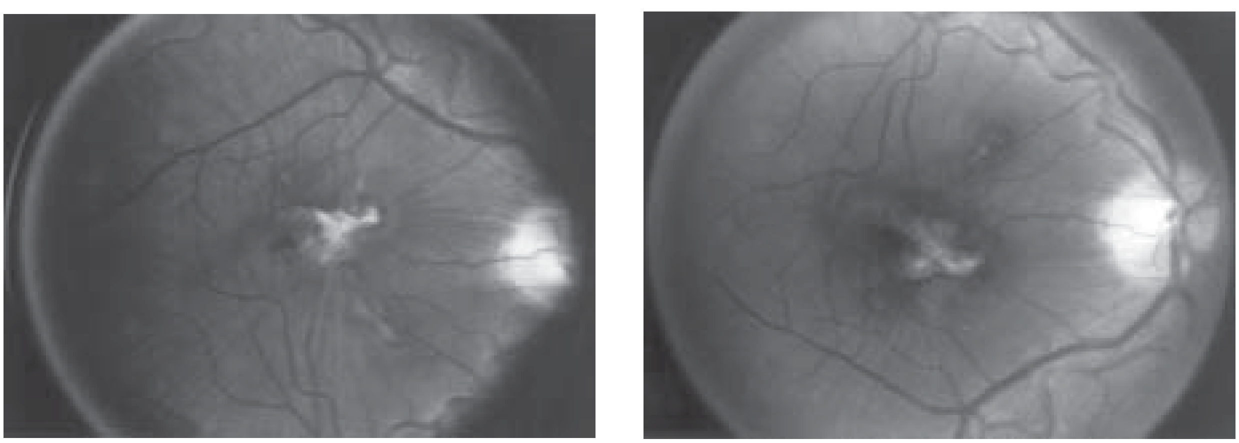

Fig. 15-21. (**a**) This retinal photograph of the patient's right eye was taken 3 weeks after the incident. Little change is noted and vision has not improved beyond 20/400. (**b**) This retinal photograph of the patient's right eye was taken approximately 1 month after exposure to an AN/GVS-5 laser.

The Laser Protection Program

The installation or activity commander has control over the Laser Protection Program elements; the installation or activity RPO is responsible for implementing the program. A typical Laser Protection Program includes elements such as (*a*) laser inventory and threat classification, (*b*) engineering controls, (*c*) training, (*d*) administrative controls, and (*e*) laser eye protection.

Inventory and Threat Classification

Complete program files should be maintained by the RPO to include the current records of inventory, SOPs, and records of related safety instruction.

Lasers and laser systems are evaluated to determine the severity of hazard that they are capable of posing. Each laser or laser system is classified in one of four basic hazard categories, with Class 1 being the least hazardous and Class 4 being the most.[64] Class 1 lasers do not pose a hazard to personnel, even if all the energy emitted can be focused into a person's eye. A few training lasers and laser-diode systems fall into this category, but most *open-beam* (unenclosed) lasers are too powerful. In many systems, however, powerful Class 4 lasers are enclosed inside interlocked cabinets within the system. These *enclosed* lasers present no hazard during normal operation and are therefore categorized Class 1.

Class 2 lasers, which are visible, only pose a hazard if an individual overcomes his or her normal aversion response and stares into the laser for more than 0.25 seconds. Lasers less than 1 mW are categorized Class 2, and lasers that do not exceed the EL for 1,000 seconds (approximately 16 min) are categorized Class 2a.

In general, lasers that exceed the Class 1 and Class 2 criteria, but are less than 0.5 W in their average power, are categorized Class 3. This category is subdivided into Class 3a and Class 3b, with Class 3a posing the lesser threat. Class 3a lasers do not pose an immediate hazard to personnel who either view the source directly or view a reflection from a specular surface. However, Class 3a lasers pose an *immediate hazard* to personnel who are using magnifying optics. A visible laser is categorized Class 3a if the output power is 1- to 5-fold greater than the Class 2 accessible exposure limits (AELs). A UV or near-IR laser is classified Class 3a if the output power or energy is 1- to 5-fold greater than the Class 1 limit. Class 3 lasers, or laser systems that do not meet the previous requirement (such as single-pulsed neodymium rangefinders), are classified as Class 3b.

Class 4 lasers have an average output exceeding 0.5 W. Some are capable of producing thermal injuries to the skin; others pose hazards from combustion or diffuse reflection.

