Rationalizing nomenclature for UV doses and effects on humans

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TECHNICAL REPORT

RATIONALIZING NOMENCLATURE FOR UV DOSES AND EFFECTS ON HUMANS

Joint publication of CIE and WMO (World Meteorological Organization)

CIE 209:2014 **WMO/GAW Report No. 211**

UDC: 612.014.481-06 Descriptor: Optical radiation effects on humans

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The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

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3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organizations concerned with matters related to the science, technology, standardization and art in the fields of light and lighting.

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La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.
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Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

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1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.
Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen überprüft, berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by the Joint Technical Committee (JTC) 3 of CIE Division 6 “Photobiology and Photochemistry" in cooperation with the World Meteorological Organization / Global Atmosphere Watch (WMO/GAW). It has been approved by the Board of Administration and Division 6 of the Commission Internationale de l'Eclairage as well as by the Scientific Advisory Group for UV Solar Radiation (SAG-UV) of the WMO/GAW. The document reports on current knowledge and experience within the specific field of light and lighting described and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique mixte (JTC) 3 de la CIE Division 6 "Photobiologie et Photochimie" conjointement avec l’Organisation météorologique mondiale (OMM). Il a été approuvé par le Bureau et Division 6 de la Commission Internationale de l'Eclairage et par SAG-UV de l’Organisation météorologique mondiale. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

Dieser Technische Bericht ist vom gemeinschaftlichen Technischen Komitee (JTC) 3 der CIE Division 6 "Photobiologie und Photochemie" in Zusammenatbeit mit der Weltorganisation für Meteorologie / Global Atmosphere Watch (WMO/GAW) ausgearbeitet worden. Er ist vom Vorstand und Division 6 der Commission Internationale de l'Eclairage sowie der 'Scientific Advisory Group for UV Solar Radiation‘ (SAG-UV) der WMO/GAW gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, dass das Dokument eine Empfehlung und keine Vorschrift ist.

The following members of JTC 3 “Rationalizing UV Units“ took part in the preparation of this Technical Report. The JTC is a joint venture between CIE and the World Meteorological Organization (WMO). The committee comes under Division 6 “Photobiology and Photochemistry”, the corresponding body at WMO is the Scientific Advisory Group for UV Solar Radiation (SAG-UV).

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RATIONALIZING NOMENCLATURE FOR UV DOSES AND EFFECTS ON HUMANS

Summary

The field of atmospheric ultraviolet radiation (UV) research is plagued with difficulties in nomenclature. The problems arise from (a) the strong wavelength dependence of UV radiation received at the Earth's surface, (b) the ad-hoc way disparate groups have approached the subject and (c) the incorrect use of units when action spectra for different UV effects are incorporated. This report highlights some of the issues, taking vitamin-D synthesis, a beneficial effect, as a specific example. Standard vitamin-D dose (SDD) and minimum vitamin-D dose (MDD) are proposed, analogous to the standard erythema dose (SED) and minimum erythema dose (MED) that are in common use for erythema. In recognition of the fact that currently accepted action spectra may be revised in future if new data become available, it is recommended that spectrally resolved irradiance measurements are maintained and continued so that biologically effective irradiances and doses may be reprocessed.

RATIONALISATION DE LA NOMENCLATURE POUR LES DOSES ET EFFETS DU RAYONNEMENT UV CHEZ L'HOMME

Résumé

Le domaine de la recherche sur le rayonnement ultraviolet (RUV) atmosphérique est handicapé par des difficultés de nomenclature. Les problèmes proviennent de (a) la forte dépendance du RUV reçu à la surface terrestre aux longueurs d'onde, (b) l'hétérogénéité des groupes ad hoc qui ont traité le sujet et (c) l'usage incorrect des unités quand les spectres d'efficacité pour les effets bénéfiques ont été intégrés. Le rapport souligne certains problèmes, prenant comme exemple significatif un effet bénéfique tel que la synthèse de vitamine D. Dose standard de vitamine D (SDD) et dose minimale de vitamine D (MDD) sont proposées par analogie avec la dose érythémale standardisée (SED) et la dose minimale érythémateuse (MED) qui sont d'usage courant dans le domaine de l'érythème actinique. Tout en prenant en compte le fait que les spectres d'action actuellement acceptés puissent être modifiés dans le futur si de nouvelles données étaient obtenues, il est recommandé que les mesures de l'éclairement énergétique pondéré par le spectre d'action soient maintenues et poursuivies de sorte que les éclairements énergétiques biologiquement effectifs et les doses puissent être recalculés.

ERKLÄRUNG DER BEGRIFFLICHKEITEN FÜR UV-DOSEN UND EFFEKTE AUF MENSCHEN

Zusammenfassung

Das Forschungsgebiet zur atmosphärischen Ultraviolett-(UV-)Strahlung sieht sich Schwierigkeiten im Gebrauch von Begrifflichkeiten ausgesetzt. Die Probleme entstehen durch (a) die starke Wellenlängenabhängigkeit der an der Erdoberfläche empfangenen UV-Strahlung, (b) die Ad-hoc-Herangehensweise unterschiedlicher Gruppen an die Fragestellung und (c) den falschen Gebrauch von Einheiten, wenn Empfindlichkeitsfunktionen für unterschiedliche UV-Effekte eingearbeitet werden. Dieser Bericht stellt einige dieser Punkte heraus, wobei die Vitamin-D-Synthese, ein nutzbringender Effekt, als spezifisches Beispiel herangezogen wird. Die Begriffe Standard-Vitamin-Dosis (SDD) und Minimal-Vitamin-Dosis (MDD) werden vorgeschlagen in Analogie zu den für das Erythem gebräuchlichen Begriffen Standard-Erythem-Dosis (SED) und Minimal-Erythem-Dosis (MED). Unter Berücksichtigung der Tatsache, dass derzeit anerkannte spektrale Wirkungsfunktionen in der Zukunft bei Vorlage neuer Daten revidiert werden können, wird empfohlen, dass spektral aufgelöste Bestrahlungsstärkemessungen beibehalten und fortgesetzt werden, sodass biologisch effektive Bestrahlungsstärken und Dosen neu ermittelt werden können.

