Five Frequently Asked Questions About UV-Safety

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ABSTRACT

Human UV exposure can lead to acute effects (skin: erythema; eyes: photokeratitis, photoconjunctivitis) and long term effects (skin: accelerated skin aging, basal cell carcinoma, squamous cell carcinoma, malignant melanoma; eyes: cataracts). The International Commission for Non-Ionizing Radiation Protection (ICNIRP) has published international recommendations for maximum UV-exposure levels. For the effective radiant exposure H_{eff} (biologically weighted dose) the daily exposure (8 h) limit value is 30 J m^{-2} with an additional requirement that the unweighted UVA dose H_{UVA} shall not exceed a daily exposure limit value of 10^4 J m^{-2}. These ICNIRP UV-exposure limit values have been incorporated in a recently published European Union Directive on Optical Radiation exposure by artificial sources during work. Measurement and assessment methods are standardized by EN 14255-1. In response to a previous article in IUVA News [Wieringa and Vermeulen 2004], many questions related to UV safety were received by the IUVA which have been summarized here in five questions with associated short-form explanations.

DOES THE ICNIRP UV-HAZARD ACTION SPECTRUM APPLY TO SKIN ONLY, OR ALSO TO THE EYES ?

The ICNIRP UV-hazard spectral weighting function $S(\lambda)$ takes the combined hazards for eyes and skin into account. Figure 1 shows the ICNIRP UV-hazard weighting function in combination with the absorption spectra of three important biological molecules.

How do you calculate a biologically effective dose from a lamp spectrum?

Let's suppose one has measured a lamp spectrum of interest at the considered position of exposure with a calibrated spectroradiometer equipped with cosine diffused input optics. Then one knows the physical spectral irradiance $E(\lambda,t)$. Several different biological effects may result from the lamp's irradiance, depending on which kind of tissue is exposed and for how long (and/or how often). The biological effects of UV radiation are strongly wavelength dependent. The efficiency of UV radiation to induce a certain biological effect can be described by a spectral weighting function. Multiplication of the spectral irradiance by the pertaining spectral weighting function, followed by integration over time gives the biological weighted dose $H_{eff}(\lambda)$. The ICNIRP UV-hazard spectral weighting function $S(\lambda)$, which takes the combined hazards for eyes and skin into account, is thus applied via a simple calculation:

[1] $H_{eff} = \int_{0}^{t} \int_{\lambda=180}^{\lambda=400} E(\lambda,t) \cdot S(\lambda) \cdot d\lambda \cdot dt$ should be ≤ 30 J m^{-2} per working day (8 h).

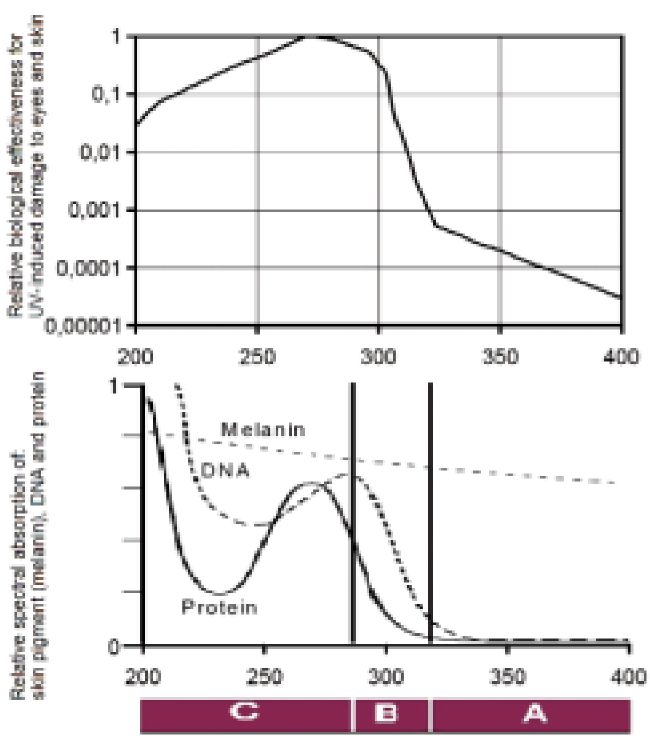


Figure 1: *Top curve: ICNIRP UV-hazard weighting function for the combined risks for skin and eyes. Lower curves: three absorption spectra of important bio-molecules. Source [Wieringa 2006].*

where: H_{eff} is the *effective radiant exposure*, that is, the radiant exposure spectrally weighted by $S(\lambda)$, expressed in joules per square meter [J m^{-2}]; H_{eff} is only relevant in the range 180 to 400 nm.

