ACTINIC ULTRAVIOLET EXPOSURES TO HUMANS

ASSESSED WITH A DOSIMETRIC TECHNIQUE

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Running title: Actinic Exposures to Humans

Abstract

A spectrum evaluator based on a system of four materials has been applied to the evaluation of actinic ultraviolet exposures to humans. The exposures were evaluated between early morning and near noon in summer and the actinic irradiances calculated ranged from 3 $\mu W\ cm^{-2}$ to 5 $\mu W\ cm^{-2}$. Simultaneously, the broad band irradiances which induced the actinic exposures and/or the biologically effective exposures for any other process may be evaluated with the method. The erythemal exposures ranged from 13 to 23 $\mu W\ cm^{-2}$. The method can be useful both for solar UV studies and research with UV lamps which possess radiation wavelengths shorter than 295 nm where the actinic and erythemal action spectra differ significantly.

Keywords: actinic; ultraviolet; erythema; dosimeters;

INTRODUCTION

Excessive exposure to ultraviolet (UV) radiation both from the sun and from artificial sources constitutes an environmental health hazard. In order to assess the effects of human exposure to UV radiation, knowledge of the UV source spectral irradiance is necessary in calculating the biologically effective irradiance (UV_{BE}) for a particular process. For a particular biological effect with an action spectrum A(λ), this is defined as:

$$UV_{BE} = \int_{UV} S(\lambda,t)A(\lambda)d\lambda \qquad (1)$$

where S(λ,t) is the source spectral irradiance. The CIE (1987) erythemal action spectrum for humans (Figure 1) has been employed widely for assessing the UV effect on human skin. The IRPA (1989) actinic action spectrum (Figure 1) has been employed for assessing the UV effects on both human skin and the human eye. The actinic action spectrum differs from the erythemal action spectrum significantly in the waveband shorter than 290 nm. The erythemal action spectrum is normalised to unity at 298 nm and the actinic action spectrum is normalised at 270 nm. For solar radiation, the energy spectrum cuts off at around 290 nm. Thus, the exposure to the erythemally effective irradiance is approximately proportional to the exposure due to the actinic irradiance. It is sufficient to use the erythemal exposure for assessing the hazard of solar UV. For a lamp source, the energy spectrum may consist of substantial amounts of radiation in the waveband shorter than 290 nm. As a result, the actinic exposure may differ significantly from the erythemal exposure.

To assess the actinic irradiance, the source spectrum may be measured with a spectroradiometer, then Eq. (1) may be used to calculate the irradiance. However, this

equipment is expensive, bulky and unsuitable for simultaneous multi-site measurements over the object of study. Alternatively, the UV_{BE} may be measured directly with sensors with a spectral response that approximates the actinic action spectrum. If the spectral response is substantially different from the actinic spectrum, then the sensor must be calibrated against the source prior to the measurement. This is not only inconvenient but also could be difficult as the source spectrum may vary with time.

Although polysulphone (Davis et al, 1976) and CR-39 dosimeters (Wong et al, 1989) are suitable for determining erythemal exposures, they are not suitable for the application of assessing actinic exposures if the source contains wavelengths shorter than 290 nm. There is no readily available dosimeter for measuring actinic exposures. No readily available dosimeter can evaluate the actinic exposure at any orientation or location over the object of study. Neither is it possible to obtain information about actinic and erythemal irradiances simultaneously with one dosimeter unless the spectral irradiance is measured with a spectroradiometer. In this paper, a method developed previously (Parisi et al, 1997) for assessing the erythemal UV exposure by the evaluation of the solar UV spectrum using a dosimetric technique is employed to evaluate the UV source spectrum, from which the actinic UV is calculated. Additionally, from the evaluated spectrum, the UV irradiance in any waveband and the erythemal irradiance or the UV_{BE} for any human biological process may be calculated.

METHODS

Spectrum Evaluation

The materials polysulphone, nalidixic acid (NDA), 8-methoxypsoralen (8MOP), and phenothiazine are sensitive to various wavebands of UV radiation and undergo a change in optical absorbance upon exposure. The spectral response of these materials (Parisi et al, 1997) extends over the entire ultraviolet waveband (200 – 400 nm). The substances employed in a thin film form of the order of 26 to 40 μm thick are mounted as described elsewhere (Parisi and Wong, 1996) in a holder 30 mm square with four holes of 6 mm diameter with a different material in each of the holes as shown in Figure 2. The holder is in the form of a sticky label folded in half and cut to size. The holes were punched with a hole punch constructed for this application that ensured the holes were at the same position for every holder. The materials were mounted over the holes in subdued lighting and stored in the dark till used. The system of four dosimeters will be referred to as a spectrum evaluator.

