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Radiometric Quantities and Units Used in Photobiology and Photochemistry: Recommendations of the Commission Internationale de l'Eclairage (International Commission on Illumination)

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ABSTRACT

To characterize photobiological and photochemical phenomena, standardized terms and units are required. Without a uniform set of descriptors, much of the scientific value of publications can be lost. Attempting to achieve an international consensus for a common language has always been difficult, but now with truly international scientific publications, it is all the more important. As photobiology and photochemistry both represent the fusion of several scientific disciplines, it is not surprising that the physical terms used to describe exposures and dosimetric concepts can vary from author to author. There are, however, international organizations that were established to minimize the confusion produced by poor or inconsistent technical terminology. This note is to review the standardized terms and provide a background on how such terms are developed, with the hope that all readers will attempt to follow the standardized terminology.

INTRODUCTION

The most fundamental physical quantities and units used in photobiology and photochemistry are based upon the fundamental quantities of power and energy and basic units (m, kg, s, A, K, mol, cd) in the international system of units (*le Système International d'Unités*, abbreviated as: SI) (1). Additionally, there are dosimetric measures used in photochemistry and photobiology that are not as familiar to scientists and engineers who routinely work with the international standardized quantities of radiometry (measurement of radiation) and photometry (measurement of light as perceived by a human standard observer) (2–4). The radiometric quantities as used in photobiology for received radiation as modified by an action spectrum to provide an effective *exposure dose rate, exposure dose*, or *fluence* are primary examples. From time to time over the last century differing approaches to standardized terminology have been published in text books and journals by individual authors, which has not always helped assure uniform definitions throughout photochemistry and the photobiological sciences.

The International Commission on Illumination, the CIE, has provided international guidance in the science, terminology and measurement of light and optical radiation since 1913. The International Lighting Vocabulary (parts of which are also issued as an ISO or IEC standard) has been an international reference for photochemists and photobiologists for many decades; and the next revision is due to be published later this year or next (2). Despite its stature, many research scientists are unfamiliar with some of the subtle distinctions between several widely used radiometric terms. Tables 1–4 provide several standardized terms that are routinely used in photobiology and photochemistry, which have been extracted verbatim from the CIE International Lighting Vocabulary. Table 1 concerns the terminology of optical spectral regions. Although "optical radiation" in the CIE definition refers to radiant energy down to 1 nm, the CIE photobiological spectral bands in the ultraviolet (UV) region extend only to 100 nm; both limiting wavelengths being in the vacuum ultraviolet, where biological effects are not meaningful (4). One very basic definition that frequently engenders a spirited discussion is: "What is the meaning of the term *light* in contrast to *optical radiation*?" See the CIE definition of *visible radiation* in Table 1, which describes the spectral range of vision (and the overlap into the UV-A and IR-A spectral regions). Although many would like to define sharp borders between the visible and ultraviolet regions, the CIE provides an overlap—to emphasize the lack of a clear border; visibility being dependent upon the brightness of the source.

Dosimetry in Photobiology

In medicine, pharmacology and toxicology, the term "dose" can refer to an initial administration to a human or animal subject of a chemical agent or to that which is actually absorbed in a target tissue. In radiology and radiological physics, "exposure" (in air) and "absorbed dose" have very carefully defined meanings with regard to ionizing radiation exposure and its absorption in a volume mass of tissue (5). In photobiology and photomedicine, the term "dose" has been applied in a variety of different ways, but as optical penetration into tissue is superficial, a surface exposure dose is most generally in the context of the CIE dose H_{eff} , *i.e.* a spectrally weighted radiant exposure:

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Table 1. Some CIE definitions of special interest—spectral regions and what is "light."

Optical radiation: Electromagnetic radiation at wavelengths between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm)

Light: (1) Perceived light, or (2) Visible radiation

Note: The world *light* is sometimes used in sense 2 for optical radiation extending outside the visible range, but this usage is not recommended

Visible radiation: Any radiation capable of causing a visual sensation directly

Note: There are no precise limits for the spectral range of visible radiation since they depend upon the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 and 400 nm and the upper limit between 760 and 830 nm

Ultraviolet radiation: Optical radiation for which the wavelengths are shorter than those for visible radiation

Note: For ultraviolet radiation, the range between 100 and 400 nm is commonly subdivided into

UV-A	315 . . . . 400 nm
UV-B	280 . . . . 315 nm
UV-C	100 . . . . 280 nm

Infrared radiation: Optical radiation for which the wavelengths are longer that those for visible radiation

Note: For infrared radiation, the range between 780 nm and 1 mm is commonly subdivided into

