

**OPTICAL RADIATIONS  
IN MEDICINE**

## F O R E W A R D

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The present publication is a survey prepared under the auspices of the Optical Radiation Task Force at the direction of the General Medical physics committee (chairmen, Paul L. Carson) established by the AAPM Science council.

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OPTICAL RADIATIONS IN MEDICINE  
A SURVEY OF USES, MEASUREMENT AND SOURCES

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ABSTRACT: The extensive use of optical radiations in the diagnostic and therapeutic management of patients invites the interested physicist to provide calibration and quality control. Various medical uses of optical radiations in medicine as well as measurement instrumentation and radiation sources are surveyed.

### **INTRODUCTION**

If one surveys the uses of nonionizing radiation at any hospital one finds that a large number of patients are exposed to nonionizing radiation during diagnostic and therapeutic management. Although nonionizing radiation includes ultrasound, microwaves, and radiowaves in addition to "optical" radiations (ultraviolet, visible and infrared), this survey will include only the diagnostic and therapeutic uses of optical radiations. Infrared thermography will not be treated here. In addition to the applications discussed in this report, optical radiations are used frequently in laboratories involved in clinical analysis or research or both.

The medical physicist is rarely called upon to provide technical expertise in areas of clinical applications of optical radiations. This situation is due in part to a lack of communication between the clinician and the physicist. One or the other does not realize that a combination of their skills may be beneficial to the patient. This survey will point out applications of optical radiations to patient care and indicate the need for physics-related services in these areas.

### Ultraviolet Radiation

Ultraviolet (UV) radiation (100 to 400 nm) has had a long and distinguished use in clinical medicine. Several excellent textbooks are available reviewing in detail the biologic effects and clinical applications of ultraviolet radiation.<sup>1-3</sup>

The biologic and photochemical effects of W radiation are related in part to the similarity of the photon energy (eV) and the binding energies of most chemical and biologic molecules. For example, UV radiation with wavelengths of approximately 180 nm efficiently dissociates oxygen into ozone. The layer of ozone that surrounds the earth is due, in part, to UV-induced dissociation of atmospheric gases<sup>4</sup>. Longer wavelength UV at the surface of the earth can create ozone when atmospheric pollution is present, giving rise to the ubiquitous "ozone alert".

At wavelengths of approximately 250 nm there is a marked increase in the absorption of UV radiation by DNA and other intranuclear molecules. Long before this was understood, a number of investigators noted that UV radiation at 250 nm was germicidal. The approximate effectiveness of UV radiation for this application varies as a function of wavelength (Fig. 1). Local applications of germicidal UV radiation promote healing of ulcers (e.g., in sinuses). Because both common glass and the atmosphere surrounding the earth do not transmit appreciable amounts of UV radiation with wavelengths less than 300 to 320 nm<sup>4</sup>, ozone production and germicidal uses such as sterilization occur only with artificial sources that have special UV-transmitting quartz envelopes.

For "natural" UV radiation at the surface of the earth (wavelength > 290 nm)<sup>4</sup> a wide variety of biologic effects are evident. For example, children who lived during the industrial period in England, in which a constant smog blocked out solar radiation, had a very high incidence of vitamin D deficiency.

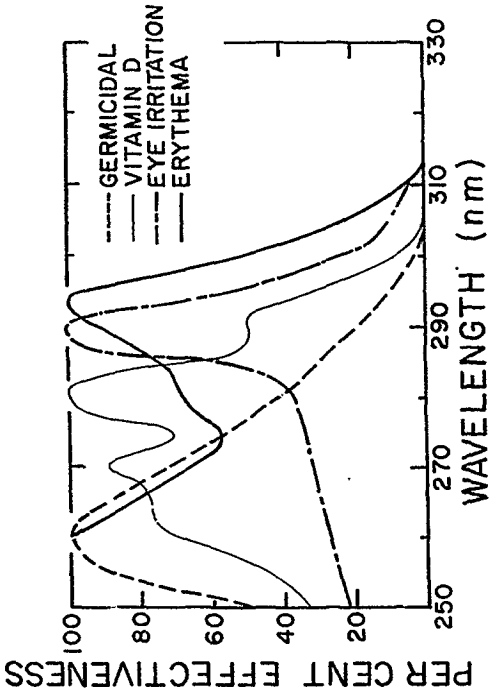


Fig. 1. Relative effectiveness of UV radiation for four effects: (1) germicidal (peak at ~260 nm); (2) vitamin D production (peak at ~280 nm); (3) production of skin erythema (peak at ~295 nm); and (4) eye irritation (peak at ~290 nm).

Eskimo children take vitamin D supplements because the paucity of UV wavelengths effective in vitamin D formation (also shown in Figure 1) at their geographic latitudes in the winter.

A common biologic result of terrestrial UV radiation is the sunburn-tanning (erythema) cycle. The wavelengths of UV radiation principally effective for this cycle are below 320 nm<sup>5</sup> (Figure 1). For a time, wavelengths longer than 320 nm were felt to induce tanning without an actual burn, which of course, had wide implications in the commercial field of suntan preparations. However, now it is believed that getting a tan from the longer wavelengths requires first having erythema or sunburn<sup>4</sup>. The most effective sunscreen constituent is para-aminobenzoic acid (PADA) in alcohol which increases penetration into the skin. Common window glass also prevents passage of a substantial fraction of the erythema-producing wavelengths.