In each of the materials, exposure to UV radiation causes a deterioration that is quantified by measuring the change in optical absorbance, (ΔA) with a spectrophotometer. The wavelength selected for measuring ΔA is that at which the largest change occurs, namely, 330 nm for polysulphone and NDA, 305 nm for 8MOP and 280 nm for phenothiazine. In order to minimise errors due to any possible ‘dark reaction’ following exposure, it was necessary to standardise the readout times. In this case, the optical absorbance was measured immediately prior and post exposure. However, some other readout time may have been employed provided it was

maintained as constant. The change in optical absorbance for each material for an exposure period T, is given by:

$$\Delta A_i = T\int_{UV} \overline{S(\lambda)} R_i(\lambda) d\lambda \qquad (2)$$

where $\overline{S(\lambda)}$ is the source spectrum averaged over the exposure period and $R_i(\lambda)$ is the spectral response of each material. Knowledge of the response function and measurement of ΔA allows the evaluation of the source spectrum using a non-linear iterative technique described previously by Parisi et al. (1997). The four materials employed as dosimeters have been chosen as firstly, they possess different spectral responses and secondly they undergo a measurable ΔA within a short solar exposure period. The second is necessary as the method extracts a spectrum which is time averaged over the exposure period.

Solar Exposures

The spectrum evaluators were exposed on a white background at a number of periods to summer sunshine on 17 December 1994 at Brisbane, Australia within 30 cm of and at the same level as the input aperture of the integrating sphere of a double holographic grating spectroradiometer (Wong et al, 1995). This instrument has a calibration traceable to the primary Australian standard lamp housed at the National Measurement Laboratory, Lindfield, NSW, Australia. The spectroradiometer scan was started at the beginning of the exposure period for the dosimetric system. The uncertainty in measuring the solar spectral irradiance with the spectroradiometer is less than 5% (Wong et al, 1995).

Six exposure periods were employed between 08:54 and 13:08 Australian Eastern Standard Time (EST) with only light cloud during this period. A five minute exposure

period was chosen for the spectrum evaluators as a balance between producing a measurable ΔA and a period over which the change in the solar spectrum was minimised. The change in this period was less than 5% as measured by starting the scan of the spectroradiometer at consecutive four minute intervals.

The evaluated spectra were weighted according to Equation 1 with the action spectrum in Figure 1 for assessing human UV exposure to actinic radiation. As an example to illustrate the advantage of the spectrum evaluators in providing a knowledge of the source spectrum which can be employed to calculate the UV_{BE} for any biological process, the erythemal action spectrum in Figure 1 was employed to calculate the erythemal irradiances. Additionally, the spectra were integrated over the UVB, UVA and total UV wavebands to provide these broadband irradiances. These broadband irradiances and the biologically effective irradiances were compared to those obtained from the spectra measured with the calibrated spectroradiometer.

Lamp Actinic Exposures

The spectrum evaluator was applied in the laboratory to evaluate the spectrum from a quartz tungsten halogen lamp powered by a current regulated power supply at 9.5 A and producing an irradiance that contained wavelengths shorter than 290 nm. The experiment was performed at distances of 10 cm and 14 cm from the lamp filament.

RESULTS

Spectrum Evaluation

The solar UV spectrum evaluated at 13:08 EST on 17 December 1994 is presented in Figure 3 as the solid line. The square data points represent the spectra measured with

the calibrated spectroradiometer. This figure is provided as an example of the comparison of the evaluated and measured spectra. The extracted spectra are smoothed versions of the measured ones. For each exposure period, the differences between the two spectra were quantified as an 'integrated difference' by summing the absolute differences between the spectra at 1 nm intervals and dividing by the integrated spectral irradiance of the spectrum measured with the calibrated spectroradiometer. For each case, these differences were less than 20%.

Solar Exposures

The UVB, UVA and total UV irradiances calculated for both the evaluated and measured spectra are shown in Table 1 for the exposure periods on 17 December. The largest difference between the irradiances calculated with the evaluated and measured spectra is 20%. The actinic exposures evaluated with the spectrum evaluators have been compared in Table 2 with those calculated employing the spectra measured with the spectroradiometer. The largest difference between the actinic irradiances calculated from the evaluated and measured spectra is less than 20%. The spectral actinic irradiance is calculated for 11:39 EST on 17 December using both the evaluated and measured spectra and the two plotted for comparison in Figure 4. The advantage of the method for evaluating the UV_{BE} for any biological process has been illustrated by calculating, in this case, the erythemal irradiances for each of the exposure periods as shown in Table 2. As expected, due to the higher relative spectral effectiveness of the respective action spectra, the erythemal irradiances are higher than the actinic irradiances for each exposure period.