IR-A	780 . . . . 1400 nm
IR-B	1.4 . . . . 3 µm
IR-C	3 µm . . . . 1 mm

$$H_{\mathrm{eff}} = \int_{\lambda 1}^{\lambda 2} H_\lambda \cdot S(\lambda) \cdot \mathrm{d}\lambda \quad \mathrm{J} \cdot \mathrm{m}^{-2} \text{ [effective]}$$

where $S(\lambda)$ is the action spectrum of interest. This is the uniform convention for spectral weighting with a photobiological action spectrum to obtain the *effective exposure*. The spectral characteristics of the exposure are quantified by spectral quantities such as the spectral irradiance E_λ or spectral radiant exposure H_λ. Radiometric quantities and units can quantify only the exposure responsible for the initial event—the optical radiation exposure of the target substance or biological tissue. The most widely used CIE radiometric quantities are defined in Table 2 (extracted from the International Lighting Vocabulary). These terms are also found in widespread use in international standards and are also included in the publications of the International Union of Pure and Applied Chemistry (IUPAC) (6,7). Table 3 provides dosimetric terminology from the CIE, and a few examples that are standardized (in photodermatology).

Quantifying external and internal exposures. The *irradiance*, with the unit watt-per square-meter (W m^{-2}) properly quantifies the exposure rate at an external surface or interface, but unless spectrally weighted by an action spectrum should not be termed either the "exposure dose rate" or "dose rate" in photobiology (as defined above). The unit of watt-per-square-centimeter (W cm^{-2}) and joule-per-square-centimeter (J cm^{-2}) are still frequently—indeed widely—used in photobiology and photomedicine, where a targeted surface area is quite small, even though m^{-2} is preferred by radiometrists. The *radiant exposure* with the unit of joule-per-square-meter (J m^{-2}) properly quantifies the time-integrated irradiance at a surface. Irradiance and radiant exposure are generally the most fundamental quantities used in photobiology, photochemistry, photodermatology and illuminating science. There are also parallel exposure-rate and exposure concepts that are useful to quantify events within a scattering medium, such as biological tissue, and these quantities are termed *radiant fluence rate*, also with the unit watt-per-square-meter (W m^{-2}), and exposure within tissue that is termed the *radiant fluence*, also with the unit joule-per-square-meter (J m^{-2}). If spectrally weighted with an action spectrum, they are termed the *fluence dose* and *fluence dose-rate*. The existence of two terms with the same radiometric unit seems curious, and this has confused many scientists, with the result that the terms are frequently misused, one substituted for the other. But the concepts are different and the distinctions are important. The quantities irradiance and radiant exposure are what instruments measure at the exposed surface (and follow Lambert's Cosine Law), but fluence rate and fluence include backscattered light and are useful for photochemical calculations within tissue as in photodynamic therapy, in photodermatology or in studies where radiant energy arrives from many directions, such as the exposure of plankton in the sea or aerosolized microorganisms. These quantities are particularly useful in theoretical calculations of "dose" distributions where photochemistry at the molecular level in tissue is enhanced as a result of multiple scattering events in tissue. Several other names have been applied to fluence rate: *spherical irradiance* and *scalar irradiance*. Figure 1 illustrates these quantities in tissue, and how radiant fluence rate is the quotient of all the radiant power incident on the outer surface of an infinitely small sphere centered at the point of interest, by the area of the circular cross-section of that sphere.

Radiometric Description of a Source

Although the irradiation quantities shown in Fig. 1 are probably of greatest use in photobiology and photochemistry, one may need to scientifically describe the output of an optical source. For that purpose, the emitted radiant power flux Φ (also termed radiant power, P) of a lamp (or a continuous-wave laser) or radiant energy Q output of a pulsed laser or flashlamp, radiant intensity and radiance may prove useful. These are illustrated in Fig. 2.

Radiance (irradiance per solid angle) is an important quantity used by physicists in specifying a source. This

Table 2. Some CIE definitions of special interest—radiometric quantities.

Radiant energy: Time integral of the radiant flux over a given duration Δt

$$Q_e = \int_{\Delta t} \Phi_e \, dt$$

Symbol: Q_e, Q; unit: J = W·s

Radiant power; *radiant flux*: power emitted, transmitted or received in the form of radiation

Symbol: P, Φ, Φ_e; unit: W

Note: The use of Φ as a symbol for radiant power in photochemistry has been discouraged because of the general use of the symbol Φ for quantum yield

Radiant intensity (of a source, in a given direction): quotient of the radiant flux $d\Phi_e$ leaving the source and propagated in the element of solid angle $d\Omega$ containing the given direction, by the element of solid angle

$$I_e = \frac{d\Phi_e}{d\Omega}$$

Symbol: I_e, I; unit: $W \cdot sr^{-1}$

Irradiance (at a point of a surface): quotient of the radiant flux $d\Phi_e$ incident on an element of the surface containing the point, by the area dA of that element