1 Introduction

The field of solar ultraviolet radiation (UV radiation, UVR, UV[1]) research is plagued with difficulties in nomenclature. The problems arise from (a) the strong wavelength dependence of UV radiation received at the Earth's surface caused primarily by ozone absorption, (b) the inherent requirements on complex geometries, (c) the ad-hoc way disparate groups have approached the subject and (d) the diversion from strict SI units. These problems will become more severe in the event that the relevant biological action spectra are changed. This Technical Report highlights some of the issues and suggests ways to redress some of them.

2 Discussion

2.1 Angular Response Considerations

The first issue with the measurement of UV radiation is to specify the quantity to be measured. Meteorological instruments usually measure the radiation impinging on a horizontal surface. That quantity is the irradiance, which is usually measured in $W \cdot m^{-2}$. Essentially irradiance is a measure for the amount of radiation that would go through a horizontal hole, for which the effect of radiation inclined to the vertical has a lower weighting. This is the so-called "cosine" weighting, where, for example, radiation from 30° above the horizon (i.e. at a solar zenith angle (SZA) of 60°) has only half the weighting of radiation from directly overhead (i.e. the zenith direction, at a SZA of 0°). Because of this directionality, quantities of that kind, usually simply named irradiances, are sometimes called "vector" irradiances, in contrast with "scalar" irradiances or "spherical" irradiances which do not depend on direction. One can derive either the vector or scalar irradiances by measuring the directional radiance (in $W \cdot m^{-2} \cdot sr^{-1}$) from a large number of directions, then integrating over all angles and, for the case of vector irradiances, applying appropriate angular weighting factors. Difficulties arise from the complex geometry of biological systems and the lack of appropriate measurements of radiance as a function of incident and azimuth angle, and in case of the measurement of spectral radiance additionally as a function of wavelength. However, a multidirectional spectroradiometer (MUDIS) has been developed recently (Riechelmann et.al. 2013) that allows a measurement of spectral radiance from more than 100 directions simultaneously. In many chemical processes (considering small spherical particles or randomly oriented non-spherical particles) the direction of the incoming radiation is not relevant. In that case, the omni-directional quantity is appropriate, which is often called "actinic flux" in the atmospheric sciences. This term can be misleading as it denominates a quantity which intrinsically is an irradiance, not a radiant flux, and not necessarily implies an actinic effect. The term preferably to be used is "spherical irradiance", which is defined in the International Lighting Vocabulary (CIE, 2011) and according to that is equivalent to the term "radiant fluence rate". Instruments to measure spherical irradiance (radiant fluence rate) are less common because manufacturing optical heads to measure equally from all directions is more challenging than manufacturing optical heads (e.g. diffusers or integrating spheres) whose angular sensitivity matches the cosine response. For some biological or chemical processes the measurement of spherical irradiance (radiant fluence rate) might lead to an appropriate approximation of the biological or chemical effect (Seckmeyer et al., 2013). For the evaluation of some biological or chemical effects the irradiance incident on the surface in question integrated over time is needed. That quantity is called "exposure".

In this document the focus lies on (vector) irradiances. For visible and infrared (IR) solar radiation under cloudless skies, the irradiance is dominated by the direct solar radiant flux beam. However this is not necessarily the case in the UV region where diffuse skylight is usually the dominant component. For example at a SZA of 45°, the ratio of direct to global (direct plus diffuse) irradiance is about 0,9 for visible radiation, but it is only about 0,5 for

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1 Strictly, "UV" is an abbreviation for "ultraviolet" and is therefore, like the names of colours (e.g. red, violet), principally an adjective. But in many instances it is used as a noun, in which case UV can be considered as an abbreviation of "UV radiation".

310 nm UV-B under cloudless skies with very low aerosol content (Zeng, 1994; Blumthaler, 1988).

2.2 UV Irradiances

As any action spectrum is dimensionless, with the SI unit one, photobiologically or photochemically weighted irradiances, for whatever photobiological or photochemical effect, are expressed in the unit of irradiance ($W \cdot m^{-2}$). When giving a quantitative amount, it is essential to specify which actinic action spectrum has been applied, as the unit is the same (see Appendix 3, Clause 2 in BIPM (2006)).

But even for unweighted quantities like UV-A irradiance and UV-B irradiance, there is debate on their definition, with the wavelength thresholds for UV-B irradiance varying from discipline to discipline. According to the Commission Internationale de l'Eclairage (CIE), the boundary between UV-B and UV-A is at 315 nm (UV-B: 280 nm to 315 nm and UV-A 315 nm to 400 nm) (CIE, 2011); but others assume a boundary at 320 nm. For sunlight, the distinction makes little difference in the UV-A, but because the spectrum of sunlight is so steep due to ozone absorption, UV-B values from the latter definition (boundary at 320 nm) can be approximately twice as large as from the former (boundary at 315 nm) (McKenzie, 2004). Because of this steep slope, the end point of integration to calculate UV-B irradiance from spectral irradiances must be carefully considered. Improper treatment of these end points can result in large discrepancies. In addition, the measurement process can introduce uncertainties due to the steep slope, especially when the instrument bandpass is large. Even for instrument bandpasses of bandwidth as small as 1 nm full width at half maximum (FWHM) the error can be significant.

