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# Solar Ultraviolet Radiation: Definitions and Terminology

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Is "UV" (ultraviolet) a ray, or is it light, a wave, energy, or radiation? Does the "A" in UVA really stand for "aging" and the "B" in UVB for "burning?" Should one use a minimum or standard erythema dose? The definition of and terminology associated with UV and its effects on human biology have been, and continue to be, an area where there is abundant potential for confusion and inaccuracy. In recent years, matters have been made worse as the highly exacting field of photobiology has been popularized due to dramatic rises in the incidence of skin cancer in developed geographies and the ensuing need for national education programs. This article includes a brief review of modern definitions, nomenclature, and terminology associated with this topic.

## Definition of ultraviolet radiation

"UV" is only a relatively small component of a broad *electromagnetic spectrum* that is defined by *wavelength* and *frequency*. As shown in Table 1, the entire electromagnetic spectrum spans a huge waveband of radiation with wavelengths ranging from $10^{-14}$ m (γ radiation) to $10^{4}$ m (radio waves). "UV" refers to a narrow waveband of radiation with wavelengths in the $10^{-7}$-m (hundreds of nm) range, specifically 100 nm to 400 nm. Radiation in the 400- to 700-nm wavelength region constitutes "light," principally because the photoreactive cells of the human retina are sensitive only to this waveband, driving the phenomenon of human vision. Importantly, therefore, it is inappropriate to refer to "UV" as "light," rather as *ultraviolet radiation* or *UVR*. According to quantum theory, light and other forms of electromagnetic radiation may at times exhibit properties like those of particles in their interaction with matter. The individual quantum of excitation of electromagnetic radiation is known as the *photon* (from the Greek word φοτος, meaning light) and is symbolized by the Greek letter gamma (γ). As electromagnetic radiation, thus, UVR is no exception and is quantized in photons.

Table 1. Approximate wavebands of the electromagnetic spectrum

| **Electromagnetic radiation** | **Waveband (m)** |
|---|---|
| Gamma radiation | $10^{-14}$ to $19^{-10}$ |
| X rays | $10^{-10}$ to $10^{-8}$ |
| UV radiation | $10^{-7}$ to $4\times10^{-7}$ |
| Visible light | $4\times10^{-7}$ to $7\times10^{-7}$ |
| Infrared radiation | $7\times10^{-7}$ to $10^{-3}$ |
| Microwaves | $10^{-3}$ to $10^{-2}$ |
| Radio waves | $10^{-2}$ to $10^{4}$ |

UVR is, therefore, a specific, narrow waveband of electromagnetic radiation that travels, quantized as photons, in waves. Waves are measured not only by their wavelength, however, but also by *frequency*. Whereas, wavelength is measured in meters, frequency is measured by the number of waves or cycles that pass a given point in 1 s (one cycle per second termed a Hertz [Hz]). Because electromagnetic radiation travels at a constant speed (approximately 300,000,000 m/s), wavelength and frequency are related on a fundamental one-to-one basis by Eq. 1:

$$c = f \cdot \lambda \text{or} f = c/\lambda \text{or} \lambda = c/f \tag{1}$$

where $c$ is the speed of light (~300,000,000 m/s), $f$ is the frequency in Hertz (cycles/s), and λ is wavelength in meters.

Shorter wavelength electromagnetic radiation, therefore, has a higher frequency. Frequency and energy are also related at a fundamental level through the Planck constant (the constant of proportionality relating the energy of a photon to frequency; Eq. 2):

$$Q_p = h \cdot f \tag{2}$$

where $Q_p$ is photon energy (electron volts or eV), $h$ is the *Planck constant* ($6.626 \times 10^{-34}$ J s), and $f$ is the frequency in Hertz.