Equivalent definition. Integral taken over the hemisphere visible from the given point, of the expression $L_e \cdot \cos\theta \cdot d\Omega$, where L_e is the radiance at the given point in the various directions of the incident elementary beams of solid angle $d\Omega$, and θ is the angle between any of these beams and the normal to the surface at the given point

$$E_e = \frac{d\Phi_e}{dA} = \int_{2\pi sr} L_e \cdot \cos\theta \cdot d\Omega$$

Symbol: E_e, E unit: $W \cdot m^{-2}$

Radiant exposure (at a point of a surface, for a given duration)—quotient of dQ_e, radiant energy incident on an element of the surface containing the point over the given duration, by the area dA of that element

Equivalent definition. Time integral of E_e, irradiance at the given point, over the given duration Δt

$$H_e = \frac{dQ_e}{dA} = \int_{\Delta t} E_e \cdot dt$$

Symbol: H_e, H; unit: $J \cdot m^{-2}$

Note: The quantity *exposure* here defined must not be confused with the quantity also named exposure which is used in the field of X- and γ-rays, the unit of which is coulomb per kilogram ($C \cdot kg^{-1}$)

Fluence; radiant fluence; photobiological fluence; radiant spherical exposure: Quotient of the radiant energy of all radiation incident on the outer surface of an infinitely small sphere centered at the given point by the areas of the diametrical cross-section of that sphere. See *radiant fluence* below for a comprehensive definition

Symbol: $H_{e,o}$; unit: $J \cdot m^{-2}$

Note: This is the appropriate radiometric quantity for describing a dose for a photobiological or photochemical effect in a scattering medium (*e.g.* light in skin). It is also the appropriate radiometric quantity for describing the irradiation of microorganisms. Unfortunately, it has frequently been used incorrectly as a substitute for radiant exposure in some publications. The analogous quantity is photon fluence

Radiant fluence: Time integral of the spherical irradiance $E_{e,o}$ at the given point over the given duration Δt

$$H_{e,o} = \int_{\Delta t} E_{e,o} \cdot dt$$

Symbol: $H_{e,o}$; unit: $J \cdot m^{-2} = W \cdot s \cdot m^{-2}$

Note: The analogous quantities *luminous spherical exposure* $H_{v,o}$ and *photon spherical exposure* $H_{p,o}$ are defined in a similar way, replacing spherical irradiance $E_{e,o}$ by spherical illuminance $E_{v,o}$ or photon spherical irradiance $E_{p,o}$

Radiant fluence rate; *spherical irradiance* (at a point): quantity defined by the $E_{e,o} = \int_{4\pi sr} L_e \, d\Omega$ where $d\Omega$ is the solid angle of each elementary beam passing through the given point and L_e its radiance at that point

Symbol: $E_{e,o}$, E_o; unit: $W \cdot m^{-2}$

Notes: (1) This quantity is the quotient of the radiant flux of all the radiation incident on the outer surface of an infinitely small sphere centered at the given point, by the area of the diametrical cross-section of that sphere

(2) The analogous quantities *spherical illuminance* $E_{v,o}$ and *photon spherical irradiance* $E_{p,o}$ are defined in a similar way, replacing radiance L_e by *luminance* L_v or *photon radiance* L_p

(3) The term "spherical irradiance," or *scalar irradiance*, or similar terms may be found in the literature, in the definition of which the area of the cross-section is sometimes replaced by the surface area of the spherical element which is four times larger

Table 2. Continued.

Geometric extent (of a beam of rays): Integral taken over the whole beam of the elementary quantity dG defined by the equivalent formulae

$$\mathrm{d}G = \frac{\mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}A' \cdot \cos\theta'}{l^2} = \mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega$$

where dA and dA' are the areas of two sections of an element of the beam separated by the distance l; θ and θ are the angles between the direction of that elementary beam and the normals to dA and dA'; $\mathrm{d}\Omega = \frac{\mathrm{d}A' \cdot \cos\theta'}{l^2}$ is the solid angle subtended by dA' from a point on dA

Symbol: G ; unit: $\mathrm{m}^2 \cdot \mathrm{sr}$

Note: For a beam propagating through successive non-diffusing media, the quantity

$G \cdot n^2$, where n is the refractive index, is invariant. That quantity is called the *optical extent*

[*Commentary*: The French term for geometric extent is: *étendue géométrique* and for optical extent is: *étendue optique*; and in scientific English, the French terms are frequently used rather than the English, and unfortunately both are sometimes loosely referred to only as "the étendue."]