$E_\lambda(\lambda,t)$ is the *spectral irradiance or spectral power density*, that is, the radiant power incident per unit area on a surface, expressed in watts per square meter per nanometer [W m^{-2} nm^{-1}]; values of $E_\lambda(\lambda,t)$ come from measurements or may be provided (for a defined geometry) by the manufacturer of the equipment;

$S(\lambda)$ is a *spectral weighting function* taking into account the wavelength dependence of the health effects of UV radiation on eye and skin [dimensionless].

Figure 2 shows a lamp spectrum before and after application of the ICNIRP UV-hazard weighting function $S(\lambda)$.

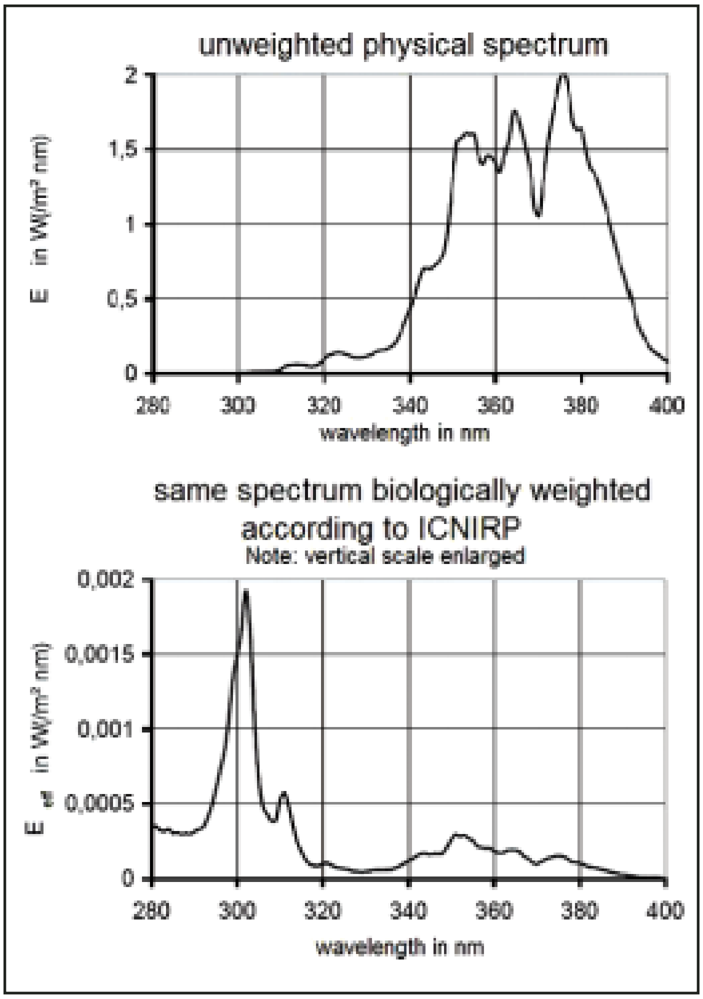


Figure 2. *Top curve: Spectral irradiance of a lamp used for welding quality inspection (only the emission from 400 to around 365 nm forms the useful lamp output and is needed for inspection purposes). Lower curve: The same lamp spectrum after multiplication with the ICNIRP UV-hazard weighting function. It is clear that the main part of a worker's personal UV-exposure comes from spectral regions that are not needed for inspection purposes. Reproduced with kind permission from* [*Schwaß 2004*].

For an ozone-free low pressure mercury UVC lamp, measurement data from a radiometer with a flat response spectrum can be used as an input value. Here the calculation is quite easy. Since there is only one emission line of biological significance at 254 nm, the unweighted value of a calibrated broadband meter may be simply multiplied with the corresponding value from Table 1 (which is 0.5). Thus, for a 254 nm lamp a maximum unweighted dose of 60 J m^{-2} over 8 h is allowed (because it corresponds to a biologically effective dose of 0.5 x 60 = 30 J m^{-2}). As one can clearly see from Figure 1, this simple calculation by hand is not feasible with more complex spectra. Therefore, broadband UV-radiometers have been developed that closely match the ICNIRP UV-hazard function using a carefully designed filter/detector combination, thus offering direct readings of biologically effective irradiance E_{eff}. Sophisticated devices can be equipped with the possibility to integrate over time to measure H_{eff}. For dose measurements over prolonged exposure duration, the noise behavior and stability of the integrating function are crucial for accuracy.