Further issues have arisen using biological spectral weighting functions (action spectra) published in the literature that have been re-digitized. This has resulted for example in significant differences in the DNA-absorption weighted UV or previtamin-D-production-rate weighted UV, for which the first published action spectra appeared as plots or were specified at only a few wavelengths, rather than in tabular form at high spectral resolution. Even in tabular form there are ambiguities due to the interpolation, dependent on the density of interpolation points and the type of interpolation (linear, quadratic, spline, etc.). Potential issues can also arise if the units used when expressing the value of a given quantity are not consistent with that quantity. For example, the quantity "irradiance" refers to the flux falling on a surface and it is always expressed in $W \cdot m^{-2}$ (or equivalently $J \cdot m^{-2} \cdot s^{-1}$). If, however, what is measured is the number of photons falling on the surface, with units $m^{-2} \cdot s^{-1}$, then the quantity measured is "photon irradiance", not "irradiance".

One of the most pressing needs for information on UV radiation came from the health community who were concerned about the effects of skin damage by UV radiation, which can be a precursor to several forms of skin cancer. Impetus for that research was stimulated by the realization that the protective ozone layer was under threat. However, prior to the 1990s, lack of standardization was an impediment. It was only after the widespread adoption of McKinlay and Diffey's action spectrum for erythema (McKinlay, 1987) that it became possible to easily compare results from different research groups working in different geographic locations. While it may be argued whether that action spectrum is an accurate representation of erythema, its strong advantages are (a) that it is defined mathematically and therefore there is less ambiguity[1], (b) it was published by CIE which effectively endorsed its use, and (c) it was widely accepted by the research community.

Figure 1 shows the CIE action spectrum for erythema, which is defined as follows (ISO/CIE, 1999):

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1 In fact, there is some ambiguity (Webb, 2011a) about the precise mathematical form of the action spectrum as originally formulated by McKinlay and Diffey. The ambiguity was resolved in the final CIE formulation (ISO/CIE, 1999). However, while at some wavelengths these result in significant differences, they lead to only small differences in practice for the normally used integral of weighted irradiances.

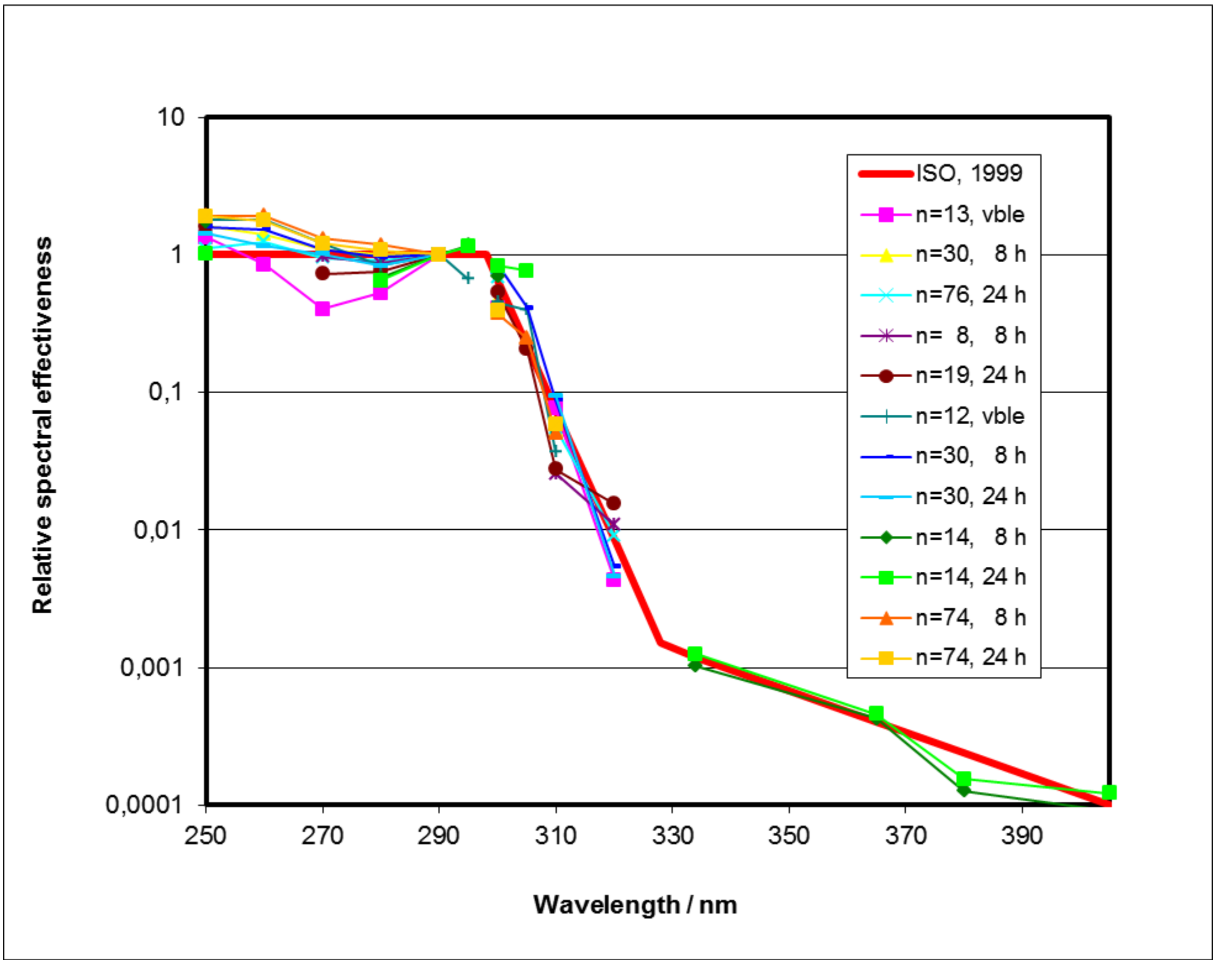
$s_{er}(\lambda) = 1,0$ for 250 nm $\leq \lambda \leq$ 298 nm (1)

$s_{er}(\lambda) = 10^{0,094\ (298\ -\ \lambda/\text{nm})}$ for 298 nm $< \lambda \leq$ 328 nm (2)

$s_{er}(\lambda) = 10^{0,015\ (140\ -\ \lambda/\text{nm})}$ for 328 nm $< \lambda \leq$ 400 nm (3)

and the renormalized data points that were used to construct the CIE action spectrum (Webb 2011a).