Radiance (in a given direction, at a given point of a real or imaginary surface)—Quantity defined by the formula $L_e = \frac{\mathrm{d}\Phi_e}{\mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega}$, where $\mathrm{d}\Phi_e$ is the radiant flux transmitted by an elementary beam passing through the given point and propagating in the solid angle dΩ containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam

Symbol: L_e, L ; unit: $\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1}$

Notes (1–5) In the five following notes the symbols for the quantities are without subscripts because the formulas are also valid for the terms luminance and photon radiance

(1) For an area dA of the surface of a source, since the intensity dI of dA in the given direction is $\mathrm{d}I = \mathrm{d}\Phi/\mathrm{d}\Omega$, then an equivalent formula is $L = \frac{\mathrm{d}I}{\mathrm{d}A \cdot \cos\theta}$, a form mostly used in illuminating engineering

(2) For an area *dA* of a surface receiving the beam, since the irradiance or illuminance dE produced by the beam on dA is $\mathrm{d}E = \mathrm{d}\Phi/\mathrm{d}A$, then an equivalent formula is $L = \frac{\mathrm{d}E}{\mathrm{d}\Omega \cdot \cos\theta}$, a form useful when the source has no surface (*e.g.* the sky, the plasma of a discharge)

(3) Making use of the geometric extent dG of the elementary beam, since $\mathrm{d}G = \mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega$, then an equivalent formula is $L = \mathrm{d}\Phi/\mathrm{d}G$

(4) Since the optical extent $G \cdot n^2$ (see Note to geometric extent) is invariant, then the quantity $L \cdot n^{-2}$ is also invariant along the path of the beam if the losses by the absorption, reflection and diffusion are taken as zero. That quantity is called the *basic radiance* or *basic luminance* or *basic photon radiance*

(5) The relation between dΦ and L given in the formulae above is sometimes called *basic law of radiometry and photometry*

$\mathrm{d}\Phi = L \frac{\mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}A' \cdot \cos\theta'}{l^2} = L \cdot \mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega = L \cdot \mathrm{d}A' \cdot \cos\theta' \cdot \mathrm{d}\Omega'$ with the notation given here and for geometric extent

Lambert's (cosine) law: For a surface element whose radiance or luminance is the same in all directions of the hemisphere above the surface

$$I(\Theta) = I_n \cdot \cos\Theta$$

where $I(\Theta)$ and I_n are the radiant or luminous intensities of the surface element in a direction at an angle Θ from the normal to the surface and in the direction of that normal, respectively

quantity limits the ability of lenses and reflective optics in concentrating a light source. For example, a xenon-arc lamp has a very high radiance and its energy can be focused to produce a very high *irradiance* on a target tissue (8,9). By contrast, a fluorescent lamp tube has a much lower radiance, and its energy cannot be focused to a high concentration. The unit is W m^{-2} sr^{-1}. This quantity is useful in determining retinal exposure when viewing a light source.

Radiant intensity (radiant power per solid angle) is used to indicate how collimated a light source really is. Although useful for characterizing searchlights and light emitting diodes (LEDs), it normally has very limited use in photobiology. The unit is W sr^{-1}.

Spectral quantities. Spectral radiometric quantities (quantities per wavelength) are used for specifying the energy, power or irradiance per wavelength interval. When calculating a *photobiologically effective radiant exposure*, or *dose* the spectral quantity must be integrated with the action spectrum. Examples include: spectral radiant power, spectral irradiance, spectral radiant exposure, *etc*. The unit for each quantity is modified by adding "per nanometer," *e.g.* W m^{-2} becomes W m^{-2} nm^{-1}. The mathematical symbol is altered by adding a "λ" subscript.

Photon (Quantum) quantities. Photon quantities (unit of photon) are used primarily in theoretical photobiological calculations, and in photochemistry. In this case, the *photon radiant exposure* is specified in photons m^{-2} or photons cm^{-2} and *photon irradiance* is specified in photons m^{-2} s^{-1} or photons cm^{-2} s^{-1}.

Properties of Optical Media

The transmission of light through optical media and its absorption can be quantified by several ratiometric (dimensionless) quantities. The CIE defines a number of terms that apply to absorption, scattering and transmission properties of optical media, whether gaseous, liquid or solids. Once again, different technical fields apply these terms somewhat differently. Table 4 provides some of the relevant definitions from the IEV. For example, the term *optical density* is discouraged for use in

Table 3. CIE photobiologic dosimetric terminology.

Spectral: An adjective that, when applied to a quantity X pertaining to electromagnetic radiation, indicates

either that X is a function of the wavelength λ, symbol: $X(\lambda)$,
or that the quantity referred to is the spectral concentration of X, symbol: $X_\lambda \equiv \frac{dX}{d\lambda}$; in the latter case, in French, "spectrique" is preferred to "spectral"

X_λ is also a function of λ and in order to stress this may be written $X_\lambda(\lambda)$ without any change of meaning

Note: The quantity X can also be expressed as a function of frequency v, wave number σ, *etc.*; the corresponding symbols are $X(v)$, $X(\sigma)$, *etc.* and X_v, X_σ, *etc.*

Dose (of optical radiation of specified spectral distribution): Term used in phototherapy and photobiology for the quantity radiant exposure. See also "effective dose."