The distribution of the actinic and erythemal irradiances during the measurement period on 17 December are shown in Figure 5. The actinic irradiances increased from about 3 μW cm^{-2} at 08:54 EST to a peak of 5 μW cm^{-2} at 11:39 EST. Similarly, the erythemal irradiances increased from about 13 μW cm^{-2} to about 23 μW cm^{-2} over the same interval.

Lamp Actinic Exposures

The actinic irradiances calculated from the evaluated spectra for the quartz halogen lamp at distances of 10 cm and 14 cm are shown in Table 3. The ratio of the actinic irradiances to erythemal irradiances for the lamp is approximately 0.6 compared to approximately 0.2 for the solar UV spectra. This is due to the wavelengths shorter than 290 nm present in the lamp output.

DISCUSSION

A spectrum evaluator based on a dosimetric technique has been applied to the evaluation of the solar UV spectrum at a number of times in Brisbane, Australia. The integrated difference between the evaluated spectra and the spectra measured with a calibrated spectroradiometer was less than 20%. The result (Table 2) for solar exposure yields a ratio of erythemal irradiance to actinic irradiance. The mean ratio is 4.8 with a maximum deviation of 0.2. If this ratio is used to calculate the actinic exposure for the erythemal exposure tabulated in Table 3, it produces an error of more than 65%. This suggests that unless the action spectrum resembles the spectral response of the sensor, an error as high as 65% could be introduced for an uncalibrated source of radiation.

The evaluated spectra also allow the evaluation of the actinic irradiances to be used in assessing environmental human UV exposure. Conventional methods using electronic systems, for example spectroradiometers to measure the spectrum for calculating the actinic exposure are difficult to be used in the field because of their requirement for the supply of electric power to the instruments. The bulk and size of the equipment does not permit its attachment to the test body for measurements of solar spectra at selected sites for any selected orientation with respect to the direct sunlight. The method presented in this paper can be used to measure actinic exposures to humans at multiple sites simultaneously for any selected orientation with respect to the direct sunlight. The method is cost effective and rugged and ideal for application in field studies.

CONCLUSIONS

The actinic exposures obtained with the method presented in this paper cannot be provided with other dosimetric techniques such as polysulphone or CR-39 dosimeters or radiometric methods, for example, Robertson Berger meters. A further advantage of the method is that it is possible to extract the biologically effective exposure simultaneously for any other biological process, for example, erythema. This is useful both for solar UV studies and research with UV lamps that possess radiation wavelengths shorter than 295 nm where the actinic and erythemal action spectra differ significantly.

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Table 1 - UVB, UVA and total UV irradiances calculated from the spectra evaluated with the spectrum evaluator and spectra measured with the calibrated spectroradiometer.

Time of day EST	Evaluated irradiance ($\mu W\ cm^{-2}$)			Measured irradiance ($\mu W\ cm^{-2}$)		
	UVB	UVA	Total UV	UVB	UVA	Total UV
08:54	183	3785	3968	221	4206	4427
09:18	231	4605	4837	265	5013	5278
09:59	248	5075	5323	295	5282	5577
11:04	303	4899	5202	344	6156	6500
11:39	317	5131	5448	344	6114	6458
13:08	288	4655	4943	312	5640	5951

Table 2 - Actinic and erythemal irradiances obtained with the spectrum evaluator compared to those obtained with the spectroradiometer.

Time EST	Actinic irradiance ($\mu W\ cm^{-2}$)		Erythemal irradiance ($\mu W\ cm^{-2}$)	
	Spectrum Evaluator	Spectroradiometer	Spectrum Evaluator	Spectroradiometer
08:54	2.8	3.2	13	13
09:18	3.5	4.0	17	16
09:59	3.8	4.6	18	18
11:04	4.5	5.6	22	22
11:39	4.8	5.7	23	22
13:08	4.3	4.9	21	20

Table 3 – Actinic and erythemal irradiances for the quartz tungsten halogen lamp.

Lamp height (cm)	Actinic Irradiance ($\mu W\ cm^{-2}$)	Erythemal irradiance ($\mu W\ cm^{-2}$)
10	27	43
14	11	18

FIGURE CAPTIONS

Figure 1 – (1) Erythema action spectrum (CIE, 1987) and (2) actinic action spectrum (IRPA, 1989).

Figure 2 - Spectrum evaluator of the dosimeter materials NDA, polysulphone, 8MOP and phenothiazine (Parisi and Wong, 1996).