For the latter, the normalization wavelength is 290 nm, which lies within the wavelength range for which the CIE action spectrum has a value of unity and for which data were available from all 12 studies. The fitted line is in reasonable agreement with the experimental data, though it must be noted that there is a wide divergence between the various experimental results. Note the logarithmic y-axis, which disguises the magnitude of the differences. In recent times, there has been discussion that it should perhaps be revised further to reflect the fact that recent evidence suggests a greater role for UV-A (Peter Gies, pers. comm.).



NOTE All of the raw data have been normalized to unity at a wavelength of 290 nm, which was common to all measurements. Curves from each of the 12 contributing studies are labelled in the legend according to the number n of participants in the study, and the time period between exposure and testing ("vble" means that the number of hours was variable).

Figure 1 — Spectral weighting function for erythema and raw data

Information about sun-burning UV radiation is currently presented to the public in terms of the UV Index (UVI) (WHO, 2002). The UV Index is simply a scaled version of erythemally-weighted UV (UV-Ery). The concept of UVI originated in Canada, where the scaling factor was chosen to ensure that in Canada the maximum UVI value was 10. This was later formalized by introducing the formula $I_{UV} = 40 \times E_{er}/W{\cdot}m^{-2}$, where I_{UV} is the UVI and E_{er} is the erythemal irradiance. Often behavioural messages are included (e.g. the so-called "Slip, Slap, Slop" messages used in Australia) to educate the public and to optimize health outcomes.

In more recent times there has been a new health concern about sub-optimal levels of vitamin D in the blood, as determined by measurements of serum 25-hydroxyvitamin D (25(OH)D). The first step in that process is the photo-conversion of pro-vitamin D in the skin (7-dehydrocholesterol or 7-DHC) to previtamin D. The action spectrum for that process was measured in the 1980s (MacLaughlin, 1982), but was specified only at a few wavelengths.

Different workers digitized that spectrum and produced different results. As for the case with erythema, an agreed-upon digitization was published by the CIE (2006), as shown in Figure 2. Striking differences compared with Figure 1 are (a) the dearth of experimental data included (just one study with results given at a few wavelengths – and a spectral resolution of 1 nm to 2 nm FWHM), (b) the precise fit of the fitted curve to these few data points, (c) the absence of a simple analytic function that describes the curve, and (d) the extrapolation in the CIE curve to wavelengths longer than those measured. Some have questioned whether the action spectrum is correct (McKenzie, 2009; Norval, 2009). The action spectrum seems to be inconsistent with the assertion that no measureable vitamin D is made in winter months at mid-latitudes (Webb, 1988). Calculations using the action spectrum demonstrate that for clear-sky conditions the noon-time availability of previtamin-D-production-rate weighted UV during midwinter should be approximately 5 % of that at midsummer (McKenzie, 2009). However, if the 3D-geometry of a human is taken into account, it has been shown that relevant Vitamin-D production cannot be expected at least for the northern hemisphere mid-winter (Seckmeyer et al., 2013). Nonetheless, there is a difference between an idealized model and a physiologically relevant production of vitamin D, and vitamin-D status demonstrably declines from late summer onwards (Rockell, 2005; Rockell, 2006; Webb, 2010). Another issue is that the action spectrum extends to wavelengths longer than the longest wavelength where 7-DHC absorbs UV radiation. This raises questions about where the energy comes from to effect the transformation. Nevertheless, the availability of this digitized version has been helpful.