In recent years, as a result of new instrumentation, the UV radiation action spectrum for the production of erythema has been investigated by a number of laboratories. These have revealed that even in a group of people who are "normal," wide variability in sensitivity to the different wavelengths exists<sup>5</sup>. Hence, it is not possible to give a precise single time in which anyone will receive minimal erythema. In addition, this estimated time obviously would depend on the time of year, time of day, geographic latitude, altitude, and the individual's inherent biologic sensitivity for erythema production. At noon for midlatitudes in summer, a minimal erythema for untanned white skin will result from a 15- to 20-minute exposure to the sun at sea level. A "brisk" erythema would require an exposure three times longer<sup>1</sup>,

At the wavelength of maximum sensitivity for production of erythema (295 nm the minimal erythema dose (MED) is 50 Joules/m<sup>2</sup>.<sup>5</sup> If this energy is absorbed in

the outer 60  $\mu\text{m}$  of skin, the "absorbed dose" is equivalent to  $10^5$  rads!

Because most UV radiation sources that produce erythema are polychromatic, the spectral irradiance (microwatts per square centimeter per nanometer) weighted by the relative erythematous effectiveness yields a measure of the effectiveness of the various wavelength polychromatic radiation to produce an erythema compared to monochromatic radiation at a reference wavelength. The weighted radiant power (flux) producing the same effect as 10  $\mu\text{W}$  of homogeneous radiation at 297 nm is termed an E-viton. In the production of erythema (and most biologic effects) the appropriate quantification is in terms of energy rate (or total energy) per square centimeter. One E-viton/ $\text{cm}^2$  is termed a Finsen, a unit in honor of the man who first brought UV radiation into prominence and put UV therapy on a quantitative basis. A MED is usually obtained following exposure to 500 Finsen-seconds ( $50 \text{ J/m}^2$ ), which is usually obtained from a 10- to 20-minute exposure to sunlight because the maximum effective irradiance in sunlight is not likely to exceed 1.0 Finsens. In actual fact, one usually observes the maximum irradiance to be less than 1.0 Finsen indicating that a minimal erythema is usually obtained from a 15-25 minute irradiation under maximum conditions. With snow on the ground, this time is greatly shortened; but fortunately in the winter, the incident UV irradiance is lower.

The induction of skin carcinoma has been of interest for a number of years. Studies by Blum<sup>6</sup> and others showed a definite link between skin cancer and exposure to UV radiation. Recently it has been postulated that a fleet of supersonic transports (SSTs), via their impact on the upper atmosphere and its amount of ozone, would permit more solar UV radiation to reach the surface of the earth. Hence, the SSTs might have a significant effect on the incidence of skin cancer, although the sensitivity of humans to the induction of skin



cancer varies widely. Very little quantitative data exists on an action spectrum for the induction of skin cancer by UV radiation, but it is believed to be similar to that observed for the induction of erythema, that is, radiation with wavelengths longer than 320 nm are ineffective in producing skin cancer<sup>6</sup>.

Another biologic affect of UV radiation, which is vary familiar to snow skiers (snow is an excellent reflector of UV radiation), is the induction of conjunctivitis. in Figure 1, a typical action spectrum for the induction of eye irritation is shown. Because UP radiation does not penetrate to the interior of the eye (Figure 2), most of the biologic damage is confined to the cornea or the protective conjunctiva. Corneal damage by UV radiation usually involves histopathologic changes. In particular, the cornea becomes opaque to radiation, causing temporary blindness; hence snow skiers who ignore adequate eye protection develop "snow blindness." Conjunctivitis and corneal keratosis are also side effects of welding if improper or no protective eyewear is worn. The effects of UV radiation on the eye are usually transitory and clear in 24 to 48 hours without long-term damage.<sup>7</sup> Because UV radiation does not penetrate the eye readily, retinal damage by UV radiation is unlikely. The question of cataract induction by UV radiation has never been satisfactorily resolved.

Biologic effects discussed so far have been limited to UV radiations with wavelengths shorter than 320 nm but effects also may occur with sufficiently intense sources of wavelengths longer than 320 nm. Obviously, it is the integrated sum of the product of the biologic effectiveness, the spectral irradiance at each wavelength and total time and fractionation of irradiation which determines the net biologic effect. Action spectra have not been measured beyond 320 nm because of the difficulty in obtaining sufficient quantities of monochromatic, long wave-length radiation without significant contamination by the shorter, more biologically potent wavelengths.

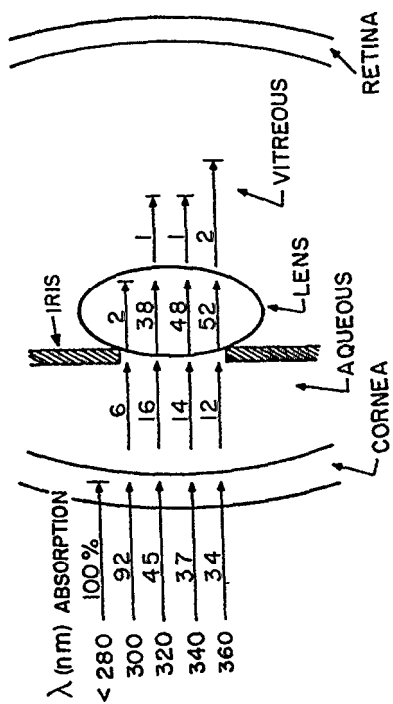


Fig. 2. Percent penetration of various UV wavelengths through various structures of eye.<sup>7</sup>

The clinical subspecialties which utilize UV radiation most frequently are the Departments of Dermatology and Physical Medicine. For example, there are a number of disorders of the skin that are either caused by or aggravated by exposure to electromagnetic radiation. Among these is lupus erythematosus, a grave condition marked by patches of discoloration and scars. The antagonistic radiation usually is UV radiation. Within the UV spectrum, two wavelength bands exist; they are antagonists in different categories of skin disease. For example, in some patients extreme sensitivity to wavelengths shorter than 320 nm is seen; in others, the offending wavelengths are longer than 320 nm. Wavelengths between 320 and 400 nm usually are classified in the UV-A wavelength band whereas those between 290 and 320 nm are in the W-B wavelength band. Phototesting for the UV wavelength band sensitivity is most routinely carried out using a simple glass plate that screens out wavelengths shorter than 320 nm. Other "cutoff" filters can be employed. In some institutions. monochromatic radiation frequently is used. However, the irradiance from most commercially available monochromators may be less than satisfactory for use in a busy dermatology department.