Figure 3 - Evaluated (—) and measured (◆) solar UV spectra at 13:08 EST on 17 December 1994.

Figure 4 - Spectral actinic irradiance at 11:39 EST calculated with the evaluated (—) and measured solar (◆) spectra.

Figure 5 - Distribution of erythemal and actinic irradiances on 17 December 1994 calculated using the evaluated (□) and measured (◆) spectra.

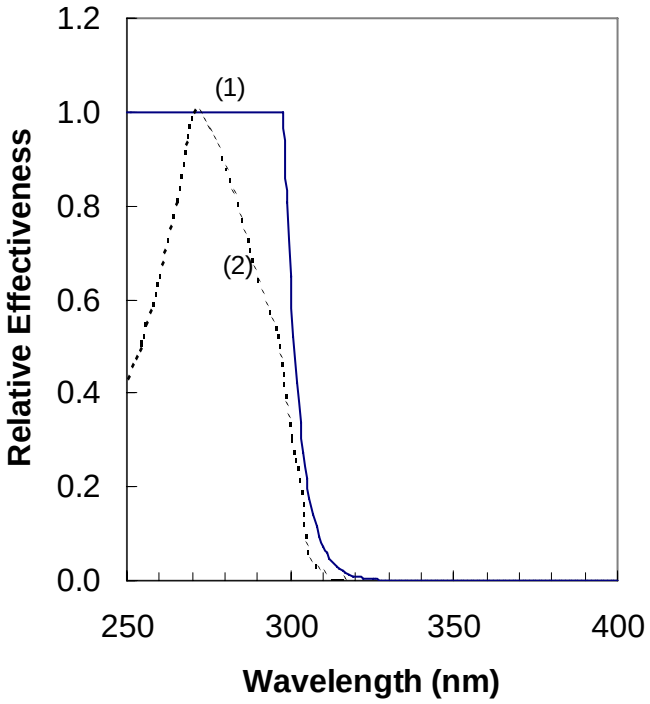
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Relative Effectiveness
(1)
(2)
250
300
350
400
Wavelength (nm)

Figure 1

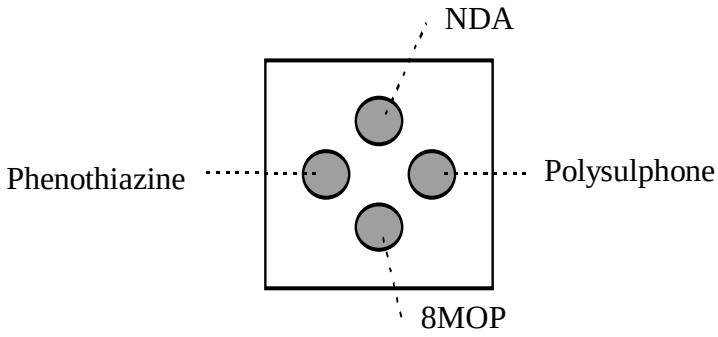

Figure 2.

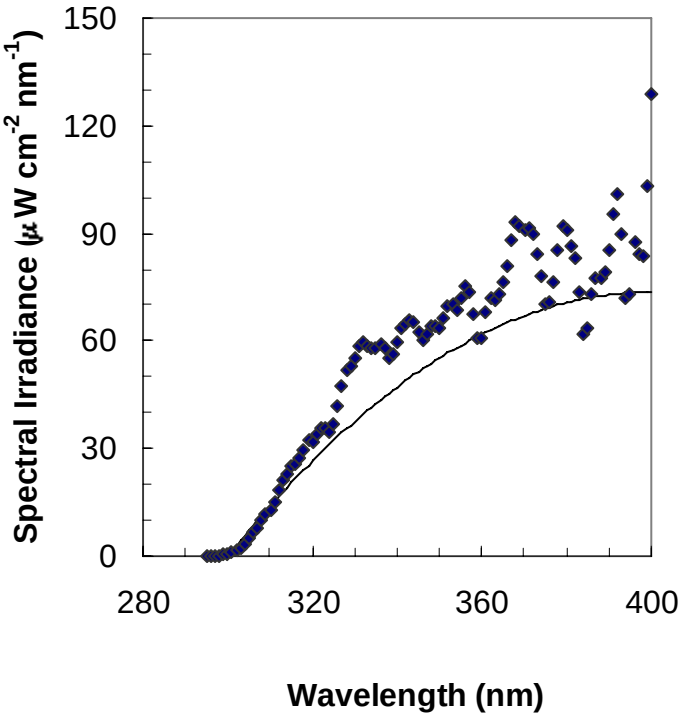
150
120
90
60
30
0
280
320
360
400
Spectral Irradiance (μW cm-2 nm-1)
Wavelength (nm)