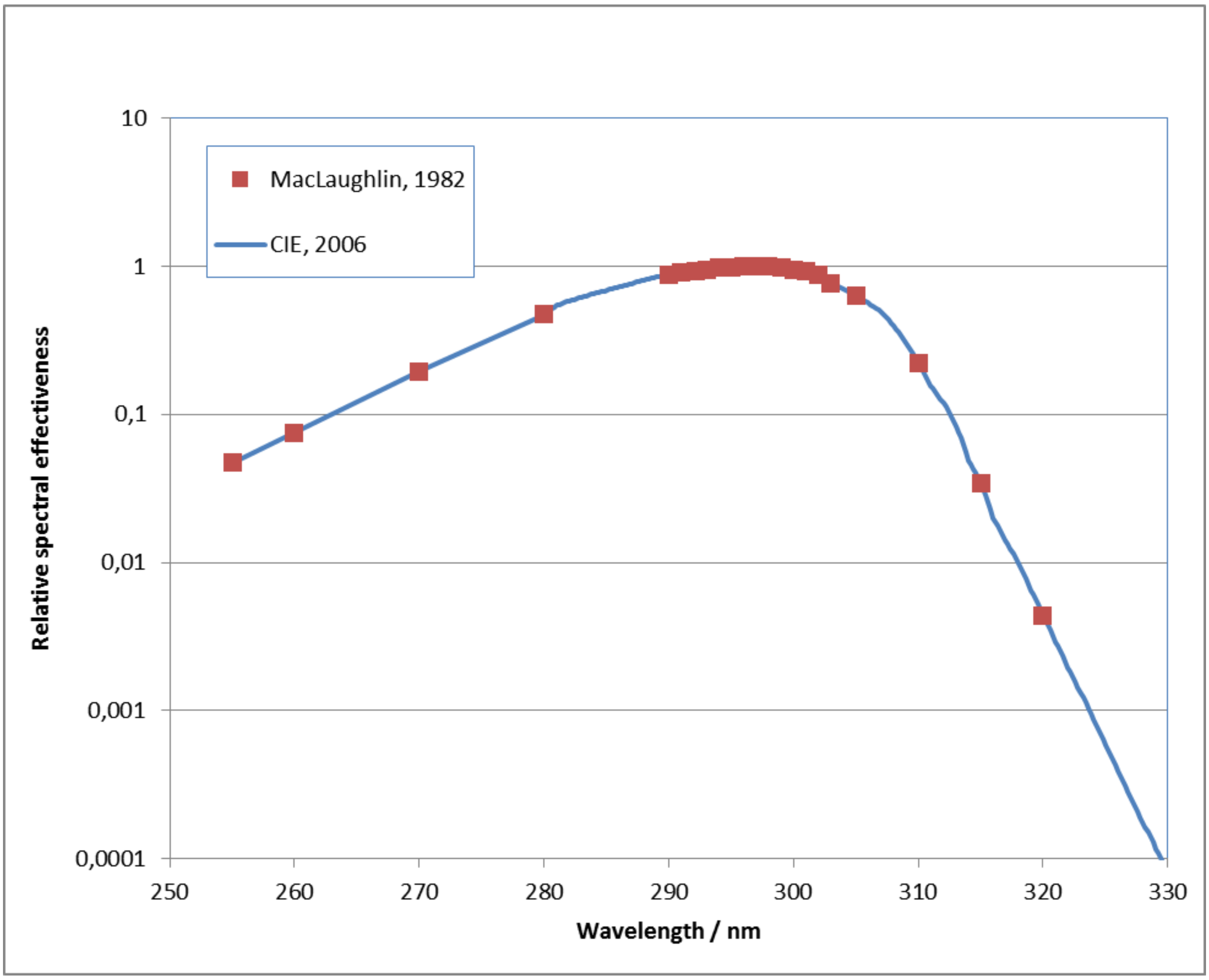


Figure 2 — Spectral weighting function for previtamin-D production and the raw data on which it is based

Further measurements of the action spectrum for previtamin-D production from exposure to UV radiation are recommended. However, this task is not simple, and until further in vivo studies have been completed to complement the original data from the 1980s, the continuing use of the CIE action spectrum for previtamin-D production is recommended, despite its obvious limitations.

2.3 Weighted UV Irradiances in Sunlight

Erythemally-weighted UV (UV-Ery) and previtamin-D-production-rate weighted UV (UV-VitD) irradiances (symbolized mathematically as E_{er} and E_{VitD} respectively) are calculated by integrating the spectral irradiances multiplied by the corresponding value of the weighting function at each wavelength. Examples of the spectrum of solar irradiance received at the Earth's surface in summer and winter are shown in Figure 3 along with the two CIE weighting functions discussed above. Results are shown in Table 1.

Table 1 — Measured parameters from noon sunlight at the Lauder clean-air site (45°S, 170°E, altitude 370 m) under cloudless skies near the summer and winter solstices

	Winter Sun	**Summer Sun**
Day of year	171	357
Solar zenith angle / °	68,5	21,6
Total column ozone / DU (*)	310	285
UV-A irradiance, E_{UVA} / W·m^{-2} (**)	17,97 (17,74)	61,61 (60,14)
UV-B irradiance, E_{UVB} / W·m^{-2} (**)	0,18 (0,48)	2,07 (3,76)
UV-Ery irradiance, E_{er} / W·m^{-2}	0,026	0,282
UV-VitD irradiance, E_{VitD} / W·m^{-2}	0,0316	0,567
$E_{\mathrm{VitD}}/E_{\mathrm{er}}$	1,2	2,0
UVI	1,04	11,3
Time for 2 SED / min	128,1	11,8

* The amount of ozone in the atmospheric column is measured in Dobson units (DU), where 1 DU is $2{,}69 \times 10^{16}$ ozone molecules per square centimetre.

