MEASUREMENT OF UVA EXPOSURE TO SOLAR RADIATION

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Abbreviation: MED, minimal erythema dose; erythema UV, biologically effective irradiance for erythema; UVA, 320-400 nm; UVB, 280-320 nm; CR-39, trade name for diglycol carbonate; NDA, nalidixic acid; 8MOP; 8-methoxypsoralen; UV or UVR, 280-400 nm; hr, hour; ΔA, change in optical absorbance; EST, eastern standard time

Abstract

Exposure to solar UVA radiation can lead to damage of DNA and other types of skin disorder. Conventional dosimetry using a single piece of polysulphone or CR-39 cannot provide accurate measurement of biologically effective irradiance for erythema for the UVA waveband. A package employing four dosimeters: polysulphone, nalidixic acid, 8-methoxypsoralen and phenothiazine has been shown to be effective for usage as a spectrum evaluator for evaluating the UVA source spectrum. In Brisbane, on a horizontal position, the spectrum evaluator requires about 5 minutes exposure in summer and about 20 minutes in winter. This amounts to about 10 mJ cm^{-2} of erythema UV.

INTRODUCTION

The effect of solar UV radiation can be assessed using the human action spectrum for erythema[1]. Biologically effective irradiance for erythema (erythema UV) can be determined from the measurement of spectral irradiance using a spectro-radiometer[2]. The method is not only uneconomical but it is also very difficult to use for measurements of personal exposure to humans. Passive dosimeters such as polysulphone[3] and CR-39[4] have been used for measuring exposure of humans to erythema UV. Because these dosimeters do not have a response identical to the human action spectrum for erythema, the error[2] introduced by this method of measurements could be as high as 40%.

It was found[5] that UVA exposure can induce pyrimidine dimers and, therefore, can cause DNA damage in human skin. A recent publication[6] suggests that daily UVA exposure of 50-200 kJ m^{-2} (less than 0.5 MED) for 8 days can induce morphological skin alterations indicative of early tissue injury. Both polysulphone and CR-39 dosimeters are only sensitive to solar UVB radiation (290 - 320 nm) but not sensitive to UVA radiation (320 - 400 nm). If solar UVB is removed with a barrier, for example, a glass window, then UVA provides significant exposure to erythema UV. This paper describes a new technique of utilizing a composite system (spectrum evaluator) consisting of the four materials: polysulphone, nalidixic acid (NDA), 8-methoxypsoralen (8MOP) and phenothiazine to determine erythema exposure in the UVA band.

MATERIALS AND METHODS

Solar UVA

Spectral irradiance of ambient UV was measured using a spectroradiometer as described elsewhere[2]. The spectro-radiometer was calibrated against a quartz tungsten halogen lamp (A1/235, supplied by the Thorn Co., U.K.) at a current of 9.5 A. The calibration of the lamp was traceable to the Australian standard lamp at the National Measurement Laboratory, CSIRO, Lindfield. The measurements were made at around 12:00 noon Eastern Standard Time (EST) in Australia in mid summer and in mid winter under a clear sky.

Dosimeters

Four types of dosimeters[7-10] (polysulphone, NDA, 8MOP and phenothiazine), in thin film form, were used in the spectrum evaluator. These materials undergo chemical changes after exposure to ultraviolet radiation. The effect can induce a change in the optical absorbance of the films. The change depends on the fluence of the exposure but it is independent of the dose rate and the temperature. The change in optical absorbance of a dosimeter exposed to a source spectrum of $S(\lambda,t)$ over a time interval T is given by the expression

$$\Delta A = \int_0^T \int_{uv} S(\lambda, t) R(\lambda) d\lambda dt \quad (1)$$

where R(λ) is the spectral response of the dosimeter. The wavelength dependence of the change in optical absorbance (i.e. the spectral response) due to ultraviolet radiation was measured using an irradiation monochromator supplied by the Spectral Energy Co., 57 Woodland Ave., Westwood, New Jersey 07675, U.S.A. The instrument consists of a fan cooled xenon mercury lamp powered by an LPS255 HR universal arc lamp power supply at 23 A and 21 V. An electrical shutter operated by a switch controls the beam which was passed through a Spectral Energy GM252 single grating monochromator before reaching the sample for irradiation. The bandwidth for the beam was adjusted to 2 nm full width at half maximum. The output irradiance was measured with a double monochromator system (Model H10DUV, Jobin Yvon Co., 16-18 rue du Canal, 91165 Longjumeau Cedex, France). The contribution of higher order spectra was checked for and was negligible. Samples fabricated from the four materials mentioned above were exposed to the beam from the irradiation monochromator in 10 nm steps to achieve a change in absorbance of at least 10%. The results were used to derive the spectral response.