Quite simply, the shorter the wavelength of electromagnetic radiation, the higher its respective frequency and energy. As regards expanding the definition of UVR, this is a very important relationship as the higher the energy of a UVR photon, the more reactive it is with human biology. This has led to a subdivision of the UVR waveband (100 nm to 400 nm) into three further spectral regions: UVC, UVB, and UVA, based principally on differing biologic effect. The bounds of these spectral regions were determined initially in the 1930s by W.W. Coblentz, of the U.S. National Bureau of Standards, and colleagues [1] by using the transmission properties of three common filters. A pyrex filter determined the UVC waveband (100 nm to 280 nm, “germicidal” UVR, absorbed almost entirely by stratospheric ozone), a barium-flint-pyrex filter, the UVB waveband (280 nm to 315 nm, so-called “erythemal” UVR, the lower end of this waveband also marking the upper cut-off for the absorption spectra of protein and DNA), and a barium-flint filter defined the UVA (315 nm to 400 nm; “black light”). These wavebands became endorsed at the 2nd International Congress on Light in Copenhagen in 1932 and again by the La Commission Internationale de l'Eclairage (CIE) in 1970 [2]. These spectral divisions are, therefore, somewhat arbitrary. Most modern dermatologists and photobiologists have redefined and cite these three wavebands thus:

UVC: 200 nm to 290 nm

UVB: 290 nm to 320 nm

UVA: 320 nm to 400 nm

Clearly, therefore, the origin of the “A” and “B” nomenclature of these wavebands has nothing to do with “aging” or “burning.” Most recently, the subdivision of the 290- to 400-nm waveband into UVB and UVA has been reviewed, and there is now growing support for recognition of a further subdivision of the UVA waveband into:

UVAI: 340 nm to 400 nm

UVAII: 320 nm to 340 nm

The UVAII subdivision now recognizes the relatively high erythemal potential (and, hence, biologic interaction) that the 320- to 340-nm waveband possesses when compared with the remainder of the UV spectral region (ie, UVAI, 340 nm to 400 nm). Although at first appearing confusing and even retrograde, this is actually a perfectly logical outcome of fitting rigid broad spectral regions to a continuous electromagnetic spectrum; after all, it would be nonsense to maintain that a UV photon of 319 nm is meaningfully different in biologic effect to one of 321 nm, even though they would be classed as UVB and UVA photons, respectively. As we shall see, creation of further subdivisions, such as those above, within these relatively large wavebands is acknowledgment of the broad gradation and range of biologic effect across the portion of electromagnetic spectrum occupied by UVR.

## Ultraviolet radiation radiometric symbols, units, and nomenclature

Before defining solar UVR, we must first introduce the language and terminology of *radiometry*, the science of measurement of electromagnetic radiation spanning wavelengths from $10^{-8}$ m to $10^{-3}$ m (including, of course, UVR). This should be differentiated from *photometry*, which relates to electromagnetic radiation detectable by the human eye (all terms, thus, weighted correspondingly by the eye's spectral response).

To simplify the text of this short summary, the most commonly used radiometric terms and their respective meanings and recommended symbols are listed in Table 2. In general, radiometric units can be divided into two conceptual areas—those relating to (1) either *energy* or *flux* (ie, specific to a wave of electromagnetic radiation passing through space) and (2) those related to the geometric quantities of area and solid angle (ie, specific to the relationship of this radiation to either the source [*radiant intensity* and *radiance*] or the object that is struck by it [*irradiance*]).

Table 2. Common radiometric terms, units, and recommended symbols

| Term | Unit | Recommended symbol |
|---|---|---|
| Wavelength | nm | $\lambda$ |
| Flux | W | $\phi$ |
| Energy | J | $Q$ |
| Radiant intensity | W $sr^{-1}$ | $I$ |
| Radiance | W $m^{-2}$ $sr^{-1}$ | $L$ |
| Irradiance | W $m^{-2}$ | $E$ |
| Dose (radiant exposure) | J $m^{-2}$ | $H$ |
| Spectral irradiance | W $m^{-2}$ $\lambda^{-1}$ | $E_\lambda$ |

It should be noted that the terms described previously give no information about the distribution of these quantities as a function of wavelength. Spectral quantities, therefore, are derivative quantities per unit wavelength and usually have the prefix *spectral* and the term $\lambda^{-1}$ in their units. When integrated over wavelength, they give the total quantity and are denoted by using the subscript $\lambda$ (eg, $E_\lambda$, $I_\lambda$, and so forth).

Lastly, irradiance integrated over time gives expressions of *dose* (often used as a term in its own right), commonly referred to in radiometry as *radiant exposure*.