If one measures UV with a broadband radiometer, one must know whether the radiometer has a flat response curve and measures the unweighted (physical) UV or that it has a biological response curve and thus measures the weighted (biological) UV. Note that, apart from the ICNIRP curve, there are several other weighting functions too (e.g. for erythema, for the beneficial effect of vitamin D production, or the CIE NMSC weighting function shown in Figure 3, etc.). To make it even more complicated, the response bandwidth may only partly cover the whole lamp output spectrum, and you have to be aware of this too!

Note that an additional requirement also applies, namely that the unweighted (i.e. physical) UVA dose H_{UVA} shall not exceed a daily exposure limit value of 104 J m^{-2} :

$$[2] \quad H_{UVA} = \int_{0}^{t} \int_{\lambda=315}^{\lambda=400} E_\lambda(\lambda,t) \cdot d\lambda \cdot dt$$

where: H_{UVA} is the *radiant exposure*, that is, the time and wavelength integral or sum of the irradiance within the UVA wavelength range 315 to 400 nm, expressed in joules per square meter [J m^{-2}]; H_{UVA} is only relevant in the range 315 to 400 nm.

$E_\lambda(\lambda,t)$ is the *spectral irradiance or spectral power density*, i.e., the radiant power incident per unit area on a surface, expressed in watts per square meter per nanometer [W m^{-2} nm^{-1}]; values of $E_\lambda(\lambda,t)$ come from measurements or may be provided (for a defined geometry) by the manufacturer of the equipment;

It is important to use consistent methods for Occupational Health and Safety related UV-measurements and their according assessment. In Europe, for UV safety measurements the standard EN 14255-1 "Ultraviolet radiation emitted by artificial sources in the workplace" applies. This standard describes how to perform measurements and assessments of personal exposures to artificial ultraviolet radiation sources within the wavelength band of 180 to 400 nm. The standard became effective in March 2005 and supports implementation of the recently released EU Directive about artificial optical radiation exposure by artificial sources in the workplace [EU 2006].

The Directive on Optical Radiation Safety applies for the whole EU, while at least the following countries are bound to implement EN 14255-1: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Table 1. *UV exposure limits and general weighting factors*

λa / nm	EL[d] / J m^{-2}	EL[d] / mJ cm^{-2}	$S(\lambda)$[b]	EL[d] λ[a] / nm	EL[d] / J m^{-2}	/ mJ cm^{-2}	$S(\lambda)$[b]
180	2,500	250	0.012	310	2,000	200	0.015
190	1,600	160	0.019	313[c]	5,000	500	0.006
200	1,000	100	0.030	315	1.0×10^4	1.0×10^3	0.003
205	590	59	0.051	316	1.3×10^4	1.3×10^3	0.0024
210	400	40	0.075	317	1.5×10^4	1.5×10^3	0.0020
215	320	32	0.095	318	1.9×10^4	1.9×10^3	0.0016
220	250	25	0.120	319	2.5×10^4	2.5×10^3	0.0012
225	200	20	0.150	320	2.9×10^4	2.9×10^3	0.0010
230	160	16	0.190	322	4.5×10^4	4.5×10^3	0.00067
235	130	13	0.240	323	5.6×10^4	5.6×10^3	0.00054
240	100	10	0.300	325	6.0×10^4	6.0×10^3	0.00050
245	83	8.8	0.306	328	6.8×10^4	6.8×10^3	0.00044
250	70	7	0.430	330	7.3×10^4	7.3×10^3	0.00041
254[c]	60	6	0.500	333	8.1×10^4	8.1×10^3	0.00037
255	58	5.8	0.520	335	8.8×10^4	8.8×10^3	0.00034
260	46	4.6	0.650	340	1.1×10^5	1.1×10^4	0.00028
265	37	3.7	0.810	345	1.3×10^5	1.3×10^4	0.00024
270	30	3.0	1.000	350	1.5×10^5	1.5×10^4	0.00020
275	31	3.1	0.960	355	1.9×10^5	1.9×10^4	0.00016
280[c]	34	3.4	0.880	360	2.3×10^5	2.3×10^4	0.00013
285	39	3.9	0.770	365[c]	2.7×10^5	2.7×10^4	0.00011
290	47	4.7	0.640	370	3.2×10^5	3.2×10^4	0.000093
295	56	5.6	0.540	375	3.9×10^5	3.9×10^4	0.000077
297[c]	65	6.5	0.460	380	4.7×10^5	4.7×10^4	0.000064
300	100	10	0.300	385	5.7×10^5	5.7×10^4	0.000053
303[c]	250	25	0.120	390	6.8×10^5	6.8×10^4	0.000044
305	500	50	0.060	395	8.3×10^5	8.3×10^4	0.000036
308	1,200	120	0.026	400	1.0×10^6	1.0×10^5	0.000030