The Spectrum Evaluator

The spectrum evaluator consists of the four dosimeters as described previously. Each dosimeter was fabricated as a circular film of less than 1 cm in diameter. The four dosimeters; one of each type were attached to a square sample holder about 3 cm each side. The film was pasted to one of the four holes (6 mm diameter) in the sample holder. The dosimetric system of polysulphone, NDA, 8MOP and phenothiazine along with a single polysulphone dosimeter were exposed under a filter to the quartz tungsten halogen lamp at 9.5 A. The filter was a Schott WG335 filter with a thickness of 3 mm. This filter transmitted UVA only and the spectral irradiance of the lamp and filter was measured with the spectroradiometer as described previously. The optical absorbance was measured before and after the exposure at 330 nm for polysulphone and NDA, 305 nm for 8MOP and 280 nm for phenothiazine with a spectrophotometer (Shimadzu Co., Kyoto, Japan). These are the wavelengths at which the largest change in absorbance occurs for the particular materials. Using Eq. 1, the source spectrum from the lamp and the filter system can be evaluated using a numerical method[11]. The fitted function was constrained to possess a root at 320 nm because UVB was filtered out of the source spectrum. The function was

$$S(\lambda) = (\lambda - 320) * \left(\sum_{i=1}^{4} a_i \lambda^{t-1}\right) \quad (2)$$

where a_i are the coefficients to be determined using an iterative method[11]. The χ^2 value is defined as

$$\chi^2 = \sum_{i=1}^{4} \frac{1}{\sigma_i^2} (\Delta A_i - \Delta A_i')^2 \quad (3)$$

where $\Delta A_i'$ is the change in optical absorbance, for each type of dosimeter, determined using the spectrophotometer as described previously. The factor σ_i is the error in $\Delta A_i'$. The change in absorbance, ΔA_i, was calculated with Eq. (1) for each type of dosimeter. The coefficients in Eq. (2) are derived by minimizing[11] the χ^2 value.

Solar spectra were evaluated in the same manner. The exposure takes about 5 minutes in summer and 20 minutes in winter. The results of the evaluated spectrum were used to calculate the biologically effective irradiance for erythema (erythema irradiance):

$$I_{UV} = \int_{\lambda_{min}}^{\lambda_{max}} S(\lambda)E(\lambda)d\lambda \qquad (4)$$

where $E(\lambda)$ is the human action spectrum for erythema. The limits λ_{min} and λ_{max} define the spectral region over which the contribution to the erythema irradiance is to be calculated. In the case of the entire UVR region (290 - 400 nm), Eq. (4) becomes:

$$I_{UVR} = \int_{290}^{400} S(\lambda)E(\lambda)d\lambda \qquad (5)$$

RESULTS

Solar UVA

The source spectra measured in Brisbane, Australia, during the period between 1994 and 1995 were used to calculate the erythema irradiance in the UVA region, UVB region and the entire UVR region with Eqs. (4) and (5). The results of the average erythema irradiance measured in Brisbane are presented in Table 1. The tolerance in these calculations was estimated to be less than 10%.

The last column in the Table gives the ratio of erythema UVA to that of UVB. Using the values of the ratio, it can be shown that the contribution of UVA to the erythema irradiance increases from about 15% in summer to 32% in winter. The increase in the contribution of UVA to erythemal irradiance from summer to winter is due to the smaller proportion of UVB in solar UV radiation in winter.

Dosimeters

The results of the spectral response (change in optical absorbance per unit fluence versus the wavelength) for polysulphone, NDA, 8MOP and phenothiazine are presented in Figure 1. At about 320 nm, the sensitivity or the response of polysulphone reduced to about 1% of the maximum value (at 295 nm). For the other three materials, their spectral response extends into the UVA region but the peaks are not located in the UVB region. As a result, the use of a single polysulphone dosimeter can be employed to obtain a good estimation of the effect of UVB but it is necessary to use other materials to obtain information about the contribution of UVA.