For more information relating to radiometry symbols, units, and nomenclature (SUN), the reader is referred to the work and publications of the Consultative Committee on Photometry and Radiometry (CCPR; for useful links go to http://www1.bipm.org/en/home ↗), a subcommittee of the General Conference on Weights and Measures (CGPM).

## Definition of extraterrestrial and terrestrial solar ultraviolet radiation

So far, UVR has been discussed in general terms. Apart from artificial sources of this radiation, which forms a separate topic, human exposure to UVR can be attributed solely to the sun. *Extraterrestrial UVR* can be defined as solar UVR impinging on the outermost surface of the earth's atmosphere. The *solar constant* $I_0$ is the amount of energy received at the outermost surface of the earth's atmosphere on a plane oriented perpendicular to the sun's rays (at the mean distance of the earth from the sun). The generally accepted solar constant of 1368 W $m^{-2}$ is a satellite-measured yearly average. Variations of 3.4% in the distance of the earth from the sun due to the elliptical nature of the earth's solar orbit (from a minimum at *perihelion* on approximately January 3 to a maximum at *aphelion* on approximately July 5) cause the actual intensity of solar radiation at the outer surface of the atmosphere to depart correspondingly from $I_0$ by a few percent. Further minor fluctuations in solar output can be attributed to the 27-day rotation of the sun and a 22-year sunspot cycle.

What is the quality, or spectrum, of this extraterrestrial irradiance? The Stefan-Boltzmann law predicts intensity output across varying wavelengths as a function of temperature and describes the "ideal" blackbody radiator. The sun approximates a blackbody radiator at a temperature of 5900°K and, as a result, approximately 8% of extraterrestrial solar electromagnetic radiation is UVR.

Given that human exposure to solar UVR is normally limited to ground-level, what are the factors shaping the quantity and quality of this radiation reaching the earth's surface? The overwhelming phenomena influencing these quantities are *attenuation* and *scattering* by the earth's atmosphere. At altitudes greater than 40 km, stratospheric ozone drives a dramatic spectrally-dependent attenuation of solar UVR. As a result, lethal solar UVC wavelengths of 290 nm and lower are completely absorbed, UVB is strongly attenuated, but UVA is transmitted virtually unaffected. This effect can be seen in Fig. 1, constructed using data supplied by the Meteorological Service of Canada, showing the virtual one-for-one correlation between the stratospheric ozone absorption spectrum and resulting ground-level solar spectrum between 290 nm and 320 nm. Note the flat spectral irradiance of extraterrestrial solar light with its characteristic "Fraunhofer" lines. The spectral quality of ground-level solar UVR is shaped predominantly, therefore, by stratospheric ozone absorption, with a relatively constant attenuation of approximately 40% due to air molecules and background aerosols. It can be see that, whereas depletion of the ozone column would significantly impact surface UVB irradiance, there would be minimal effect on broadband UVA (a phenomenon that climatologists use to verify or otherwise increases in ground-level UV due to ozone depletion).