Unit: $J{\cdot}m^{-2}$

Action spectrum: Relative spectral effectiveness of optical radiation, for a specified actinic phenomenon, in a specified system; also referred to as: actinic spectrum

Note: The normalized action spectrum is the wavelength dependence of the inverse of the dose of monochromatic radiation required to induce a certain (biologic) response; the action spectrum is commonly normalized to "1" at the wavelength of "maximum action," *i.e.* where the smallest dose suffices to induce the required effect. Also referred to as: actinic spectrum

Actinic spectrum : efficiency of equal intensities of monochromatic radiations for producing that phenomenon in that system as a function of wavelength

Effective dose; photobiological dose: That part of the dose which actually produces the actinic effect considered

Symbol: H_{eff}; unit: spectrally weighted $J{\cdot}m^{-2}$ or $J{\cdot}m^{-2}$ [effective]

Actinic dose: Quantity obtained by weighting spectrally the dose according to the actinic action spectrum value at the corresponding wavelength. Equivalent to "effective dose"

Unit: spectrally weighted $J{\cdot}m^{-2}$

Note: This definition implies that an action spectrum is adopted for the actinic (photochemical) effect considered, and that its maximum value is 1. When giving a quantitative amount, it is essential to specify which quantity *dose* or *actinic dose* is meant (and for the actinic dose, which action spectrum was used), as the unit is the same.

Erythemal effective radiant exposure; erythemal dose: The time integral of erythemally effective irradiance defined by the equation

$$H_{er} = \int\int E_\lambda(t) \cdot s_{er}(\lambda) d\lambda dt$$

where $E_\lambda(t)$ is the spectral irradiance in $W{\cdot}m^{-2}{\cdot}nm^{-1}$ and $s_{er}(\lambda)$ is the erythema action spectrum

Symbol: H_{er}

See *minimal erythema dose* and *standard erythema dose*

Minimal erythema dose; MED (abbreviation): The actinic dose, using the erythema action spectrum, that produces a just perceptible erythema on a single individual's previously unexposed skin.

Note: This is a subjective measure based on the reddening of the skin; it depends on many variables, *e.g.* individual sensitivity to UVR, radiometric characteristics of the source, skin pigmentation, anatomic site, elapsed time between irradiation and observing the reddening (typical value: 24 h), *etc.* Since it varies with each individual, it should be reserved solely for observational studies in humans and other animals. See also Standard erythema dose (SED)

Standard erythema dose (*SED*): Standardized unit of measure of erythemogenic UV radiation, 1 SED is equivalent to an erythemal effective radiant exposure of 100 $J{\cdot}m^{-2}$

Dose rate—Term used in photochemistry, phototherapy and photobiology for the quantity-irradiance

Unit: $W{\cdot}m^{-2}$

Notes: (1) As in the case of *dose*, the spectral distribution of the radiation must be specified

(2) The notion of *rate* applies similarly to *actinic dose* and *effective dose*

Dose–response curve: Relative biological response with increasing radiant exposure (photobiological dose).

Photon flux: Quotient of the number of photons dN_p emitted, transmitted, or received in an element of time dt, by that element

$$\Phi_p = \frac{dN_p}{dt}$$

Symbol: Φ_p; Φ Unit: s^{-1}

Note: For a beam of radiation whose spectral distribution is $\frac{d\Phi_e(\lambda)}{d\lambda}$or $\frac{d\Phi_e(\upsilon)}{d\upsilon}$, the photon flux Φ_p is $\Phi_p = \int_0^\infty \frac{d\Phi_e(\lambda)}{d\lambda} \cdot \frac{\lambda}{hc_0} d\lambda = \int_0^\infty \frac{d\Phi_e(\upsilon)}{d\upsilon} \cdot \frac{1}{h\upsilon} d\upsilon$, where h, Planck's constant $= (6.6260755 \pm 0.0000040) \times 10^{-34}$ J $\cdot$ s and c_0, speed of light in vacuum $=$ 299 792 458 $m{\cdot}s^{-1}$.

Table 4. CIE terminology for absorption and transmission of optical media.