a. Wavelengths chosen are representative; other values should be interpolated (see eqs. 3a-c).

b. Relative spectral effectiveness. This is the ICNIRP spectral weighting function $S(\lambda)$ for determination of H_{eff} and exposure limits.

c. Emission lines of a mercury discharge spectrum [ICNIRP 2004].

d. EL for a monochromatic source, but also limited by a dose-rate of 10 kW m^{-2} (1 W cm^{-2}) for durations greater than 1 s, as well in order to preclude thermal effects.

Values of $S(\lambda)$ for wavelengths not listed in Table 1 may be interpolated with reasonable accuracy using the following three expressions which apply only from 210 – 400 nm [ICNIRP 2004]:

[3a] for $210 \leq \lambda \leq 270$ nm $S(\lambda) = 0.959^{(270-\lambda)}$

[3b] for $270 < \lambda \leq 300$ nm $S(\lambda) = 1 - 0.36 * \left[\frac{\lambda - 270}{20}\right]^{(1.64)}$

[3c] for $300 < \lambda \leq 400$ nm $S(\lambda) = 0.3 * 0.736^{(\lambda - 300)} + 10^{(2 - 0.0163\lambda)}$

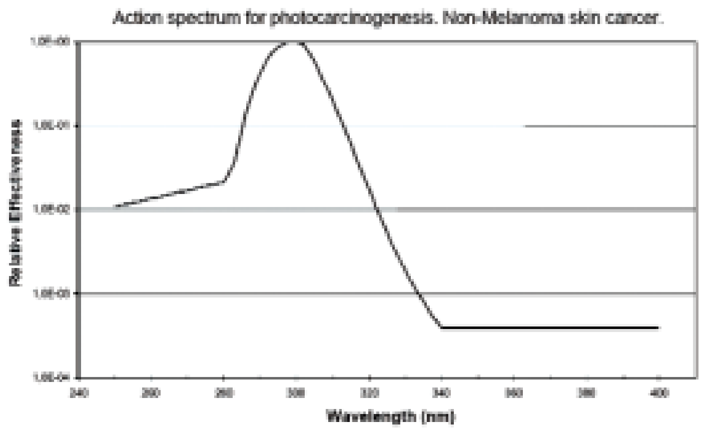
Is UVC (e.g. 254 nm) strongly absorbed in the uppermost skin layer?

Yes, this is true. In skin, at 254 nm over 99% of the incoming radiation is absorbed in the first 100 µm where most cells will not replicate any more. This is very fortunate, because in this way only very few of the highly energetic UVC photons can reach the basal cell membrane where the new skin cells grow. Note, however, that absorption is a statistical process, which means that although only a very small fraction of the UVC photons may penetrate into living cells, the higher the irradiance at the surface becomes, the higher the absolute number of damaged cells. The longer the wavelength, the deeper UV radiation can penetrate the skin, but also the photons possess less energy to produce damage.

Broad-spectrum ultraviolet radiation (solar UV, as well as UV from sunbeds and sunlamps) is *known to be a human carcinogen*, based on sufficient evidence of carcinogenicity from studies in humans, which indicates a causal relationship between exposure to broad-spectrum ultraviolet radiation and human cancer. The separate spectral bands of UVA, UVB and UVC radiation are *reasonably anticipated to be a human carcinogen* based on limited evidence of carcinogenicity from studies in humans and sufficient evidence of carcinogenicity from studies in experimental animals, which indicates there is an increased incidence of malignant and/or a combination of malignant and benign tumors in multiple species of experimental animals [USDHHS 2002].