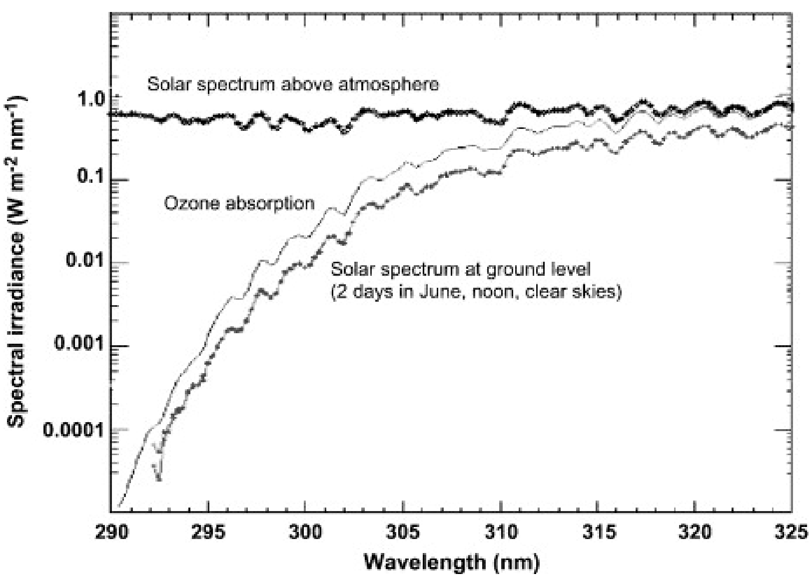


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Fig. 1. Spectral absorption of extraterrestrial ultraviolet radiation (UVR) by stratospheric ozone and consequent effect on the spectral irradiance of ground level solar UVR (290 nm to 320 nm). (*Data from* Vitali Fioletov, Meteorological Service of Canada.)

How does this weighted absorption affect ground-level UV incidence? Quite simply, we inherit a solar spectrum that is relatively rich in UVA and poor in UVB. As an approximate guide, at noon on a midsummer day in Northern European latitudes, the unshaded surface irradiance in the UVB is less than 3 W m$^{-2}$, compared with a UVA irradiance of around 40 W m$^{-2}$ (Colin MH Driscoll, UK National Radiological

Protection Board data, personal communication, 1999). As a percentage of total surface UVR irradiance (290 nm to 400 nm), therefore, UVB represents approximately only 5%, the balance being made up by UVA. The *spectral irradiance* of terrestrial UVR measured at 38°S (Melbourne) and 38°N (Albuquerque) at noon, under a clear sky is shown in Fig. 2.

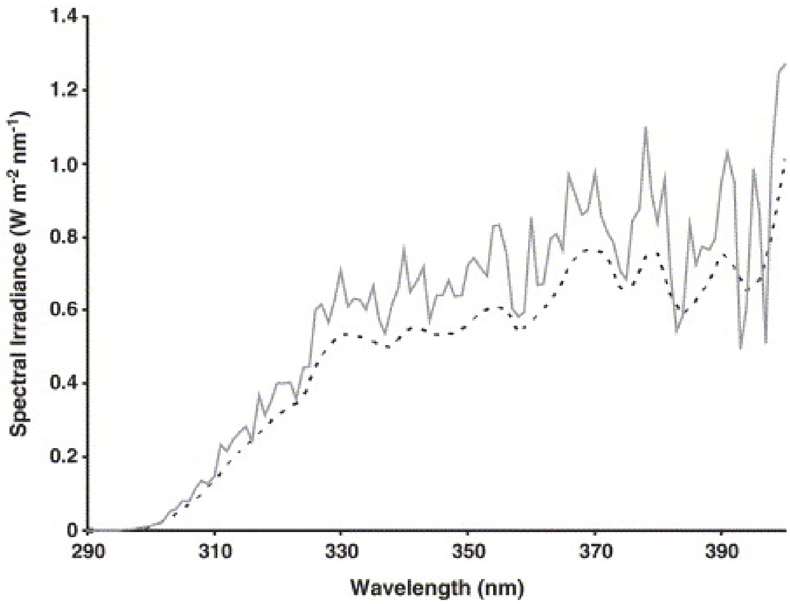


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Fig. 2. Spectral irradiance of terrestrial solar UVR measured at 38°N (Albuquerque; *dashed line*) and 38°S (Melbourne; *solid line*). (*Data from* Sayre RM, Cole C, Billhimer J, et al. Spectral comparison of solar simulators and sunlight. Photodermatol Photoimmunol Photomed 1990;7:159–65; and Gies HP, Roy CR, McLennan A, et al. UV protection by clothing: an intercomparison of measurements and methods. Health Phys 1997;73(3):456–64.)

Because of this attenuation taking place high above the earth's surface, *solar altitude* (that is, the elevation of the sun above the horizon) plays an important role in determining atmospheric path length and, thus, disproportionate relative attenuation of UVB. Solar altitude varies with

- *Time of day:* diurnal variation
- *Season:* due to the tilt of the Earth's axis of rotation, a 23.4° offset of the axis from a direction perpendicular to the Earth's orbital plane that causes the Northern Hemisphere to tilt toward the sun in the summer and away from the sun in winter, as it moves through its orbit, an effect reversed in the Southern Hemisphere
- *Geography:* latitude and longitude

Quite simply, as the *solar zenith angle* (that is, the angle between the sun and a local line of zenith drawn from the earth's center) increases and solar altitude decreases, the stratospheric ozone column becomes longer, driving a progressively greater attenuation of short-wave UVR. This results in a terrestrial solar spectrum that is relatively richer in UVA at dawn/dusk, in the winter months and at higher latitudes.