** The first value is assuming a boundary at 315 nm, and the value in parentheses assumes a boundary at 320 nm.

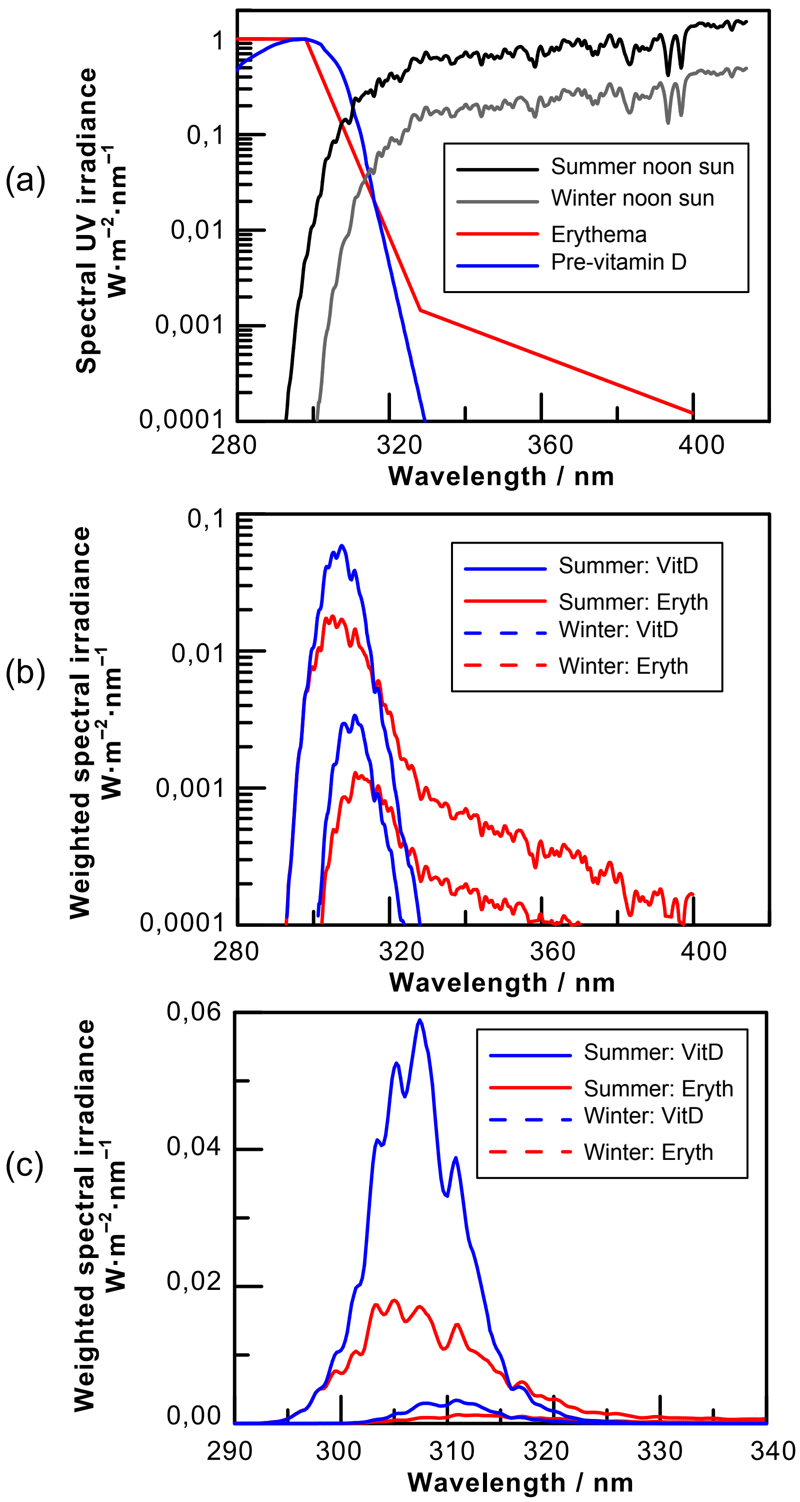


Figure 3 — a) Solar spectra measured at 45°S, during clear skies at noon close to the summer and winter solstices; also shown are the action spectra for erythema (ISO/CIE, 1999) and previtamin-D production (CIE, 2006)

b) The same solar irradiances weighted by the action spectra

c) As above, but plotted on a linear *y*-axis instead of the logarithmic and with a truncated *x*-axis (weighted values are shown in Table 1)

As with all biological spectral weighting functions, these action spectra contain an arbitrary normalization. Usually, as in the case of the CIE action spectrum for vitamin D, the normalization is set to unity at its maximum value. However, in some cases the normalization wavelength is different (e.g. see Figure 6 in McKenzie, 2011). As the action spectrum is dimensionless, with the SI unit one, photobiologically or photchemically weighted irradiances, for whatever photobiological or photochemical effect, are expressed in the units of irradiance ($W \cdot m^{-2}$). When giving a quantitative amount, it is essential to specify which actinic action spectrum has been applied, as the unit is the same. Please note that if, for example, the normalization point for erythema were arbitrarily moved from 298 nm to 300 nm, then all values would increase by 54 %.

2.4 UV Doses

2.4.1 Erythema

The problems continue when doses (irradiances accumulated over time) are considered. Initially, erythemally-weighted UV was reported in terms of its sunburning effect, rather than in SI units. The difficulty here is that different skin types have different sensitivities. For the early radiometers, with responses approximating the erythema action spectrum (Robertson-Berger meters) it had been assumed that sunburn was detectable for fair skinned individuals after exposures to approximately 200 $J \cdot m^{-2}$ of erythemally-weighted UV. The term minimal erythema dose (MED) was coined. Assuming 1 MED being equivalent to 200 $J \cdot m^{-2}$, it would take approximately 12 min of exposure to summer sunlight at mid-latitudes to induce the first perceptible erythema, as determined between 8 h and 24 h after the exposure[1] (see Table 1). Other estimates of the minimum dose before erythema was detectable for fair skins were given as approximately 250 $J \cdot m^{-2}$, and it was recognized that even within nominal skin types there will be a range of MEDs. The threshold MEDs for different skin types were established (Fitzpatrick, 1988) and ranged from 200 $J \cdot m^{-2}$ for the fairest skins to 2 000 $J \cdot m^{-2}$ for the darkest skins. A new unit, the standard erythema dose (1 SED is equivalent to 100 $J \cdot m^{-2}$) was defined (McKinlay, 1987) to measure the erythemally-weighted dose. Unlike the MED, which provides a physiological measure of skin damage, the SED is purely a physical unit (albeit with the built in biological weighting factor that includes an arbitrary normalization factor) which is independent of skin type. In terms of this unit, the thresholds for erythema ranged from 2 SED to 20 SED.

2.4.2 Vitamin D

Analogously, a dose unit (called the standard previtamin-D-production-rate weighted dose or SDD) was established for vitamin D (Webb, 2006). But unfortunately, the unit defined was inconsistent with that developed for erythema. The dose unit for vitamin D was defined in terms of the physiological response—namely the minimum daily dose required to maintain adequate levels of vitamin D—rather than the radiative quantity, so logically it should have been designated MDD by analogy with MED for erythema.

To retain better analogy with the case for erythema, a re-definition of SDD is proposed as 100 $J \cdot m^{-2}$ of UV irradiance weighted by the CIE action spectrum for conversion of 7-DHC to previtamin D.

The term MDD should be used to specify the minimum previtamin-D-production-rate weighted UV dose per day required to maintain adequate vitamin D[2]. As with the MED, the absolute

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1 Sometimes UV irradiances were expressed in terms of how long it would take for erythema to occur. This was the case with New Zealand's "Time to Burn" media messages in the 1980s. The idea was abandoned in the 1990s because it was specific to one skin type.

2 The definition of adequate vitamin D is controversial. Most health agencies recommend that serum 25(OH)D should be at least 50 nmol/l. For adults this can generally be considered as equivalent to a dietary intake of ~1 000 IU of vitamin D per day. One teaspoon full of cod-liver oil corresponds to approximately 400 IU of vitamin D.

dose will depend on individual skin pigmentation and is further complicated by skin area exposed. Furthermore, it should be emphasized that this definition of MDD (like that for MED) does not take into account the complex geometry of the human body. Therefore, the use of weighted irradiance or dose (irradiation) on a horizontal surface (as would be available from a typical meteorological measurement) may turn out to be a non-sufficient description of the UV radiation field and the minimum irradiances that lead to an adequate vitamin-D level.