Various skin disorders have been treated effectively using UV radiation (UV-A) in conjunction with drugs or various topical ointments (or both). Treatment of a major medical problem, psoriasis, with coal tar and UV-A irradiation is in its 50th year after introduction at the Mayo Clinic. Recently reported work from Harvard indicates that psoriasis can be treated with methoxsalen in conjunction with very high intensity body baths of UV-A irradiation.<sup>8</sup>

Also frequently used in clinical medicine is the knowledge that many materials fluoresce (give off longer wavelength radiation) when exposed to UV radiation. UV fluorescence has been used to diagnose a wide variety of skin disorders and rheumatologic conditions as well as to study various aspects of bacterial

buildup on teeth.<sup>2</sup> A common wavelength used to stimulate UV fluorescence (365 nm) is readily available from a mercury discharge lamp in a normal glass envelope. The glass envelope filters out wavelengths shorter than 320 nm, thereby reducing but not eliminating all potential hazards to the operator of the lamp.

At many institutions UV generators are used in departments of physical medicine for treatment of acne or psoriasis, so that the patient need not go to the department of dermatology. Some persons advocate the inclusion of a certain amount of UV radiation in environmental lighting, for example, to reduce winter colds. Most of the claims for beneficial systemic effects of UV radiation were made in the early days of UV therapy and were published without adequately controlled studies.

#### Visible Radiation

Applications of visible radiation (400-700 nm) in clinical medicine include laser photocoagulation, pediatric transilluminators, and treatment of hyperbilirubinemia (in premature infants) and herpes simplex.

Bilirubin is one of the end products of normal destruction of circulating hemoglobin. It is carried through the circulatory system to the liver, where it is efficiently removed and excreted in the bile into the duodenum. Elevated serum bilirubin occurs occasionally in newborn children. Elevated levels cause concern because brain and spinal cord damage can result, and treatment with blood transfusions has an increased risk of complications.

In 1958, Cremer et al.<sup>9</sup> noted that babies in a nursery who were placed near a window (where they were exposed to sunlight) had lower serum bilirubin levels than those far from the windows. This led to a number of studies on the use of artificial illumination in treatment of increased serum bilirubin levels in the newborn child. Phototherapy of hyperbilirubinemia has become widespread and is currently accepted in most institutions, even though some investigators warn about the possible production of harmful photo products.<sup>10</sup>

The wavelengths effective in reducing the serum bilirubin levels, based on both in vitro and in vivo observations, are in the range of 440 to 460 nm. As a result, special "blue" lamps that are said to be rich in these destructive wavelengths are often used.

Another application of optical radiations in pediatrics is the use of a high intensity light source to illuminate the inside of the head of a newborn or very young infant.\* The heat producing radiation is filtered out by an infrared absorbing filter. Other uses in neonatal medicine for such a transilluminator include the rapid diagnosis of pneumothorax<sup>11</sup> and location of veins for obtaining blood specimens.<sup>12</sup>

The use of lasers in the medical environment has undergone a significant increase in the last ten years. Lasers are frequently used in surgical procedures as well as in certain ophthalmologic procedures. For example, argon lasers with wavelengths of 515 nm and 488 nm are used for retinal coagulation. Termination of treatment usually depends on a visual observation. Additional applications of visible radiation in ophthalmology include a number of diagnostic instruments such as various devices for looking through the lens of the eye at the retina.

Herpes simplex virus (a venereal disease) causes single and recurrent infections of the skin and mucous membranes. A therapeutic procedure, involving photodynamic inactivation, has developed for treating both oral and genital forms of herpes simplex. The treatment, termed the "dye light procedure," consists of application of a dye, such as neutral red or proflavine, to herpetic lesions, which are then exposed to visible light (most frequently with

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\*Radiation Measurements Incorporated, Middleton, Wisconsin

a standard white fluorescent lamp). Loss of virus infectivity results from photodynamic inactivation.

A controversy has developed over the use of this procedure because some investigators claim it is potentially carcinogenic and therefore clinically hazardous.<sup>13</sup> On the other hand, the virus itself has been implicated as a possible cause of human cancer. Quantitative estimates of the risk are not possible at present, because there are few directly pertinent data and because exposure dosimetry in a dye stain herpetic lesion is extremely difficult. A number of animal studies are under way. These studies must have very accurate measurements of the irradiance of the animal so that a meaningful dose-effect relationship of any potentially hazardous effects can be derived. An excellent review of the controversy is available from the Bureau of Radiological Health.<sup>14</sup>

#### Infrared Radiation

Infrared irradiation (wavelengths > 700 nm) is used widely for the relief of muscular pain. Hence, one usually finds a number of infrared generators in any reasonably sized physical medicine department.

An additional use of infrared radiation in clinical medicine is the measurement of skin temperature for diagnoses of a variety of disorders. The most familiar use is infrared thermography for the detection of breast cancer. Since this use does not utilize the application of non-ionizing radiation and, more importantly, most medical physicists are relatively familiar with thermography, it will not be discussed in detail. Clearly, performance evaluation and quality control for medical thermographic instruments are areas in which a medical physicist can make a contribution.

Excessive infrared radiation can cause ophthalmologic problems. When glass blowers were noted to have a high incidence of cataracts, it was

subsequently determined that working with hot molten glass producing large amounts of infrared radiation was the primary cause of the cataracts. Protective eye wear that effectively eliminated the offending infrared wavelengths was recommended.