In broad terms, therefore, one can say that terrestrial UVA irradiance is less subject to zenith angle effects than UVB. It is a gross misrepresentation, however, to state that UVA irradiance is somehow "constant" throughout the day or year, a modern myth that has been widely propagated. UVA irradiance is subject to exactly the same diurnal, seasonal, and geographic fluctuations as UVB irradiance, only slightly less so. Several other factors determine the precise quality and quantity of UVR that reaches ground-level. These are summarized, together with those phenomena noted previously, in Table 3.

Table 3. Summary of factors that determine quality and quantity of terrestrial ultraviolet radiation

| **Factor** | **Effect** |
| --- | --- |
| Time of day | Diurnal variation in UVR, with maximum irradiance at solar noon. Approximately 20%–30% of total UVR is received at the surface between 11 AM and 1 PM; 75% is received between 9 AM and 3 PM. High zenith angles at dawn and dusk drive disproportionate attenuation of short-wave UVR, resulting in solar spectrum slightly richer in UVA. |
| Season | Pronounced annual cycle driven primarily by tilt in earth's axis, resulting in maximal irradiance in summer months, minimal in winter months in either hemisphere respectively. High zenith angles ($\theta$) in winter (eg, $\theta$=75° on December 22 vs $\theta$=28° on June 21, in London [52°N]) drive disproportionate attenuation of short-wave UVR, resulting in solar spectrum slightly richer in UVA in winter months. The degree of seasonal variation, however, is latitude-dependent, with least variation seen at the equator. |
| Geography | Terrestrial UVR incidence increases with decreasing latitude, with highest irradiance and annual surface dose values recorded at the equator. |
| Altitude | A 1-km increase in altitude results in a 10%–25% increase in UVR irradiance, depending on wavelength. At 300 nm, a 24% change has been recorded vs a 9% change at 360 nm, over a vertical kilometre. These spectral differences can be attributed to the relative contributions of Rayleigh scattering, ozone absorption and aerosol at these different wavelengths (at 300 nm, 27%, 57%, and 16% respectively; at 360 nm, 54%, 0%, and 46% respectively). |
| Surface reflection | The *albedo* (the fraction of radiation striking a surface that is reflected by that surface) of various surfaces can cause significant variation in local ambient UVR (eg, although most ground surfaces have albedos of <10%, snow has values of 30%–80% and sand 15%–30%. Water reflects only little incident UVR [<5%]). |
| Cloud cover | *Mie* scattering accounts for an attenuation of ground-level UVR with little spectral dependence. Attenuation is fairly unpredictable, with the following main factors to be taken into consideration: fractional sky coverage, cloud opacity, cloud height, solar zenith angle. Subsidiary factors include: condensed water distribution in three dimensions, solute present in condensate and other trapped chromophores/aerosols. In general terms, scattered light clouds have little effect on surface UVR and complete light cloud cover reduces surface UVR by about 50%. |

## Artificial ultraviolet radiation sources

Having defined extraterrestrial and terrestrial solar UVR, some short comment on artificial sources of UVR is necessary. These sources (eg, xenon-arc or fluorescent lamps) are used in a range of applications including phototherapy of specific skin diseases (eg, psoriasis, vitiligo) and standard industry test methods to measure the photoprotective properties of commercial sunscreen formulations (eg, "*sun protection factor*" [SPF] testing). The former applications tend to use sources filtered to produce highly artificial broad- or narrow-band "UVA" or "UVB" spectra, whereas sources filtered to produce "*solar-simulated*" UVR are used in SPF testing. With both types of filtered source, accurate measurements (using a calibrated *spectroradiometer*) of output spectrum *shape* and *power* are absolutely critical. Without these measurements, the terms "UVA," "UVB," or "solar-simulated" are meaningless and misleading, and interpretation of biologic effect is impossible. Solar-simulated UVR is a filtered approximation of a ground-level measurement taken at a specific latitude, in prevailing weather conditions, using specific instrumentation. In this sense, a filtered lamp can never hope to replicate ground-level solar UVR, and this should be recognized when considering in vivo photoprotection testing (and particularly when considering biologic endpoints driven by heavily filtered nonsolar spectra, eg, so-called "persistent pigment darkening").