One possibility is to re-label the “SDD” unit (now to be called MDD) as defined by Webb and Engelsen (Webb, 2006) as the “optimum” daily UV dose, specified as that which produces the same effect on serum vitamin D as an oral dose of about 1 000 IU vitamin D_3 per day. Two daily UV exposure regimes have been suggested as providing that end point:

1) exposure to 0,25 MED for 25 % skin exposed (Dowdy, 2010);
2) full-body exposure to 1 minute of midday sunlight for mid-latitude summer conditions (skin type not specified) (Holick, 2003).

Both of these statements are attributable to a large body of work carried out by Holick and his co-workers since the 1980s (e.g. Holick, 2007), though the precise conditions of the supporting studies are difficult to verify from the literature (Dowdy, 2010). Consequently, neither of these definitions is precisely specified. However, in practise, the lack of precision may have little relevance, since experimental studies show that increases in serum vitamin D in response to UV exposures vary widely from person to person, even for the same skin type. In addition, there is a saturation effect for vitamin-D production for exposures greater than approximately 0,5 MED (that protects against overdoses – see discussion in McKenzie, 2012).

The first definition above can give widely divergent results depending on the spectral shape of the incident radiation. Using a fluorescent lamp as a source gives the ratio $E_{\mathrm{VitD}}/E_{\mathrm{er}}$ as 1,33 (Dowdy, 2010), whereas assuming sunlight, this ratio can reach a value of 2 (Table 1). For very large SZA values, the ratio reduces to approximately 0,5 (McKenzie, 2009). As pointed out by Dowdy et al. (2010) it may also be necessary to increase the exposure times to account for the fact that in sunlight the irradiance is not omni-directional as for the artificial source with vertical lamps in a phototherapy unit, but is dominated by the downwelling component. This has been illustrated for simple situations at a variety of latitudes (Webb, 2011b). The definition also implicitly assumes that the effects of skin transmission are similar for both erythema and vitamin-D production. That is a reasonable assumption, given that the transmission of skin is relatively constant over the wavelength range concerned (300 nm to 320 nm). It is suggested that the MDD be defined in terms of the equivalent full-body[1] dose rather than that of the one-quarter body dose applied above (Webb, 2006).

Using the data from Dowdy (2010) and assuming skin type II, where 1 MED corresponds to a UV-Ery exposure of 2,5 SED or 250 $\mathrm{J \cdot m^{-2}}$, this corresponds to approximately 330 $\mathrm{J \cdot m^{-2}}$ of UV-VitD in summer sunlight. Consequently, from this definition, 1 MDD should correspond to $0{,}25 \times 0{,}25 \times 330\ \mathrm{J \cdot m^{-2}} \approx 21\ \mathrm{J \cdot m^{-2}}$ (or 0,21 SDD) for a full-body exposure.

It was estimated by Fioletov (2010) that 1 MDD for skin type II is equivalent to 106 $\mathrm{J \cdot m^{-2}}$ of previtamin-D-production-rate weighted irradiance on one quarter of the total skin surface area or 26,5 $\mathrm{J \cdot m^{-2}}$ for the equivalent full-body exposure. This assumed springtime sunlight (rather than midsummer), when the ratio of $E_{\mathrm{VitD}}/E_{\mathrm{er}}$ has not reached a maximum (Table 1) and thus is in qualitiative agreement with the value derived from Dowdy (2010).

The second definition above can be traced to the statement that 1 MED full-body exposure to summer sun corresponds to an oral dose of vitamin D_3 between 10 000 IU and 25 000 IU (Holick, 2002), so that “exposure of 6 % of the body to 1 minimal erythemal dose is equivalent to taking between 600 IU and 1 000 IU of vitamin D" (Holick, 2002). For linear changes, that is

1 Note that in calculating equivalent body areas it is considered that skin on all parts of the body makes vitamin D with the same efficiency. This is frequently assumed, but may not be correct (see Meinhardt-Wollweber, 2012).

equivalent to a full-body exposure of 0,06 MED. In this definition, neither the skin type nor the irradiance for summer sunlight is specified. However, assumed it is applicable to skin type II, Table 1 shows that this dose is indeed received in approximately 1 min. For the summer sun conditions specified in Table 1 (with a UVI of 11,28), E_{VitD} is 0,567 W·m^{-2} over an exposure time of 1 min, this amounts to a dose of 34 J·m^{-2} (or 0,34 SDD).

Taking into account all the different imprecise conditions, which are associated with each of the calculations above, one has to consider that the value given for 1 MDD has a possible range (i.e. 0,21 SDD to 0,34 SDD for skin type II). Similarly, also for the MED for skin type II different values can be found in the literature. However, the main point is the definition of the terms, rather than their absolute values.

Even with a standardized and consistent nomenclature, there is a problem of what should be done in the event that the action spectrum is changed. Questions have been raised about both the action spectrum for erythema and the action spectrum for vitamin D. For example, it has been suggested that the CIE spectral weighting function for vitamin-D production should be truncated at 315 nm, since that is the longest wavelength for which data were available (Webb, 1988). In this case, the effect is relatively small: the truncation reduces the value E_{VitD} by factors of 0,9 and 0,95 respectively for the winter and summer spectra shown in Figure 2. However in other cases the effects can be large. For example, with the action spectrum for vitamin D proposed by Olds (2004), values of E_{VitD} are reduced by factors of 0,07 and 0,16 respectively for the winter and summer spectra shown in Figure 2.

3 Conclusions

There are problems with the way UV information is presented.