Absorption terminology

Absorption: Process by which radiant energy is converted to a different form of energy by interaction with matter

Absorptance: Ratio of the absorbed radiant or luminous flux to the incident flux under specified conditions

Symbol: α; unit: 1

Spectral internal absorptance (of a homogeneous non-diffusing layer): Ratio of the spectral radiant flux absorbed between the internal entry and exit surfaces of the layer to the spectral flux that enters into the layer after crossing the entry surface

Symbol: $\alpha_i(\lambda)$; unit: 1

Note: For a given layer the spectral internal absorptance depends on the path length of the radiation in the layer, and hence, in particular, on the angle of incidence

Spectral internal transmittance density, *spectral absorbance* (of a homogeneous nondiffusing layer): Logarithm to base ten of the reciprocal of the spectral internal transmittance

$$A_i(\lambda) = -\log_{10} \tau_i(\lambda)$$

Symbol: $A_i(\lambda)$

Notes: (1) For a given layer the spectral internal transmittance depends on the path length of the radiation in the layer, and hence, in particular, on the angle of incidence

(2) The symbol $E(\lambda)$ is still in use

Naperian spectral internal transmittance density; *naperian spectral absorbance* (of a homogenous nondiffusing layer): Natural (Naperian) logarithm of the reciprocal of the spectral internal transmittance

$$A_n(\lambda) = B(\lambda) = -\ln \tau_i(\lambda)$$

Symbol: $A_n(\lambda)$; $B(\lambda)$

Optical density, *transmittance density*: Logarithm to base ten of the reciprocal of the transmittance

$$D_\tau = -\log_{10} \tau$$

Symbol: D_τ

[Note: this term is generally limited to use in describing optical filters and not media, since it includes the attenuation by both surface reflection as well as internal loss. Its use is discouraged in photochemistry.]

Transmission terminology

Transmittance (for incident radiation of given spectral composition, polarization and geometrical distribution): Ratio of the transmitted radiant or luminous flux to the incident flux in the given conditions

Symbol: τ; unit: 1

Note: $\tau = \tau_r + \tau_d$ (τ_d; diffuse transmittance, τ_r; regular transmittance)

Diffuse transmittance: Ratio of the diffusely transmitted part of the (whole) transmitted flux, to the incident flux

Symbol: τ_d; unit: 1

Notes: (1) $\tau = \tau_r + \tau_d$ (τ_d; diffuse transmittance, τ_r; regular transmittance)

(2) The results of the measurements of τ_r and τ_d depend on the instruments and the measuring techniques used

Regular transmittance: Ratio of the regularly transmitted part of the (whole) transmitted flux, to the incident flux

Symbol: τ_r; unit: 1

Notes: (1) $\tau = \tau_r + \tau_d$ (τ_d; diffuse transmittance, τ_r; regular transmittance)

(2) The results of the measurements of τ_r and τ_d depend on the instruments and the measuring techniques used

Spectral internal transmittance (of a homogeneous non-diffusing layer): Ratio of the spectral radiant flux reaching the exit internal surface of the layer to the spectral flux that enters into the layer after crossing the entry surface

Symbol: $\tau_i(\lambda)$; unit: 1

Note: For a given layer the spectral internal transmittance depends on the path length of the radiation in the layer, and hence, in particular, on the angle of incidence

Reference Source: The definitions above were extracted with the permission of the CIE Central Bureau from: CIE Publication No. 17.4, *International Lighting Vocabulary*, published jointly by the CIE, Vienna, and the International Electrotechnical Commission (as IEC Publication 50(845) (*i.e.* Chapter 845 of the International Electrotechnical Vocabulary), IEC, Geneva. Recent updates by CIE Division 6 of the definitions related to photobiological dosimetry were also included.

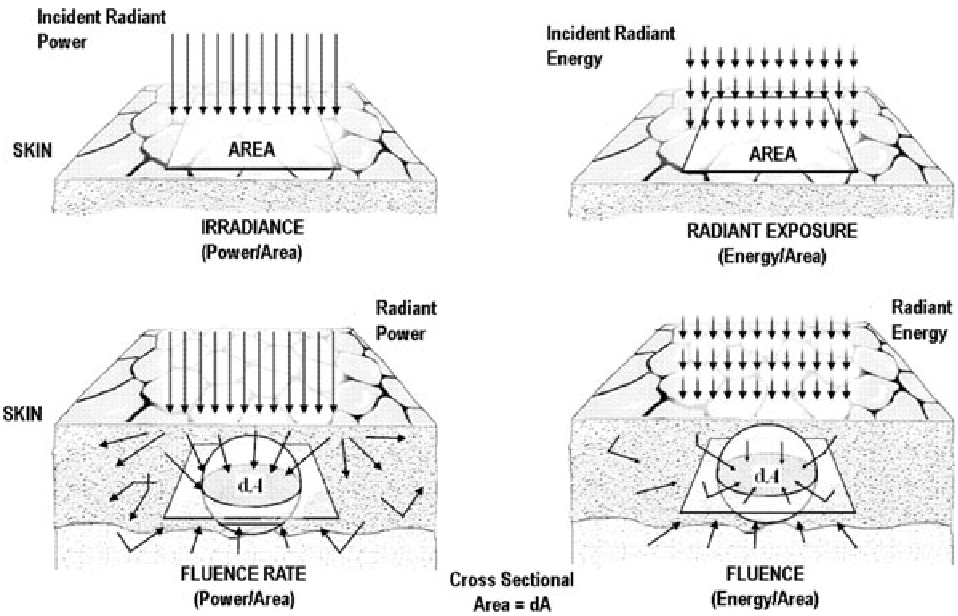

Figure 1. Radiometric concepts as they apply to photobiological descriptions of skin exposure. The arrows depict a collimated continuous beam (left) and a collimated beam of a group of pulses (right) incident on the skin surface.