## Measurement of biologically effective dose of solar ultraviolet radiation in humans

While other authors will review the wide range of biologic effects exerted by solar UVR in the human model, this is not the intent of this section. What we are concerned with here is the question of a standardized means of *measuring* and *communicating* the deleterious human biologic effects of solar UVR. While acknowledging that solar UVR may exert damaging effects on other human biology (eg, the tissues of the eye), this article is focused on skin, the human biologic substrate with most surface area (approximately 2 $m^2$ in an average adult human) and at most risk from solar UVR exposure. In seeking a standardized means of expressing UVR skin damage in a human individual, one needs to use skin itself as a "meter," ideally in vivo, using a damage endpoint that responds to solar UVR in a predictable manner. Ideally, this damage endpoint will be *acute* (ie, will present within a short period of time after solar UVR exposure), easily measurable, providing interval data that can be subjected to parametric statistical procedures for further analysis. Lastly, the value obtained from this measure should ideally also reflect inherent susceptibility to a broad range of other solar UVR damage.

Bearing in mind the ideal requirements noted earlier, *erythema* or acute "sunburn" provides a solar UVR damage endpoint that fulfils these criteria to a great extent. Erythema presents as a visible reddening of UVR-exposed skin due to dilation of vasculature in the dermal plexus and corresponding increase in dermal blood fraction volume. Although many possible peripheral mechanisms are still debated, the underlying cause of UVR-induced erythema appears to be pro-inflammatory. Although an acute response, there is a time-course of expression that, in Caucasian skin, commences with an initial presentation of barely perceptible reddening by approximately 4 hours after exposure, proceeding to full presentation within approximately 8 to 12 hours of exposure (fading within 1 to 2 days) [3], [4]. The dose required to elicit this response is termed the *minimum erythema dose* (MED) and varies from individual to individual, depending on several factors including epidermal melanin fraction volume (a function of ethnicity and tanning status) and stratum corneum thickness. The MED is often used as an expression of *biologically effective dose* (BED) in its own right, but it must be understood that an MED value is linked intrinsically with the *individual* from whom the measurement was taken. For example, even taking the classic semi-objective Fitzpatrick classification (based on susceptibility to sunburn and propensity to tanning), while an overall increase in mean MED (J $cm^{-2}$) is observed that is commensurate with skin type, intratype variability in MED is not inconsiderable [5]. Although an MED is a critical descriptor of individual susceptibility to erythemally effective UVR, therefore, it cannot be understood as a standard term.

To understand a more recent attempt to standardize a UVR erythemal BED, one must first appreciate that for any biologic response produced by electromagnetic radiation, it is critical to define the relative effectiveness of energy at different wavelengths in producing this effect. An *action spectrum* is a parameter that describes this spectral biologic response and is used as a “weighting factor” for the UVR spectrum to derive the actual BED for a given effect. The effect of using an action spectrum in this way can be described mathematically as in Eq. 3:

$$\text{biologically effective irradiance} = \int_{290}^{400} S\left(\lambda\right) A\left(\lambda\right) d\lambda \, \text{mW cm}^{-2} \quad (3)$$

where $S(\lambda)$ is the source spectrum and $A(\lambda)$ is the action spectrum in question. When integrated over time, the UVR BED for the endpoint in question can be derived from this irradiance value.