Protection against environmental radiation is also of interest to people in other occupations. Above the protective water vapor layer of the lower atmosphere (which absorbs a large fraction of the solar infrared radiation), airline pilots report severe eye discomfort if their protective glasses do not cut out the infrared radiation. Polaroid lenses transmit infrared radiation well because they do not polarize it (Figure 3); as a result, those persons who are in locations where increased solar infrared radiation is present, such as deserts, should wear good quality prescription sunglasses that come with some assurance that the infrared transmission is controlled (Figure 3). The discomfort due to infrared radiation, which is similar to that experienced when one watches a burning fire over an extended period, is termed "thermal ophthalmalagia."<sup>15</sup> The eye itself readily transmits infrared radiation; therefore it is not unusual to observe retinal burns following exposure to powerful infrared sources such as the sun or lasers. For example, many World War II aircraft spotters were observed to have retinal burns. And, the potential hazard of observing a solar eclipse is well publicized.

#### Quantification of Radiations in Medicine

The need for quantitative measurement of electromagnetic radiation in medicine and biology is apparent (see Appendix 1 as an example) but has not been pursued by the medical physics community as vigorously as is desirable. Most clinical reports of diagnostic or therapeutic applications of nonionizing radiation reveal a distinct lack of quantitative information about either the total or spectral irradiances

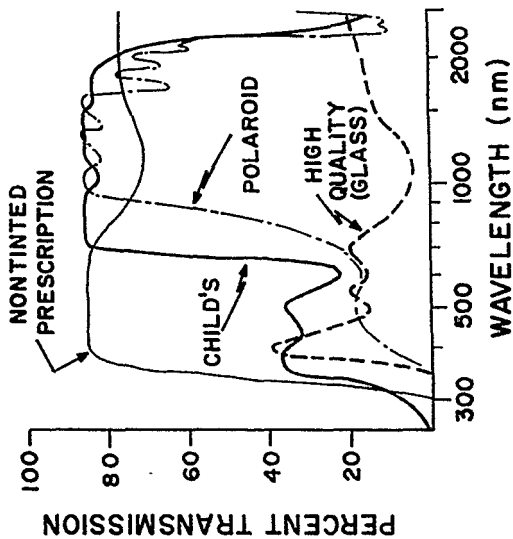


Fig. 3. Spectral transmission of sample of protective eye glasses including nontinted prescription, "children's," Polaroid, and American Optical (glass) eye wear.<sup>15</sup> Polaroid glasses were checked in two orientations to rule out any effect due to polarization in transmissometer.



involved or the constancy of light output. With the increased Federal emphasis on ascertaining the potential hazards of clinical applications of nonionizing radiation, the support of physicists will be needed in the near future.

An obvious example of the need for increased participation by the medical physicist is the area of phototherapy. Two things occur with fluorescent lamps used in phototherapy: a considerable decrease in the output of any fluorescent tube during the initial hours of operation and a shift of wavelength during operation. There is a disturbing paucity of data on the spectral outputs and irradiance of lamps used in phototherapy.<sup>10</sup> Lamps are usually changed based on the manufacturer's recommended lifetime of 150 to 200 hours. Most phototherapy light-bath units have from 6 to 10 fluorescent tubes and radiation is usually, but not always, applied to the baby on a continuous basis.

Of interest with regard to quantifying phototherapy treatment of newborn babies is the work of Mims et al.,<sup>16</sup> who noted considerable variation in light intensity over the area of a typical isolette. In addition, they discovered significant differences among various groups of lamps with different aging times and correlated the differences in bilirubin noted in a 24-hour period as a function of the light intensity in microwatts per square meter (typical irradiances, 0.04 - 0.14 W/m<sup>2</sup>),

In any section of ophthalmology one usually noted a wide variation in both the amount and uniformity of illumination of diagnostic charts. Viewboxes in a department of diagnostic radiology usually present a similar problem. One of the most widely neglected sources of light is the luminance of the output phosphor of image intensifier tubes. Even though some persons have advocated the measurement of the conversion efficiency of the image intensifier tubes as a part of the acceptance tests of fluoroscopes most physicists do not make this measurement. Without this data, the radiology department is often helpless in the

hands of the serviceman who recommends replacement of an image intensifier tube when more often than not the problem is in the electronics of the TV chain!

Measurements of optical radiation have in the past been somewhat restricted by available instrumentation. A frequent method of measuring total radiation has been the use of a thermopile to determine the thermal energy imparted by the incident radiation. Unfortunately, the outputs of these devices (in the millivolt range) and their inherent instability due to thermal drifts combine to make them less than ideal in the nonlaboratory situation. At the other end of the spectrum, in terms of sensitivity, are photomultipliers, which are not only overly sensitive for most applications but also suffer from three additional shortcomings: prominent spectral sensitivity, inherent instabilities, and lack of ruggedness and compactness (in some instances).

In recent years, several "solid-state" detectors have become available which not only are low in cost and are compact but also have outputs sufficient to be interfaced with the new generation of stable digital voltmeter devices. Silicon photo-diodes (typically with active areas of 0.1 to 1.0 cm<sup>2</sup>) have a typical detection limit (for a S/N of 10) of  $1 \times 10^{-4}$  W/m<sup>2</sup>, with the majority of the spectral sensitivity between 350 and 1,100 nm. In addition, they can be manufactured to be linear over several decades of exposure and have excellent long-term stability and rise and fall times of 10 to 15 ns. With an appropriate correction filter, a flat response (+ 7%) can be obtained for a wavelength range of 400 to 950 nm. Silicon photodiodes also can be made to duplicate the spectral response of the human eye.<sup>17</sup>

Vacuum photo-diodes have a typical detection limit of  $1 \times 10^{-4}$  W/m<sup>2</sup> with principal sensitivity between 240 and 750 nm. Solar blind detectors also are available. UV radiation measurements are best made with vacuum photo-diodes

because of the low light levels usually involved (especially in narrow wavelength bands) and the inherently lower sensitivity of silicon photo-diodes in the UV range.