Engineering Controls

Title 21, Code of Federal Regulations, Part 1040 (1988), dictates the type of engineering controls required for laser equipment, based on the laser's class.[64] This standard requires that all lasers (*a*) contain an interlocked protective housing and (*b*) display proper labeling and appropriate user and service information. In addition, Classes 2, 3, and 4 lasers must contain an emission indicator and a beam attenuator. Classes 3b and 4 lasers are further required to have (*a*) an emission indicator that is activated prior to laser emission, (*b*) a connector that can deactivate the laser remotely, and (*c*) a key-operated switch to prevent unauthorized use. Alternate control measures that do not interfere with the military mission are contained in MIL-STD 1425A for military-exempt lasers. Laser laboratories must also maintain engineering controls to preclude personnel exposure, including warning lights and signs; filtered view ports; and, for Class 4 lasers, door interlocks.

Administrative Controls

SOPs and other administrative controls such as protocols, operators manuals, and good safety practices are important components of laser-protection control. Every installation or activity that uses Classes 3 or 4 lasers should publish an SOP for proper laser use. This SOP should specifically address the hazards of the lasers in the environment where they are used and should prescribe procedures for their safe use.

Training Programs

Laser-safety training is necessary for all who operate potentially hazardous optical equipment. This training should include instruction concerning the hazards of the particular pieces of equipment, protection methods, and emergency procedures. Instructors involved in the training of laser safety and range safety personnel should receive further instruction concerning basic optics, biological effects of lasers, laser safety standards, laser-protective clothing (eyewear, gloves, and flame-retardant clothing), and preparation of laser range areas.

Eye Protection

The type of laser eye protection that the U.S. Army uses is rapidly changing due to new technology. The

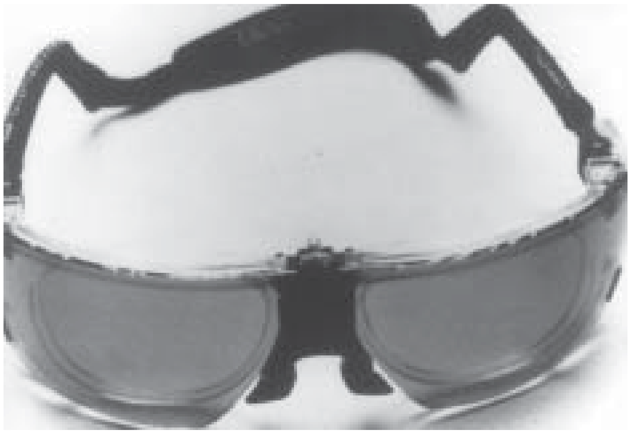

Fig. 15-22. The Ballistic/Laser Protective Spectacle. The brown spectacle provides ballistic and sun protection. The clear spectacle provides ballistic protection only. The blue-green frontsert is a laser eye protector that can be worn over either spectacle. Photograph: Courtesy of the US Army Environmental Hygiene Agency.

army is planning to distribute the Ballistic/Laser Protective Spectacle (BLPS) to all personnel. BLPS is designed to provide protection both against moving objects and against all currently fielded DoD laser equipment (Figure 15-22; see also Figure 8-29 in Chapter 8, Conserving Vision). However, BLPS is not required in a training environment, due to the administrative controls already in place. BLPS is currently available to a select few (details are classified), but other types of laser eye protection are available through commercial vendors for most army personnel.

Laser eye protectors are designed for protection against a specific wavelength and have a certain amount of attenuation known as optical density (OD). Therefore, the laser's wavelength and the required OD must be known before selecting the proper eye protection. Because the U.S. Army frequently uses the Nd:YAG laser at 1,064 nm and the ruby laser at 694.3 nm, eye protection with an OD of 6 or greater at these wavelengths will provide adequate protection from most lasers fielded by the army.

MEDICAL SURVEILLANCE

There is no scientific basis or epidemiological evidence to suggest that medical surveillance for RF radiation workers is necessary, and the army's program of periodic ocular examinations for them was eliminated in February 1992. However, the army has a medical surveillance program for laser workers, which employs both screening and diagnostic examination protocols.

The ocular surveillance examinations within the program are divided into three categories: preplacement, immediate, and termination. These examinations are based on whether the individual is classified as an *incidental* or a *laser* worker. Incidental workers are employees whose work makes it possible, but unlikely, that they will be exposed to laser energy sufficient to damage their eyes. For example, operators of fielded equipment are considered incidental workers. Laser workers are employees who routinely work in laser environments and have a higher risk of accidental overexposure; for example, laser-maintenance workers and research, development, test, and evaluation personnel work in situations where adequate protective measures cannot be provided. Regardless of their classification, all individuals who begin working with lasers must undergo a preplacement examination to determine their baseline visual status prior to potential exposure and a termination examination on termination of employment or military occupational specialty.