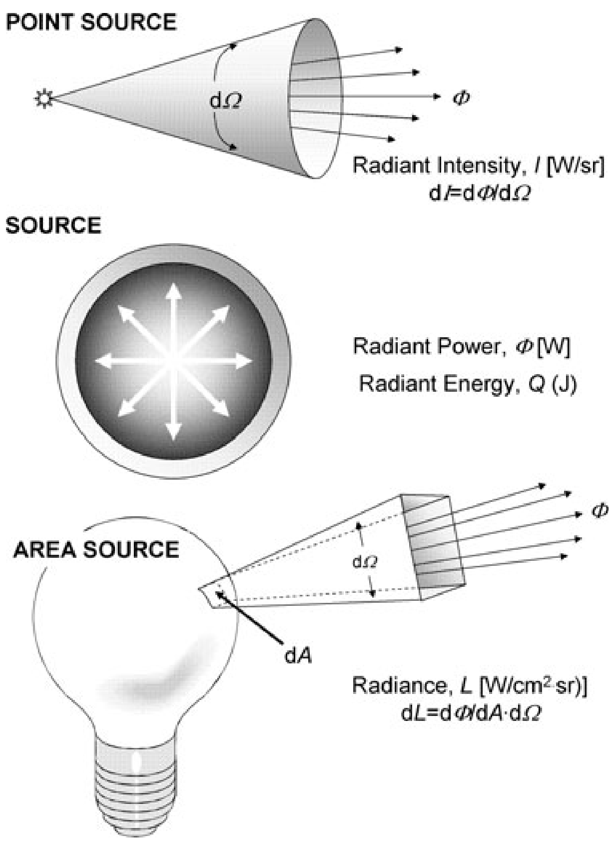

Figure 2. Describing a source. Radiant intensity describes the radiant power from a source emitted within a solid angle and presumes a relatively small source or ''point'' source. Radiant power and radiant energy are collected in all directions (*i.e.* in 4π sr). Radiance describes the power radiated within a differential solid angle and differential area of the source.

photochemistry, but is routinely used to describe the total attenuation afforded by a filter, since *optical density* includes the attenuation by both surface reflection as well as internal loss.

Table 5 summarizes useful radiometric terminology that applies to irradiation of target tissue.

WHO DECIDES WHAT IS ''STANDARD?''

Standardized definitions for the radiometric and dosimetric terms and units employed in the science of optics, photobiology and photochemistry are developed and agreed upon within the International Commission on Illumination, the CIE (Commission International de l'Eclairage), in accordance with fundamental physical measures of the international system of units, referred to as the SI (Système International). The SI is promulgated by the International Bureau of Weights and Measures (Bureau International des Poids et Mesures—the BIPM—headquartered in Sèvres, France, a suburb of Paris). The international standardized quantities and units represent a consensus among all of the 18 national representatives serving on the International Committee for Weights and Measures (*Comité International des Poids et Mesures*, the CIPM). These members represent laboratories of standards and physical sciences such as the National Institute of Science and Technology (NIST) in the US, the National Physical Laboratory (NPL) in the United Kingdom, the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the Bureau National de Métrologie (BNM) in France. The fundamental radiometric terms we all use are: wavelength (in nanometers, nm), radiant power (unit: watt), radiant energy (unit: joule), irradiance (unit: W m^{-2}) and radiant exposure (unit: J m^{-2}). Spectral irradiance (unit: watt per square meter per nanometer) may also be used. Other specialized technical terms may be found in the CIE International Lighting Vocabulary (ILV), *e.g. transmission*, *reflectance*, *diffusion*, *etc*. Section 6 of the