The Spectrum Evaluator

The results of the change in optical absorbance, ΔA, measured at hourly intervals up to 8 hours and then again for 23.4 hours exposure are presented in Table 2. The error in the optical measurement is less than 2%.

As expected the change in absorbance for polysulphone is within the experimental errors. Thus the results of polysulphone were discarded. The sum in Eq. (2) was reduced to three terms only using the values of ΔA for NDA, 8MOP and phenothiazine. The change in absorbance for phenothiazine saturates after 6 hours exposure. The values of ΔA for the one hour exposure were employed to evaluate the UV spectrum. The evaluated function for the spectral irradiance in μW cm^{-2} nm^{-1} from the lamp and the filter system is:

$$S(\lambda) = (\lambda - 320) * (0.7785 - 0.00162\lambda) \qquad (6)$$

This is plotted in Figure 2 along with the spectrum measured with the spectroradiometer. Using Eq. (5) the exposure due to erythema UV was calculated with the evaluated spectrum (column 2, Table 3) and the spectrum measured with the spectroradiometer (column 3, Table 3). In column 1 the total UVA fluence calculated using the spectrum measured with the spectroradiometer is included for comparison. The agreement between the calculated value and the experimental value is within the experimental uncertainties.

Solar measurements (Table 4) usually contain a large contribution (e.g. see Table 1) of UVB in summer. Thus, measurements with a single polysulphone dosimeter can yield reasonably good results (within experimental uncertainties) for summer exposure. In winter, the discrepancy between the result of polysulphone and that derived from the spectrum measured with the spectroradiometer is about 20%. On the other hand, the results obtained with the spectrum evaluator deviate from that of the spectroradiometer by less than 10%.

CONCLUSION

The damaging effects of UVA to DNA and to the human skin were recognised by photobiologists[5,6,12] who have suggested the need for photo protection against UVA damage to the skin. It has been demonstrated in this paper that the spectrum evaluator employing four UV dosimeters can be used to determine the UVA spectrum. The package consists of polysulphone, NDA, 8MOP and phenothiazine in the form of thin films. They are mounted on a sample holder of a size about 3 cm x 3 cm. The evaluated spectrum agrees with the spectrum measured with the spectroradiometer within experimental uncertainties (about 10%).

Following a one hour exposure to UVA radiation from a lamp and filter system, the spectrum evaluator could be used to determine the erythema UV. On the other hand, on exposure to UVA, a single polysulphone dosimeter cannot provide any change in optical absorbance which is the effect for assessing the UV exposure. The spectrum evaluator provides a method for assessing the UVA exposure. For sunlight, the result obtained with the spectrum evaluator deviates from that obtained with the

spectroradiometer by less than 10%. On a horizontal position, in Brisbane the package requires about 5 minutes exposure to summer sunshine and about 20 minutes exposure to winter sunshine to allow evaluation of the spectrum. This amounts to a total exposure of erythema UV of about 10 mJ cm^{-2}.

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Table 1 Average Erythema Irradiance in Brisbane

Season	Erythema UVA ($\mu W\ cm^{-2}$)	Erythema UVB ($\mu W\ cm^{-2}$)	Erythema UVR ($\mu W\ cm^{-2}$)	Ratio of UVA to UVB
Summer	5.7	29.3	35	0.196
Winter	4.2	8.8	13	0.471

Table 2 Change in Optical Absorbance due to UVA Exposure

Exposure time (hr)	Change in optical absorbance, ΔA’			
	Poly-sulphone	NDA	8MOP	Pheno-thiazine
1	0.0	0.039	0.012	0.384
2	0.003	0.049	0.026	0.532
3	0.003	0.077	0.040	0.607
4	0.001	0.088	0.053	0.654
5	0.003	0.102	0.058	0.685
6	0.002	0.116	0.078	0.705
7	0.001	0.134	0.081	0.760
8	0.0	0.147	0.101	0.749
23.4	0.005	0.315	0.230	0.741

Table 3 Erythema UV exposure due to a UVA source (quartz tungsten halogen lamp and Schott WG335 filter system)