Skin cancer is caused by damage to cells that are able to reproduce themselves. These are located around the basal membrane, where some UVB and relatively much UVA can penetrate. This (along with the absorption spectra of biological molecules in Figure 1) explains the shape of the CIE non-melanoma skin cancer (NMSC) action spectrum as shown in Figure 3. Although the NMSC action spectrum indicates a rather low efficiency for UVA to induce skin cancer, it must be realized that the UVA irradiance of many lamp types is much higher than that within the UVB and/or UVC range.

Figure 3. *Non Melanoma Skin Cancer (NMSC) action spectrum issued by the International Commission on Illumination (CIE – Commission Internationale de l'Eclairage), which can be used to compare lamps for their long term effects regarding to skin cancer (except for melanoma). UVB radiation clearly is most efficient for the induction of non-melanoma skin cancers and UVC to a lesser extent. Note that, although less effective, UVA is not "harmless".*



Is UVC (e.g. 254 nm) strongly absorbed in the upper layer of the eye?

Yes, indeed strong absorption takes place immediately at the surface, but unlike the skin, the cornea is <u>not</u> covered by a relatively "insensitive" protective layer. Welder's flash (or photokeratitis) is a well-known acute effect that easily occurs when eye protection is not worn during welding (even if welding only lasts a few seconds). Snow blindness is the same effect, but due to the lower irradiance values and comparably longer wavelengths in solar radiation, it requires a lot more exposure time. Chronic exposure to UVB and UVA over the years can cause cataracts (the eye lens forms a life-time "UV dosimeter").

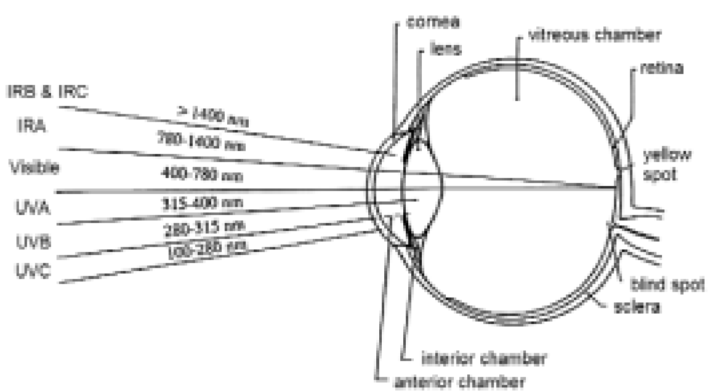
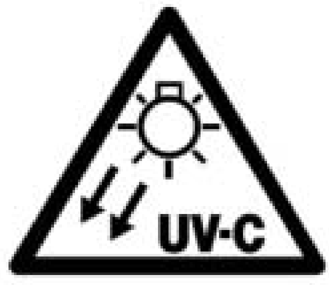


Figure 4. *Penetration in the eye for various spectral regions. Source: Dutch Health Council.*

Are there any agreed UV-warning symbols ?

The good news is that there are several symbols, the bad news is that they are not united. Some examples are shown in Figure 5a (origin IEC) and 5b (origin Comité Européen de Normalisation).

(a)



(b)

Figure 5. *The most widely used UV-warning symbols originating from IEC (5a) and CEN (5b).*

Symbols alone can sometimes be unclear. Additional warning texts, like shown in Figure 6, can be very helpful to inform workers and put the risk in proportion. Clear designation (e.g., on the floor) of safe zones where no protection is needed versus zones where eye (and in some cases even skin) protection is needed also can be very useful.

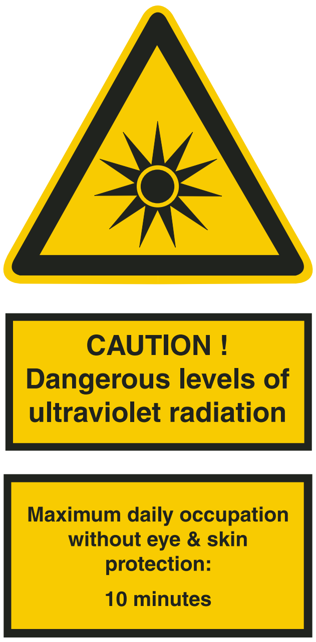


Figure 6. *Instead of only applying a UV-warning symbol, an additional clear specification of maximum allowable unprotected exposure duration helps workers to judge the risk.*

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