Several attempts have been made to measure a UVR action spectrum for erythema in human skin, all using a barely perceptible reddening of the skin, 8 to 24 hours after exposure to varying doses of different wavelengths of UVR as an endpoint [6], [7], [8], [9], [10]; it is the reciprocal of this dose that is plotted against wavelength to provide the apparent *erythema action spectrum*. Unsurprisingly, these various action spectra show some variability (inherent with biologic systems) and, therefore, some of these were combined to generate a reference erythema action spectrum that has been adopted by the CIE [11] and shown in Fig. 3. It can be seen clearly that UVR wavelengths up to 300 nm are the most effective in eliciting erythema and, thus, the remainder of the action spectrum is normalized to unity at this waveband. There is an approximate two-decade reduction in erythemal effectiveness from 300 nm to 320 nm and a further decade reduction to 340 nm. In general terms, therefore, despite its prevalence in terrestrial UVR, the UVA waveband is approximately 1000 times less effective than the UVB waveband in eliciting erythema in human skin.

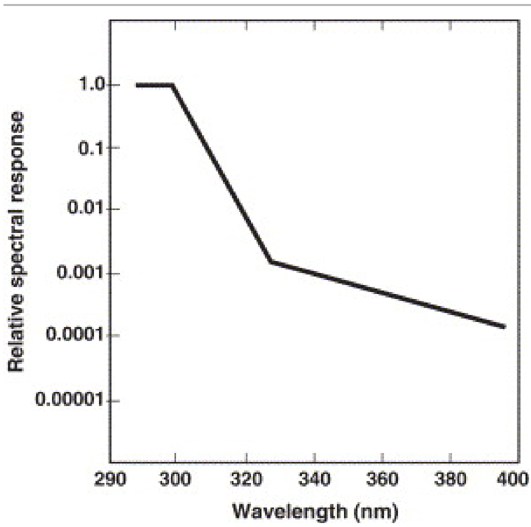


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Fig. 3. La Commission Internationale de l'Eclairage (CIE) erythema action spectrum. (*Data from* Standard CIE. Erythema reference action spectrum and standard erythema dose. Vienna: Commission Internationale

de l'Éclairage; 1998 [CIE S 007/E-1998].)

The term *standard erythema dose* (SED) has been proposed, therefore, to overcome the inherent individual variability associated with the MED term [12]. The SED represents a fixed dose of 100 J $m^{-2}$ and is weighted by the CIE erythema action spectrum and the spectral power distribution of the source. In theory, this should mean that the SED is now independent of (1) the specific spectral power distribution of the source and (2) individual erythemal thresholds. This has since been borne out in studies by Harrison and Young [5]. The SED term in no way negates the value of the MED; the two terms are equally valid but are used to describe quite separate concepts.

Does the erythema action spectrum only provide information about the relative effectiveness of UVR in eliciting an unwanted vascular response in skin and, therefore, only a limited description of biologic damage? The short answer from this author is a firm “no.” In Fig. 4, the CIE erythema action spectrum has been overlaid with the widely accepted action spectra for DNA damage [13], nonmelanoma skin cancer [14], and thymine-dimer induction [10]. All spectra are comparable, each with clear maximal effectiveness at 300 nm and at least a three-decade reduction in effectiveness from 300 nm to 320 nm and beyond. All these endpoints appear to reflect a common damage mechanism. As erythema can be understood as a surrogate for skin cancer-related endpoints, therefore, methods that use erythema as an endpoint for measuring protection against “sunburn” (ie, the in vivo SPF test) are also an indirect measure of protection against these other forms of cutaneous UVR damage. The erythemal response of skin to UVR, therefore, is of primary importance, and a proper understanding of correct associated terminology is absolutely essential.

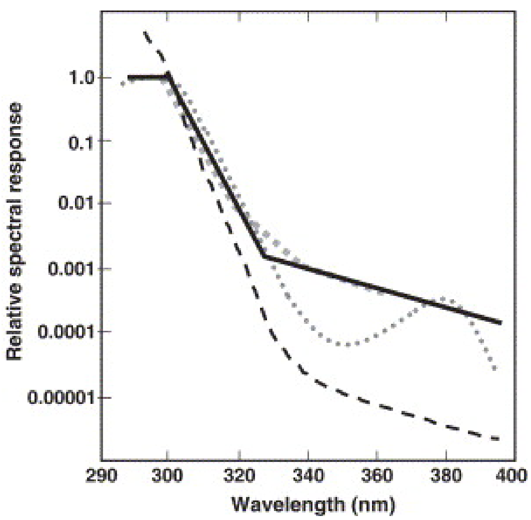


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Fig. 4. La Commission Internationale de l'Eclairage (CIE) erythema action spectrum (*solid line*) overlaid with that for DNA damage (*long dashed line*), nonmelanoma skin cancer (*dotted line*), and thymine dimer induction (*square dotted line*). (*Data from* Refs. [10], [11], [13], [14]).