Many clinical applications do not require that detailed spectral measurements will be needed other than those that are easily obtainable using broad-band probes with a set of high quality narrow-band filters. Precise measurements of the spectral values (e.g., watts per square meter per nanometer) over a large range of wavelengths usually require equipment that is relatively expensive when compared with the broad-band detector/"narrow" band-pass filter combination.

A versatile measurement system for optical (ultraviolet, visible, infrared) radiations using solid-state probes can be purchased for \$1,000 to \$2,300. At the present time, some of the "packaged" radiometers have limited capabilities for calibrated, sensitive measurements in the W range (that is, they are not available with a vacuum-diode probe nor does the manufacturer have calibration capabilities in the UV). Also, some units use probes in which the necessary filtering is an integral part of the probe. Such a system configuration leads to simplified operation but at higher cost since the basic detector or housing and cabling is duplicated on all probes.

In addition to capabilities that are obviously required, desirable qualities of a radiometer may include battery operation, metric units, ambient light cancellation and pulse integration capabilities. Features such as digital readout, autoranging, direct readout in esoteric units, pulse integration, end battery operation are eliminated in models offered by some manufacturers with savings up to 50%.

The purchase of individual radiation measuring probes may be subsidized by individual clinical specialty departments. For example, it is reasonable to ask

the Department of Dermatology to purchase a probe for the measurement of W-A so that quantitation of psoriasis treatments are possible. Likewise, the Department of Pediatrics should be willing to purchase a probe specially filtered and calibrated to measure 450-nm radiation for phototherapy of hyperbilirubinaemia.

### Radiation Units

For any person entering the field of radiation measurements, the overwhelming number of radiation units is discouraging at best. However, an order of magnitude improvement in the clarity of the situation is obtained when one understands the difference between photometric and radiometric measurements.

Radiometry generally refers to the measurement of radiation in the infrared, visible, and W portions of the spectrum. Devices used to make radiometric measurements should have equal response to light of various wavelengths. This usually is accomplished by use of a flattening filter (Figure 4). Photometry refers to the measurement of visible light with a sensor of spectral sensitivity similar to that of the average human eye. This is most easily accomplished by use of a photopic filter matched to the spectral sensitivity of the detector (Figure 4).

Radiometric units are tailored to describe not only the time variation, but also the geometrical variations encountered in the transport of the basic physical quantity, the radiant energy [joule]. For example, the rate of transfer of radiant energy is called the radiant power (flux) in units of J/sec. or watts. There is a whole series of radiometric units that describe geometrical variations in radiant power [watts] or flux (Table 1). For example, the radiant power (flux) incident upon or leaving a surface, divided by the area of the surface is called the radiant power (flux) density in units of watts -  $m^{-2}$ . Furthermore, irradiance [ $watt \cdot m^{-2}$ ] is a special case of the radiant flux

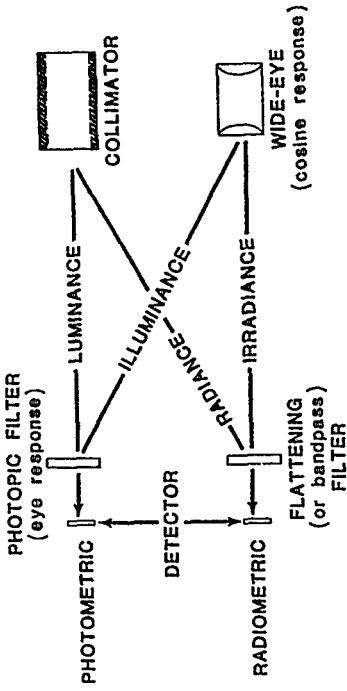


Fig. 4. Measurement of photometric (illuminance and luminance) and radiometric (irradiance and radiance) quantities.

density referring to the radiation incident on the surface. Radiant intensity [watt - sr<sup>-1</sup>] and radiance [watt - sr<sup>-1</sup>-m<sup>-2</sup>] refer to emitted radiant power [watt] per unit solid angle from a point source and surface, respectively. These quantities are forever being used incorrectly. Table 1 summarizes the symbols, names, descriptions, and units for some of the more important radiometric quantities. Analogous quantities for photometric units (i.e. those weighted by the spectral sensitivity of the human eye) can be understood by substituting luminous for radiant, illuminance for irradiance and luminance for radiance, as shown in Table 1.

Most light measurements are included in one of two categories--light received by a surface and light emanating from a surface. In both cases, either photometric or radiometric measurements may be made; these differ only in the spectral response of the sensor and in the units of expression.

The photometric determination of radiant power per unit area incident upon a surface (the radiant flux density) is said to be a measure of illuminance and may be expressed in foot-candles; while the analogous radiometric quantity, irradiance, is usually expressed in watts per square centimeter. In metric units, irradiance and illuminance are most often expressed as watts per square meter and lumens per square meter (lux), respectively (Table 1).

Figure 4 shows sensor configurations for the measurement of illuminance and irradiance. For the measurement of illuminance, a photopic (eye response filter is needed), while the determination of irradiance may require the use of a flattening filter.

Consider plane, parallel light incident at an angle on a measurement surface S; and assume that the power density in the plane normal to the direction of propagation is E watts/m<sup>2</sup>. The irradiance or illuminance on S will be E cos θ. Therefore, sensors for measurement of either illuminance or irradiance

should have a response which varies with the cosine of the angle between the incident radiation and the direction normal to the detector. This may necessitate the placing of an angular correction filter ("wide-eye" attachment) over the detector (Figure 4).