The only way to ensure against future changes is to maintain spectrally resolved data. In the future, changes may be needed to the action spectra to better reflect reality. In addition the complex 3D geometry of a human might need to be taken into account. In this case information of the spectral radiance as a function of incident and azimuth angle is necessary, rather than spectral irradiance.

If there are significant changes to action spectra, new names should be chosen for the processes to avoid confusion with the large existing data base.

A revised definition of SDD and a newly defined MDD is proposed as follows:

standard vitamin-D dose
SDD
measure of the accumulated previtamin-D-production-rate weighted UV energy where 1 SDD is equivalent to 100 J·m^{-2}

Note This is not the same definition as used by Webb (2006) or by Fioletov (2008).

minimum vitamin-D dose
MDD
minimum dose for maintaining adequate levels of vitamin D based on full-body exposure, which is equivalent to a daily dietary vitamin-D intake of 1 000 IU

Until such time as improved in vivo measurements of the action spectrum for the formation of previtamin D are available the continuing use of the CIE action spectrum for vitamin-D production is recommended, despite its obvious limitations.

Abbreviations used in this Report

25(OH)D — 25-hydroxyvitamin D

commonly-agreed indicator of vitamin-D status in blood serum assays

NOTE It is produced in the liver by hydroxylation of vitamin D_3 (cholecalciferol) by the enzyme cholecalciferol 25-hydroxylase. This is then converted in the kidneys (by the enzyme 25(OH)D-1α-hydroxylase) into calcitriol (1,25-$(OH)_2D_3$), a secosteroid hormone that is the active form of vitamin D.

7-DHC — 7-dehydrocholesterol (sometimes called pro-vitamin D)

sterol from which previtamin D is formed in the skin

IU — international unit

unit of measurement for the amount of a substance

NOTE A biological activity of 40 IU of vitamin D is equal to 1 μg cholecalciferol (vitamin D_3) or ergocalciferol (vitamin D_2), so 1 IU of vitamin D is the biological equivalent of 0,025 μg cholecalciferol/ergocalciferol.

MDD — minimum vitamin-D dose
(*Proposed definition:)*

minimum dose for maintaining adequate levels of vitamin D based on full-body exposure, which is equivalent to a daily dietary vitamin-D intake of 1 000 IU

NOTE 1 MDD is here defined as being equivalent to an exposure of between 0,21 SDD and 0,34 SDD for full-body exposure for skin type II, which in noon summer sunlight is approximately equivalent to 0,25 MED over 25 % of the skin surface area (i.e. hands, face and arms).

NOTE 2 The absolute dose (or radiant exposure), measured in $J \cdot m^{-2}$, depends on individual skin pigmentation and is further complicated by the skin area exposed.

MED — minimal erythema dose

actinic dose, using the erythema action spectrum, that produces a just noticeable erythema on a single individual’s previously unexposed skin

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

NOTE 1 This is a subjective measure based on the reddening of the skin; it depends on many variables, e.g. individual sensitivity to UV radiation, 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.

NOTE 2 The absolute dose (or erythemal radiant exposure), measured in $J \cdot m^{-2}$, depends on skin type. For the most sensitive skin types, 1 MED is approximately 200 $J \cdot m^{-2}$ (weighted using the erythema action spectrum), or 2 SED. For skin type II 1 MED is approximately 250 $J \cdot m^{-2}$ (weighted using the erythema action spectrum), or 2,5 SED (Fitzpatrick, 1988).

[SOURCE: CIE S 017/E:2011, term 17-782, NOTE 2 added]

SDD	standard vitamin-D dose *(Proposed definition:)* measure of the actinic dose, using the CIE action spectrum for vitamin-D production, where 1 SDD is equivalent to 100 J·m^{-2} NOTE This is *not* the same definition as used by Webb (2006).
SED	standard erythema dose standardized unit of measure of erythemal UV radiation NOTE 1 standard erythema dose (SED) is equivalent to an erythemal radiant exposure of 100 J·m^{-2}. [SOURCE: CIE S 017/E:2011, term 17-1255]
UV	ultraviolet (radiation)
UVR	ultraviolet radiation
UV-A	radiation in the range 315 nm to 400 nm [SOURCE: CIE S 017/E:2011, term 17-1367, NOTE 1]
UV-B	radiation in the range 280 nm to 315 nm [SOURCE: CIE S 017/E:2011, term 17-1367, NOTE 1]
UV-Ery	erythemally-weighted (or “sun-burning”) UV radiation NOTE Mainly UV-B, but including a small component of UV-A radiation (McKinlay, 1987; ISO/CIE, 1999).
UVI	UV Index, global UV Index quantity developed for the public domain, for weather forecasting and climatology, which quantifies the erythemal potential (or sunburning power) of the ambient solar ultraviolet radiation (or sunlight), but could also be applied to other sources Unit: 1 NOTE 1 The International Global UV Index, I_{UV}, is defined by the formula: $I_{\mathrm{uv}} = k_{\mathrm{er}} \int_{250\,\mathrm{nm}}^{400\,\mathrm{nm}} E_{\lambda} s_{\mathrm{er}}(\lambda)\,\mathrm{d}\lambda$ where E_{λ} is the solar spectral irradiance expressed in W·m^{-2}·nm^{-1} at wavelength λ, $s_{\mathrm{er}}(\lambda)$ is the erythema action spectrum developed by CIE and k_{er} is a constant equal to 40 m^{2}·W^{-1}. NOTE 2 Equivalent definition: a unitless measure of the erythemally-weighted UV radiation given by 40 × E_{er}/W·m^{-2}, where E_{er} is the erythemal irradiance NOTE 3 At mid-northern latitudes the peak UVI is approximately 10, and values greater than that are often considered as “extreme”. [SOURCE: CIE S 017/E:2011, term 17-498 global UV index, NOTES 2 and 3 added]
UV-VitD	previtamin-D-production-rate weighted UV radiation UV radiation that leads to the photo-production of previtamin D in the skin

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