## Summary

As the field of photobiology continues to grow with concurrent integration of its findings and recommendations into public policy, there is an increasing need for the use of correct and standardized terminology and nomenclature in this highly technical discipline. A proper understanding of the origin of many of the terms that are taken for granted and consequently misused should help to facilitate clear and correct communication, free of myth and confusion.

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## References

[1] W.W. Coblentz, R. Stair, J.M. Hogue
The spectral erythemic reaction of the human skin to ultraviolet radiation
Proc Natl Acad Sci USA, 17 (6) (1931), pp. 401-405
Crossref ↗ Google Scholar ↗

[2] CIE International Lighting Vocabulary
Paris
Bureau Central de la Commission Internationale de l'Eclairage (1970)
Google Scholar ↗

[3] R.L. Olson, R.M. Sayre, M.A. Everett
Effect of anatomic location and time on ultraviolet erythema
Arch Dermatol, 93 (1966), pp. 211-215
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[4] P.M. Farr, J.E. Besag, B.L. Diffey
The time-course of UVB and UVC erythema
J Invest Dermatol, 91 (1988), pp. 454-457
View PDF View article Crossref ↗ View in Scopus ↗ Google Scholar ↗

[5] G.I. Harrison, A.R. Young
Ultraviolet radiation-induced erythema in human skin
Methods, 28 (2002), pp. 14-19
View PDF View article View in Scopus ↗ Google Scholar ↗

[6] J.A. Parrish, K.F. Jaenicke, R.R. Anderson
Erythema and melanogenesis action spectra of normal human skin
Photochem Photobiol, 36 (1982), pp. 187-191
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[7] R.W. Gange, Y.K. Park, M. Auletta, *et al.*
Action spectra for cutaneous responses to ultraviolet radiation
F. Urbach, R.W. Gange (Eds.), The biological effects of UVA radiation, Praeger, New York (1986), pp. 57-65
Google Scholar ↗

[8] A. Anders, H.J. Altheide, M. Knalmann, H. Tronnier
Action spectrum for erythema in humans investigated with dye lasers
Photochem Photobiol, 61 (2) (1995), pp. 200-205

Crossref ↗ View in Scopus ↗ Google Scholar ↗

[9] N. Kollias, Y.H. Malallah, H. al-Ajmi, *et al.*
Erythema and melanogenesis action spectra in heavily pigmented individuals as compared to fair-skinned Caucasians
Photodermatol Photoimmunol Photomed, 12 (5) (1996), pp. 183-188
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[10] A.R. Young, C.A. Chadwick, G.I. Harrison, *et al.*
The similarity of action spectra for thymine dimers in human epidermis and erythema suggests that DNA is the chromophore for erythema
J Invest Dermatol, 111 (6) (1998), pp. 982-988
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[11] Standard CIE
Erythema reference action spectrum and standard erythema dose, Commission Internationale de l'Éclairage, Vienna (1998)
[CIE S 007/E-1998]
Google Scholar ↗

[12] B.L. Diffey, C.T. Jansen, F. Urbach, H.C. Wulf
The standard erythema dose: a new photobiological concept
Photodermatol Photoimmunol Photomed, 13 (1–2) (1997), pp. 64-66
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[13] R.B. Setlow
The wavelengths in sunlight effective in producing skin cancer: a theoretical analysis
Proc Natl Acad Sci USA, 71 (9) (1974), pp. 3363-3366
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[14] F.R. de Gruijl, J.C. Van der Leun
Estimate of the wavelength dependency of ultraviolet carcinogenesis in humans and its relevance to the risk assessment of a stratospheric ozone depletion
Health Phys, 67 (4) (1994), pp. 319-325
View in Scopus ↗ Google Scholar ↗

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