The most common photometric quantity for determination of light scattered or emitted from a surface is the luminance, and may be expressed in foot lamberts, as well as the standard metric unit, the nit (Table 1). The analogous radiometric quantity is radiance expressed in watts per square centimeter per steradian or watts per square meter per steradian. Sensors for luminance or radiance measurements usually have a narrow field of view,  $10^\circ$  or less (Figure 4), and often are arranged so that any finite-size emitting surface can be completely encompassed by the detector.

Other photometric units are the lumen, a unit of rate of transfer of energy (luminous power or flux). Candela is a unit of luminous intensity (luminous power per steradian from a point source). A radiant source with an output of 1 candela will radiate 1 lumen into 1 steradian, that is, a 1-candela source has a  $4\pi$  lumen output. At 1 meter from such a source, the illuminance is 1 lumen/m<sup>2</sup> (1 lux) while at 1 foot from the same source, the illuminance is 1 foot-candle. Hence, foot-candle and lux differ by a factor  $(3.28 \text{ ft/m})^2 = 10.75$ . Formally, 1 candela is 1/60 of the luminous flux per unit solid angle radiated from 1 cm<sup>2</sup> of a black body operated at the temperature of solidification of platinum.

Other photometric units that may be encountered include brils, brillis, nox, stilbs, blondels, glims, apostilbs, Hefnerkerzen, phots, scots, Trolands, helios, lumbergs, pharos, and Talbots! Table 2 presents the most frequently needed conversions.<sup>18</sup>

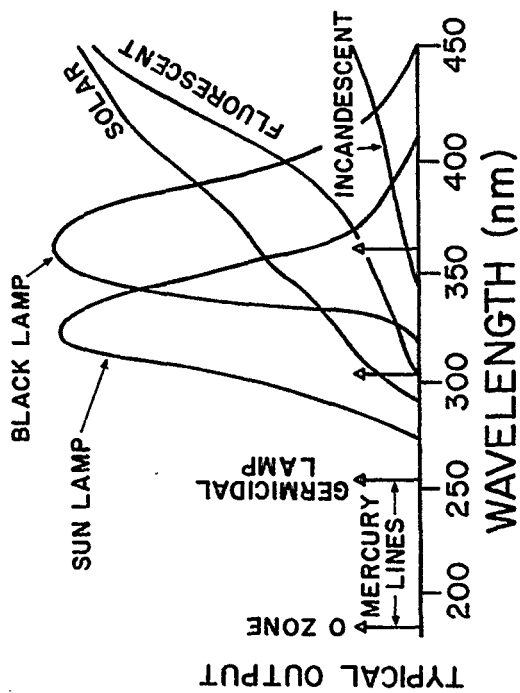


Fig. 5. Spectral distribution of UV radiation from representative UV sources.



### Optical Radiation Sources

There are many sources of UV radiation. The chief natural source, once widely used in treatment, is the sun. The minimum wavelengths observed at midlatitudes in summer and winter are 290 nm and 320 nm, respectively.<sup>4</sup> Because of the unpredictability of the radiation of the sun, solar radiation has been almost completely replaced by various mercury discharge sources. There are three major types of mercury UV lamps; their spectral differences depend on the internal pressure at which they operate--low, atmospheric, and high. Low pressure or cold quartz lamps emits over 90% of its radiation at 254 and 185 nm (Figure 5). These lamps are normally provided with envelopes that are opaque to the 185 nm line but that transmit the 254 nm line. The 185 nm line is usually not desired because it forms the obnoxious and toxic gas, ozone, to which human olfaction is very sensitive (can detect 2 to 3 parts per million). This type of lamp is usually used for its germicidal effect in various sterilization applications (e.g., for localized application for treatment of ulcers).

When a mercury discharge lamp is operated at a higher pressure a large fraction of the energy in the 254 nm line is seen in the longer wavelength lines. For example, lines are seen at 297 nm (erythema region) and 366 nm (UV-A). High-pressure mercury lamps have a high intensity, and care should be taken not to overexpose the eyes of either the patient or the operator. With use, the W output and the relative content in the various spectral lines may change. In fact, it takes several minutes before the spectral output of a high-pressure mercury lamp stabilizes.

Because of the heat generated in a high-pressure mercury lamp, it is desirable to look for alternate means of generating the longer UV wavelengths (>254 nm). One method of doing this is to use a low-pressure mercury tube

tube (in the configuration of a fluorescent lamp) coated with a phosphor that converts the 254 nm mercury discharge line to longer wavelength-s. Figure 5 includes the output spectrum for two lamps that operate on this principle. The sunburn lamp is coated with calcium-zinc-thallium phosphate and the "black light" lamp is coated with barium silicate. "Black lamps" are frequently encountered in nonmedical environments; they are used to illuminate rock collectors and pop-art poster aficionados' exhibits, and go-go dancers: The output of the black lamp to the eye irritation region usually is not sufficient to be a problem for exposure of reasonable duration. This is because the lamp is usually made of normal glass that does not readily transmit below 320 nm. These "fluorescent" sources of UV are not high-power emitters; and for this reason, they are customarily used in multiples of several lamps. Fluorescent UV lamps depreciate somewhat faster than general lighting fluorescent lamps. The useful life is about 4,000 hours.<sup>2</sup>

Lamps used for fluorescent studies in the diagnosis of disease usually are low-pressure mercury lamps in which either the 254-nm or 366 nm line is used for the fluorescent study. Also shown in Figure 5 is the portion of the spectrum of incandescent and conventional fluorescent light sources falling in the UV range.

Radiation in the visible range, that is. 400 to 700 nm, can be provided by fluorescent and incandescent sources as mentioned previously or by potentially intense line sources, such as lasers (Table 3). The spectral output of a common fluorescent tube depends on the phosphor coating of the inner surface. Most fluorescent tubes are low-pressure mercury discharge tubes in which the coating phosphor converts the mercury discharge lines to the longer wavelengths.