Table 5. Quick Summary of Useful Radiometric Quantities and their units.*,†

Term	Symbol	Defining equation	Defining equation	Unit and abbreviation
Radiant energy	Q	Energy emitted, transferred, or received in the form of radiation		Joule (J)
Radiant power	Φ P	Radiant energy per unit time	$\Phi = \frac{dQe}{dt}$	Watt (W) defined as J·s^{-1}
Radiant exposure (dose in photobiology)	H	Radiant energy per unit area incident upon a given surface	$H = \frac{dQe}{dA}$	Joule per square meter (J·m^{-2})
Irradiance or radiant flux density (dose rate in photobiology)	E	Radiant power per unit area incident upon a given surface	$E = \frac{d\Phi e}{dA}$	Watt per square meter (W m^{-2})
Fluence	I_P	Radiant energy emitted by a source per unit solid angle	$I = \frac{d\Phi e}{d\Omega}$	Joule per Steradian (J·sr^{-1})
Radiant intensity	I	Radiant power emitted by a source per unit solid angle	$I = \frac{d\Phi e}{d\Omega}$	Watt per Steradian (W·sr^{-1})
Radiant fluence rate	$E_{e,o}$	Radiant energy emitted by a source per unit solid angle per source area	$E_{e,o} = \int_{4\pi sr} L_e d\Omega$	Joules per Steradian per square centimeter (J·sr^{-1}·m^{-2})
Radiance‡	L	Radiant power emitted by a source per unit solid angle per source area	$L = \frac{d\Phi e}{d\Omega \cdot dA \cdot \cos\theta}$	Watts per Steradian per square centimeter (W·sr^{-1}·m^{-2})
Optical density (OD)	D_λ	A logarithmic expression for the attenuation produced by a filter on	$D_\lambda = -\log_{10}\left(\frac{\Phi_O}{\Phi_L}\right)$	Dimensionless Φ_O is the incident power; Φ_L is the transmitted power

*The units may be altered to refer to narrow spectral bands in which the term is preceded by the word *spectral* and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance E_λ has units of W·m^{-2}·m^{-1} or more often, W·m^{-2}·m^{-1}. †While the meter is the preferred unit of length, the centimeter is still the most commonly used unit of length for many of the terms below and the nm or µm are most commonly used to express wavelength. ‡At the source $L = \frac{dI}{dA \bullet cos\theta}$; and at a receptor $L = \frac{dE}{d\Omega \bullet cos\theta}$

ILV contains a large number of photobiological terms and a glossary of photobiological terms has been prepared by CIE Division 6. A new edition of the ILV is expected to be published within the next year. IUPAC publishes a series of guides on nomenclature (7,10) and their guide *Quantities, Units and Symbols in Physical Chemistry (The Green Book)*, 2nd Edition is currently being updated for a third edition.

CONFLICTING GUIDANCE

This review has centered on the terms and symbols recommended by the CIE as being most useful in photobiology and photochemistry. However, authors publishing in a range of medical, scientific and engineering journals should recognize that the use of one CIE quantity or symbol may not be universally accepted. For example, electrical engineers or chemists may use the same Greek symbol for a different quantity and this may lead to confusion in certain sectors. There can never be universality of symbols since there are only so many letters in the Greek and Latin alphabets. The Greek letter Φ can have other meanings than radiant power (flux) and therefore P can be used in place of Φ. Also, τ can be the symbol for pulse duration as well as for transmittance. Thus, it is always useful to define such terms and symbols when initially introduced in the text.

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REFERENCES

1. Bureau International des Poids et Mesures (BIPM) (2006) *The International System of Units (SI)*, 8th Edition. Organisation Intergouvernementale de la Convention du Mètre, Paris.
2. Commission International de l'Eclairage (CIE) (1987) *International Lighting Vocabulary* (next edition is scheduled in 2007). CIE Publication No. 17.4, IEC 50846, Vienna, CIE.
3. CIE (1998) Erythemal reference action spectrum and standard erythemal dose. CIE Standard S007-1998. CIE, Vienna; also available as ISO 17166, 1999.
4. CIE (1999) Standardization of the terms UV-A1, UV-A2 and UV-B, Report CIE-134/1. CIE, Vienna.
5. International Commission on Radiation Units, Measurements (ICRU) (1998) *Fundamental Quantities and Units for Ionizing Radiation, ICRU Report 60*. ICRU, Bethesda, Maryland, USA.
6. International Organization for Standardization (ISO) (1992) Quantities and Units—Part 6: Light and Related Electromagnetic Radiations, ISO 31-6:1992. ISO, Geneva.
7. International Union of Pure and Applied Chemistry (1997) *Compendium of Chemical Terminology, The Gold Book*, 2nd Edition (Edited by A. D. McNaught and A. Wilkinson). Blackwell Science. Available online at: http://www.iupac.org/publications/compendium/index.html.
8. Sliney, D. H. (1995) UV radiation ocular exposure dosimetry. *J. Photochem. Photobiol.* **31**, 69–77.
9. Sliney D. H. and R. Matthes (Eds) (1999) *The Measurement of Optical Radiation Hazards*. ICNIRP Publication 6/98; CIE Publication CIE-x016-1998, ICNIRP: Munich and CIE, Vienna.
10. International Union of Pure and Applied Chemistry (1993) *Quantities, Units and Symbols in Physical Chemistry (The Green Book)*, 2nd Edition (Edited by I. Mills, T. Cvitas, K. Homann, N. Kallay and K. Kuchitsu). Blackwell Science. Available online at: http://www.iupac.org/publications/books/gbook/green_book_2ed.pdf.