If at any time during employment, an individual suspects that he or she has been exposed to a laser beam in excess of the ELs, that individual must be examined within 24 hours of the suspected incident.[65] This action initiates a preliminary investigation and records the incident in a registry of alleged laser overexposures.

Two different protocols—screening and diagnostic—are used for ocular surveillance examinations. The screening protocol is used for preplacement and termination examinations of incidental and laser workers. The diagnostic protocol is used for immediate examinations, and will be performed by an optometrist, ophthalmologist, or physician who possesses the necessary skills.[39]

SUMMARY

EM radiation may be ionizing or nonionizing. Nonionizing radiation includes EM radiation with wavelengths greater than 1 nm and is classified as UV radiation, visible light, IR radiation, microwave radiation, and RF radiation. Nonionizing radiation possesses a variety of physical characteristics such as divergence, interference, coherence, and polarization. These characteristics, together with the media with which it interacts, determines how the radiation is scattered, absorbed, transmitted, refracted or diffracted. When nonionizing EM radiation is absorbed by matter, either translational, vibrational, rotational, or electronic energy modes of constituent atoms and molecules are excited. Excitation of translational modes generates heat. Excitation of electronic modes generates photochemical reactions.

Nonionizing EM radiation can interact with tissue in a variety of ways, the most medically important being absorption and excitation of electronic modes. Therefore, all direct biological effects from exposure to nonionizing radiation are thermally or photochemically induced. When radiation energy is absorbed by biological tissue, it can be converted to heat. If the total energy absorption exceeds the capacity of the tissue, then a thermal effect may be produced. Optical radiation effects occur to the eyes and the skin. RF radiation can affect all organs of the body; however, the eyes and skin are generally the most sensitive.

The direct biological effects of RF radiation exposure are dependent on the radiation frequency and mechanism of energy transfer. Conduction of RF energy requires physical contact with an active RF source and can cause an RF shock or burn. An RF burn is generally deeper than an ordinary burn. Coupling of RF energy from an RF source at the resonant frequency of the body will increase the energy 3- to 5-fold. Absorption is the only mechanism for energy transfer when the recipient is at least 0.2 λ from the source. The PELs for RF radiation are based on limiting the specific absorption rate to no more than 0.4 W/kg. The bio-logical effects from RF radiation absorption include lenticular cataracts, erythema, and tissue burns.

The direct biological effects of optical radiations are frequency dependent. In the visible and IR regions, the interaction mechanism is primarily thermal. In the UV region, the interaction mechanism is predominantly photochemical, although thermal injury is also present. The biological effects for mid- to far-IR radiation are corneal burns and cataracts. The biological effects for visible and near-IR radiation are retinal burns and degradation of color or night vision. The biological effects for UV radiation are photokeratitis, cataracts, and erythema.

Lasers are a special case of nonionizing radiation. Lasers are highly collimated, monochromatic, and intense sources of radiation; therefore the injuries caused by lasers are generally acute, and consist mostly of localized burns or retinal injuries. The military applications of laser technology consist mainly of lasers for targeting devices; these lasers do not cause injury to the skin but can cause permanent retinal injury when a soldier stares directly into the laser's beam.

Indirect biological effects may follow the use of nonionizing radiation sources. EM interference with electronic devices can disrupt the operation of life-support equipment such as pacemakers. Interference can occur at levels below the PEL for RF exposure of humans. Ancillary sources of health effects associated with lasers include caustic chemicals, noise, airborne contaminants, and electricity. Ionizing radiation, such as X rays, are also produced by some RF and optical sources where high-voltage vacuum tubes are employed.

The military uses RF radiation for communication, target detection, imaging, electronic countermeasures, medical diathermy, industrial heating, and food preparation. Ground surveillance radar assists aircraft landing under adverse weather conditions. Radios permit commanders to direct their troops and obtain information from their troops. Air-defense radars direct weapons to hostile targets and provide early warning of an attack. Satellite communication terminals provide for long-range voice and data transmissions with greater speed and capacity than radio transmissions.

The protection of army personnel from overexposure to nonionizing radiation is accomplished through a comprehensive Radiation Protection Program. The implementation of the program is the responsibility of the installation or activity commander to ensure the safety and health of his or her personnel. To this end, consensus standards for occupational exposure to nonionizing radiation have been developed and are enforced through army regulations. The primary regulation is AR 40-5. Procedures have been established for the investigation of alleged overexposure incidents.

The incidence of accidental exposure to nonionizing radiation in excess of established limits has been rare, especially considering the number and variety of sources in use today and the types of environments where they are used. The best medicine is preventive. But in the event of an accidental overexposure, it is the responsibility of the attending physician to determine if an injury has occurred and to prescribe a treatment. An eye examination should be performed as a minimum.

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