The large number of phototherapeutic applications of light to treat hyperbilirubinemia and the relatively short life-span of lamps used in this application have produced an inordinate number of claims by various manufacturers

about the superiority of their own fluorescent tube for this application over those of competitors. Unfortunately, many of these claims are based on the initial spectral outputs of these tubes and make no mention of the decrease in outputs at 450 nm with very short periods of use. Also, there appear to be no substantiated claims of the superiority of one type of lamp over another in the clinical environment.<sup>10</sup> This is to be expected when one considers the fact that there is very little dose-response data available. It is even conceivable that excessive blue light may actually be harmful.<sup>11</sup> Spectral outputs of some representative lamps used in phototherapy are shown in Figure 6.

On an environmental level, visible (400 to 700 nm) solar radiation energy at the surface of the earth is quite substantial. However, there is little evidence of any medical effects of this radiation. Infrared solar radiation provides a substantial fraction of terrestrial solar energy. About 50% of the total terrestrial solar radiant energy is due to infrared radiation with wavelengths greater than 700 nm.<sup>19</sup>

There are two principal types of artificial infrared radiation generators. The nonluminous infrared units consist of a spiral coil of resistant metal wire wrapped around a cone made of porcelain. These are similar to the resistance space heaters one finds frequently used in warming small areas of a home. They are essentially black body emitters that produce more radiation in longer wavelengths than the second basic class of infrared emitters, the luminous-type infrared generators. Typical examples of luminous-type infrared generators are the tungsten end carbon filament lamps. In such lamps it is not unusual that 30% of the radiant energy lies between 700 and 1,200 nm. The luminous infrared source is also to be preferred because of the predominance of the shorter wavelengths that penetrate deeper into the surface of the body than the nonluminous sources.

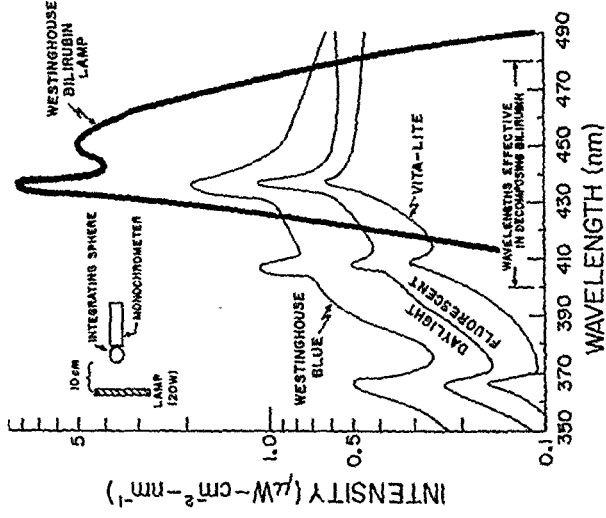


Fig. 6. Spectral intensity of a representative sample of lamps used in phototherapy of newborns. (Based on data of D. Berger, Temple University.)

Summary

The major applications of optical electromagnetic radiation in biology and medicine have been surveyed. Included is a discussion of detection and sources of these radiations. The opportunities for the interaction of the physicist and physician should be apparent and it is hoped this survey will do its part to encourage this symbiosis. A recent review<sup>20</sup> and symposium proceedings<sup>21</sup> from the Bureau of Radiological health provides information that should encourage the possibilities of increased physics participation in non-ionizing radiation effects.

Table 1. Radiometric/Photometric Units

RADIOMETRIC		PHOTOMETRIC	
Symbol and Defining Equation	Name	Description	Units
$U$	Radiant energy	-----	joule
$\dot{U} = dU/dt$	Radiant energy density	-----	joule-m <sup>-3</sup>
$\dot{Q} = dQ/dt$	Radiant power (flux)	Rate of transfer of radiant energy	watt
$W = d\dot{Q}/ds$	Radiant power (flux) density	Radiant power (flux) incident on leaving a surface, divided by the area of the surface	watt-m <sup>-2</sup>
$M^0 = d\dot{Q}/ds$	Radiant exitance	Radiant power (flux) leaving an infinitesimal element of surface divided by the area of that surface	watt-m <sup>-2</sup>
$E^0 = d\dot{Q}/ds$	Irradiance	Radiant power (flux) per unit area incident upon a surface	watt-m <sup>-2</sup>
$I^0 = d\dot{Q}/d\omega$	Radiant intensity	Radiant power (flux) leaving a point source per unit solid angle	watt-st <sup>-1</sup>
$L^0 = \frac{d^2\dot{Q}}{ds d\omega}$	Radiance	Radiant power (flux) leaving or arriving at a surface, at a given point in a given direction, per unit solid angle and per unit of surface projected orthogonal to that direction	watt-st <sup>-1</sup> -m <sup>-2</sup>

These quantities are subscripted e and v for radiometric and photometric units, respectively. Also, in photometric units, Q, q and F replace U, u and W of radiometric quantities.

\*older units still in common use are foot candles and foot-lamberts where

one lux = 10.766 foot-candles  
 one nit = 3.426 foot-lamberts

Modified from a table in C. S. Williams, and O. A. Becklund, in *Optics: A Short Course for Engineers and Scientists* (John Wiley and Sons, New York, NY 1972), P. 26. By permission.