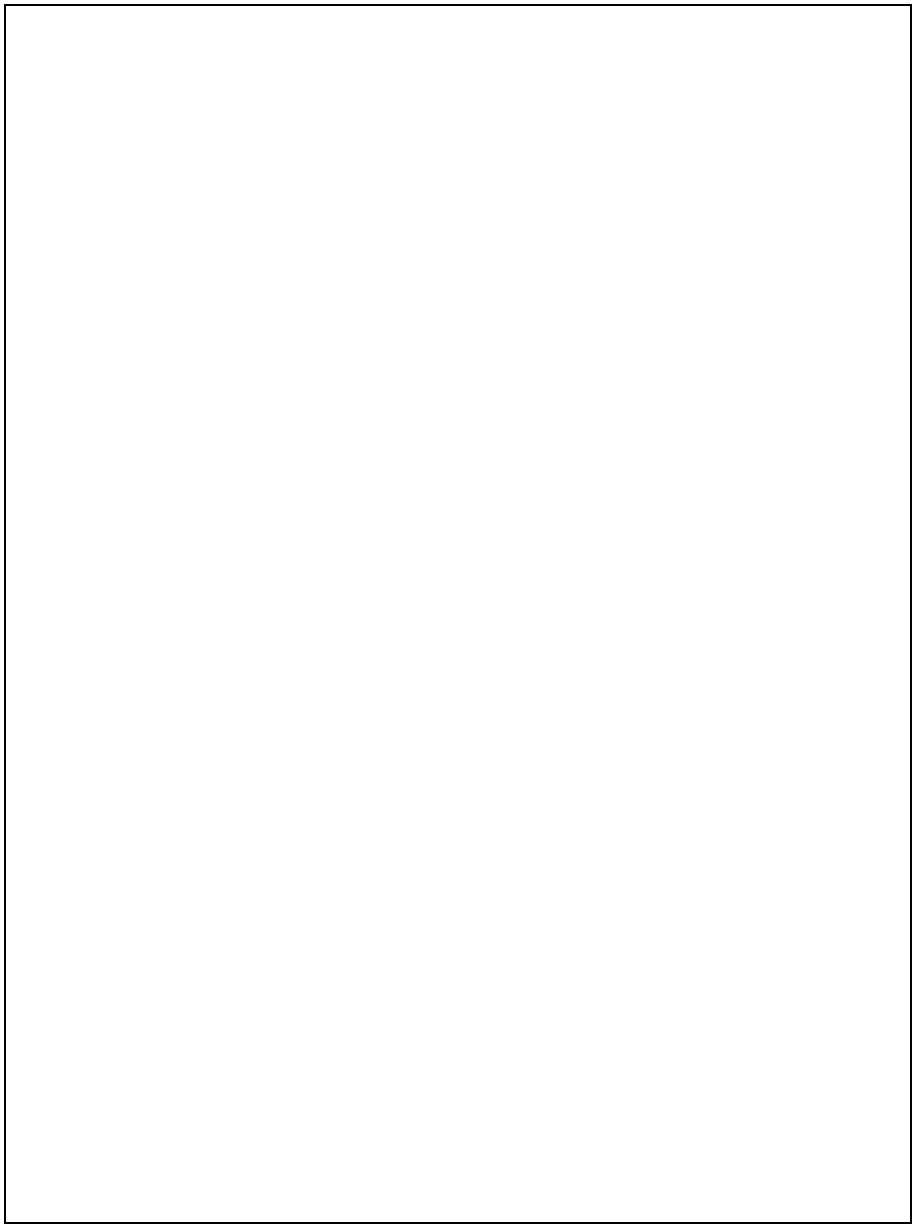
Total UVA ($J\ cm^{-2}$)	Evaluated Erythema UV ($J\ cm^{-2}$)	Measured Erythema UV ($J\ cm^{-2}$)
2.1 ± 0.2	0.91 ± 0.14	0.81 ± 0.08