Figure 3

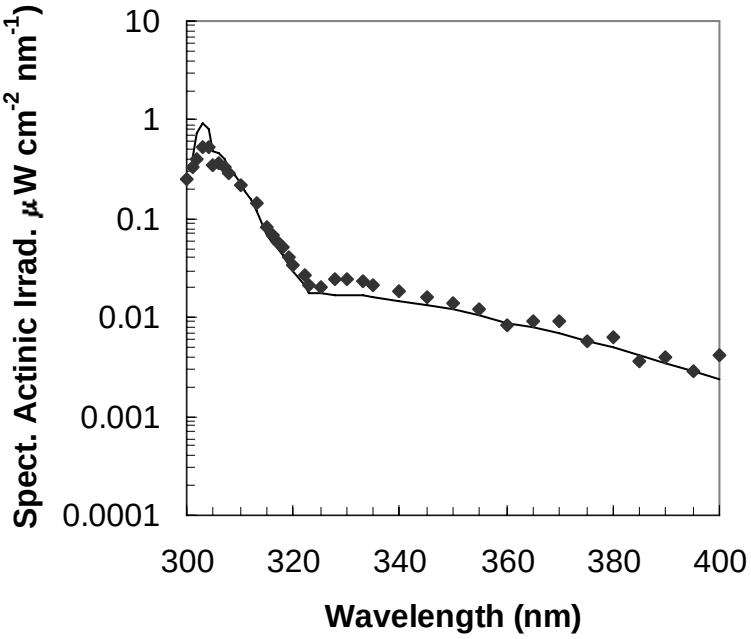
Spect. Actinic Irrad. μW cm-2 nm-1)
10
1
0.1
0.01
0.001
0.0001
300
320
340
360
380
400
Wavelength (nm)

Figure 4

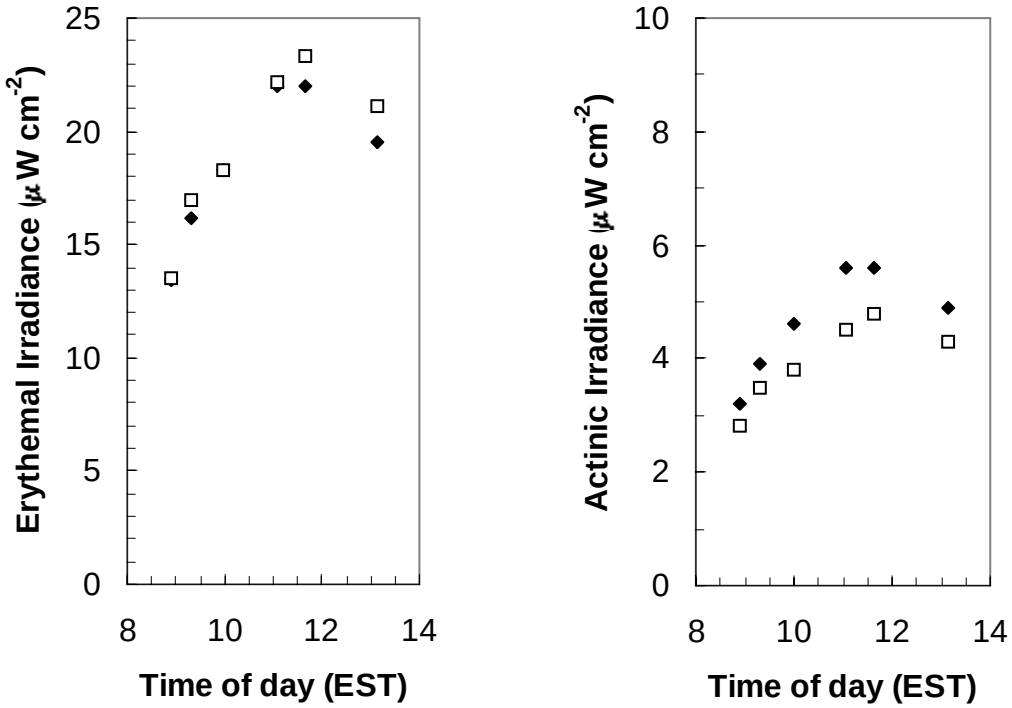
Erythemal Irradiance (μW cm-2)
25
20
15
10
5
0
8
10
12
14
Time of day (EST)
Actinic Irradiance (μW cm-2)
10
8
6
4
2
0
8
10
12
14
Time of day (EST)

Figure 5