Table 2--Conversion Table of Photometric Units\*

Some common units of illuminance			
One	Equals		
Lux	1 lm/m <sup>2</sup>	10 <sup>-4</sup> phot	9.3 x 10 <sup>-2</sup> ft candle
Phot	1 lm/cm <sup>2</sup>	10 <sup>4</sup> lux	9.3 x 10 <sup>2</sup> ft candles
Foot-candle	1 lm/ft <sup>2</sup>	10.76 lux	10.76 x 10 <sup>-4</sup> phot
Some common units of luminance			
One	Equals		
Stilb	1 cd/cm <sup>2</sup>	π lamberts	2.919 x 10 <sup>3</sup> ft lamberts
Nit	1 cd/m <sup>2</sup>	π x 10 <sup>-4</sup> lambert	0.2919 ft lambert
Lambert	1/π cd/cm <sup>2</sup>	0.318 stilb	9.29 x 10 <sup>2</sup> ft lamberts
Foot lambert	1/π cd/ft <sup>2</sup>	3.42 x 10 <sup>-4</sup> stilb	1.1 x 10 <sup>-3</sup> lambert

\*From C. S. Williams and O. A. Becklund, in Optics: A Short Course for Engineers and Scientists (John Wiley & Sons, New York, NY, 1972), p. 42. By permission.

Table 3--Typical Wavelengths Provided by Optical Lasers

Source	Wavelength (nm)
Argon	514
Helium-neon	633
Ruby	694
Gallium-aluminum-arsenic (injection)	860
Gallium-arsenic (injection)	905
CO <sub>2</sub>	1,060



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APPENDIX

Recommended Maximum Permissible Exposure

Limits - Ultraviolet Radiation

The most comprehensive occupational exposure standard which has been published is that of the American Conference of Government Industrial Hygienists (ACGIH). This standard has also been adopted by the National Institute for Occupational Safety and Health (NIOSH) in the United States<sup>1</sup>. The standard is based on the biological effects of ultraviolet radiation, including most known data on the production of erythema and kerato-conjunctivitis.

The Maximum Permissible Exposures (MPE) are expressed in radiant exposure units of joules per square meter ( $J\text{-m}^{-2}$ ), the total, i.e. time integrated) ultraviolet radiation energy falling on 1 m<sup>2</sup> of surface, or in irradiance units of watts per square meter ( $W\text{-m}^{-2}$ ), the average radiant exposure rate over the exposure period.

The standard is summarized as follows:

Wavelength range 315-400 nm

- (i) Total irradiance on unprotected eyes and skin for periods of greater than 1,000 seconds should not exceed  $10\text{ W}\text{-m}^{-2}$ .
- (ii) Total radiant exposure on unprotected eyes and skin for periods of less than 1000 seconds should not exceed  $10^4\text{ J}\text{-m}^{-2}$  ( $\text{watt}\text{-sec}\text{-m}^{-2}$ ).

Wavelength range 200-315 nm

The total radiant exposure on the unprotected eyes and skin should not exceed, within any 8-hour period the values of MPE given in the following table.

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a. "Criteria for a Recommended Standard..., Occupational Exposure to ultraviolet Radiation", U.S.D.H.E.W., Public Health Service-National Institute for Occupational Safety and Health (NIOSH), Washington, CC, 1972.

Table A-1  
 Eight-hour MPE and Spectral  
 Effectiveness (Relative to 270 nm for  
 Ultraviolet Radiations with Wavelengths 200-315 nm

Wavelength nm	MPE (J-m <sup>-2</sup> )	S <sub>λ</sub>
200	1,000	0.03
210	400	0.075
220	250	0.12
230	160	0.19
240	1010	0.30
250	70	0.43
*254	60	0.5
260	46	0.65
270	30	1.00
280	34	0.88
290	47	0.64
300	100	0.3
305	500	0.06
310	2,000	0.015
315	10,000	0.003

\*Mercury lamp-reasonance emission line

For a polychromatic source one computer using S<sub>λ</sub> values as listed in Table A-1

$$E_{\text{eff}} = \sum E_{\lambda} \cdot S_{\lambda} \cdot \Delta\lambda$$

where E<sub>eff</sub> = effective irradiance relative to monochromatic wavelength  
 270 nm (W-m<sup>-2</sup>)

E<sub>λ</sub> = source spectral irradiance at wavelength (W-m<sup>-2</sup>-nm<sup>-1</sup>)

S<sub>λ</sub> = relative spectral effectiveness

Δλ = bandwidth employed in the measurement or calculation of E<sub>λ</sub>(nm).

In those situations where E<sub>λ</sub> is not available one can use a photometer with a probe watching the S<sub>λ</sub> spectrum (available from most manufacturers) to get E<sub>eff</sub> provided the probe is calibrated absolutely! This so-called "actinic" probe also can watch the S<sub>λ</sub> curve with various degrees of accuracy!! The maximum permissible exposure, expressed in seconds, may be calculated by dividing the MPE for 270 nm radiation (30 J-m<sup>-2</sup>) by E<sub>eff</sub>(W-m<sup>-2</sup>). The Minimal Erythema Dose (MED) at 270 nm is 91 + 30 J-m<sup>-2</sup> for an **erythema** on the back of

white subjects,<sup>b</sup> while the kerato-conjunctivitis threshold dose in humans at 270 nm (which is the most effective wave-length for kerato-conjunctivitis) is  $40 \pm ? \text{ J-m}^{-2}$ .

For convenience, various Values of  $E_{\text{eff}}$  are converted to Maximum Permissible Exposure times in any 8-hour period in the following table.

Table A-2

Maximum Permissible Exposure Time  
in any 8-hour Period

$E_{\text{eff}} \text{ (W-m}^{-2}\text{)}$	Maximum Permissible Exposure Time
$10^{-3}$	8 hours
$8 \times 10^{-3}$	1 hour
$5 \times 10^{-2}$	10 minutes
$5 \times 10^{-1}$	1 minute
3	10 seconds
30	1 second
$3 \times 10^2$	0.1 second

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b. D. J. Cripps and C. A. Ramsay. Br. J. Dermatol. 82, 584 (1970)  
c. D. G. Pitts. Health Physics 25, 559-566 (December 1973)