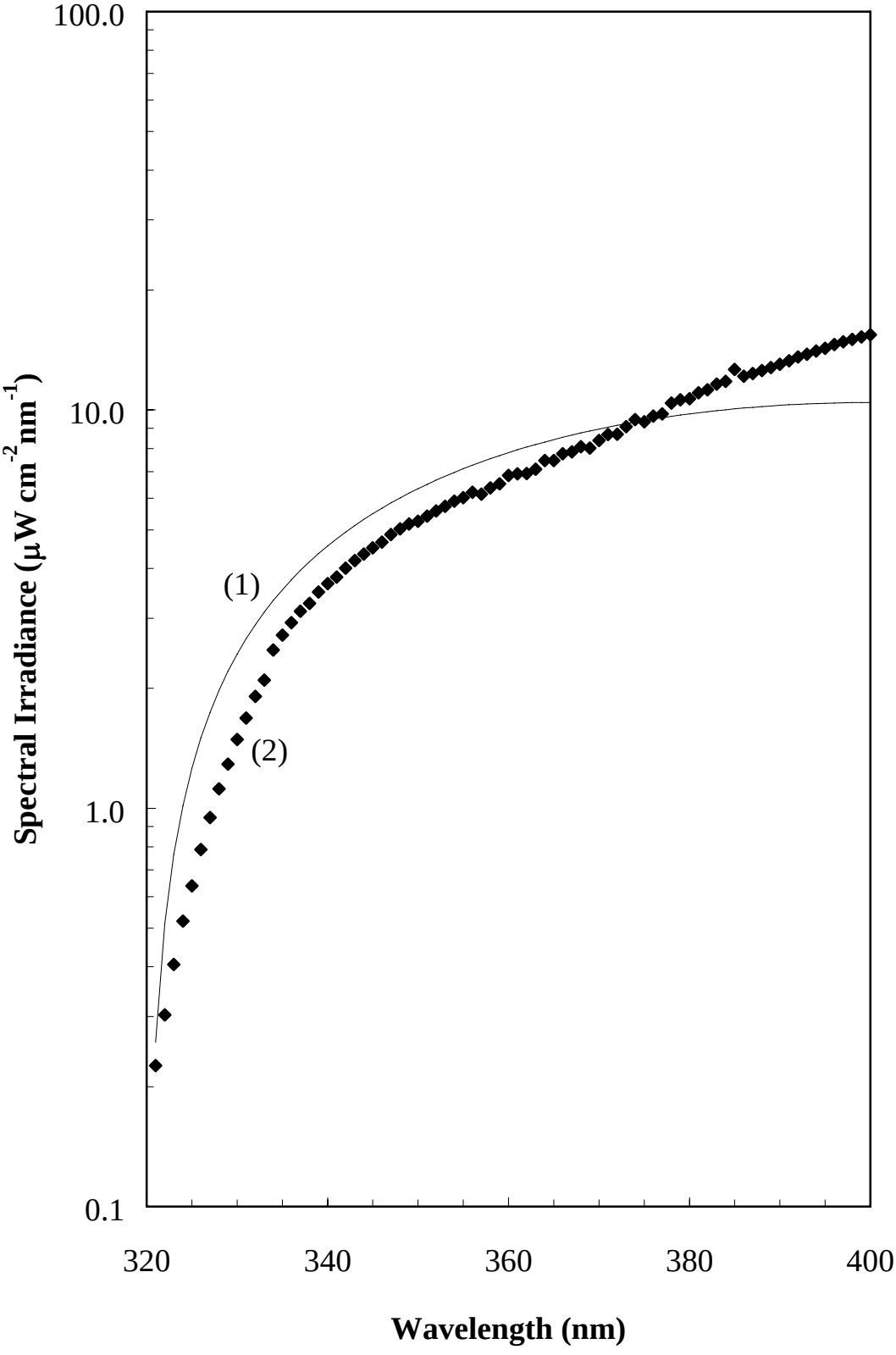
Table 4 Erythema UV for summer and winter solar measurements

Season	Erythema UV (μW cm^{-2})		
	Spectrum Evaluator	**Single Polysulphone**	**Spectro-radiometer**
Summer	23.2	25.0	25.1
Winter	10.4	7.8	9.7

Figure 1 - Spectral responses for (1) NDA, (2) 8MOP, (3) polysulphone and (4) phenothiazine.

Figure 2 - The (1) evaluated and (2) measured spectral irradiances for the quartz tungsten halogen lamp and filter system.




100.0
10.0
1.0
0.1
Spectral Irradiance (μW cm-2 nm-1)
(1)
(2)
320
340
360
380
400
Wavelength (nm)