

**A NEW METHOD FOR MEASUREMENTS
OF ERYTHEMAL IRRADIANCE**

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Abstract

A composite system of the four dosimeter materials, nalidixic acid (NDA), polysulphone, 8-methoxypsoralen (8-MOP) and phenothiazine, is presented for the passive measurement of the UV spectrum. The properties of the materials were investigated and found to be suitable to allow the materials to be applied in a system to evaluate the UV spectrum. The evaluation of the spectrum reduces the errors by 70% arising when only polysulphone dosimeters are employed to measure the exposure due to a source spectrum that differs from the spectrum they have been calibrated against. Knowledge of the spectrum provides an advantage over the Robertson-Berger meter and polysulphone dosimeters as the biologically effective exposure for any biological process may be calculated with better than 20% accuracy. The composite system was miniaturised to a size of 3 cm x 3 cm to eliminate errors due to spatial variation of the spectrum and to allow the application at any site on objects with complicated topography in a similar way as polysulphone dosimeters. Unlike the polysulphone dosimeters, the composite system does not require calibration against a specific source of UV in order to maintain a high degree of accuracy in the collected data.

Keywords: ultraviolet radiation; ultraviolet dosimetry; UV spectrum; spectrum evaluation; erythema irradiance

INTRODUCTION

The depletion of stratospheric ozone over both the Northern and Southern Hemispheres has been confirmed by various studies (1,2). This is generating concerns about increases in terrestrial UV and associated adverse effects on humans, plants and animals. Studies of these effects requires the measurement of UV radiation exposure. Passive dosimeters employing materials such as polysulphone and allyl diglycol carbonate (CR-39) have been previously tested for the measurement of UV exposures (3,4). These passive dosimeters have been applied to the measurement of erythema exposure to humans (5,6) and UV exposure to plants (7).

However, the spectral responses of polysulphone and CR-39 do not exactly match the erythema action spectrum. This is illustrated in Figure 1 where the response of polysulphone (8) is approximately the same shape as the erythema action spectrum (9) but is offset to higher wavelengths by approximately 20 nm. Similarly, the spectral response of CR-39 (4) and the Robertson Berger (RB) meter (10) do not exactly match the erythema action spectrum. As a result, if the UV spectrum changes from that for which they were calibrated or if they are used to measure radiation from different artificial sources, the errors associated with the usage of single passive dosimeters or RB meters may be very significant (11). For solar radiation, the error caused by the variation due to the change in the solar spectrum may be as high as 40% (12). Variations in the solar UV spectrum arise due to changes with time and place for the case of solar UV. For artificial UV, possible sources are fluorescent sunlamps, incandescent lamps, gas discharge arcs, welding arcs and lasers, with each possessing a different UV spectrum. The source spectrum of each of these varies significantly from one another and from the solar UV spectrum. Consequently to avoid unacceptably high errors, the usage of polysulphone to measure exposures from these sources requires calibration against a calibrated spectroradiometer for the specific source employed. This should be repeated for each usage to account for variations in the spectrum as a result of changes in lamp output due to ageing and power supply output.

This paper investigates and describes the properties of a new type of composite dosimetric system consisting of the four materials polysulphone, nalidixic acid (NDA), 8-methoxypsoralen (8-MOP) and phenothiazine for evaluating the UV spectrum. The materials have been previously employed individually to measure UV exposures, but never as a composite system to evaluate the source spectrum. In order for the materials to be suitable for this new device, the materials must have certain properties, namely: undergo a change in optical absorbance as a result of UV exposure; the change in optical absorbance must be reproducible; the effects of storage must be known; the dose response must be unaffected by temperature and dose rate; the dose response must be monotonic within the exposure range of interest; the dose response of the materials must be of the same order of magnitude and the spectral responses of the materials must be known with the combined spectral response covering the entire UV waveband. These properties will be investigated in this paper. Examples of the evaluation of UV spectra and determination of erythema exposure will be presented and compared to the erythema irradiance measured with polysulphone dosimeters and a RB meter.

MATERIALS AND METHODS

Dosimeters

The materials polysulphone (3), nalidixic acid (NDA) (13), 8-methoxypsoralen (8-MOP) (14) and phenothiazine (15) (supplied by A Davis, 3 Cumley Rd., Toothill, Ongar, Essex, CM5 9SJ, UK) have been employed in thin sheet form with a thickness of the order of 26 to 40 μm . The thin film dosimeters are no longer available from this supplier, however they can be produced in the School of Physics, Queensland University of Technology, Brisbane, Australia. Upon exposure to UV radiation, each of the materials undergoes deterioration. The degree of deterioration is quantified by measuring the change in optical absorbance (ΔA) with a spectrophotometer. In order to eliminate any errors due to minor variations over the surface of the film, the dosimeter materials are repositioned at the same point with respect to the beam of the spectrophotometer by employing a holder designed and built specifically for the purpose. All exposures have been performed with the dosimeter material on a white backing.

The wavelength at which the maximum ΔA occurs was determined by measuring the optical absorption spectrum in the waveband 250 to 400 nm with a spectrophotometer (Shimadzu Co., Kyoto, Japan) prior and post UV exposure. A wavelength in the region where the maximum ΔA occurs was selected as the wavelength for the operation of the spectrophotometer for each material. The absorbance of a batch of 25 dosimeters of each material was measured at these wavelengths in order to determine the variation in the films.

Reproducibility

The reproducibility of ΔA of the dosimeter materials for a fixed UV exposure was investigated by exposing a number of films from the same batch to UV radiation from a quartz tungsten halogen (QTH) lamp (model GEC-A1/235, Lawrence and Hanson Co., Mort St., Toowoomba, 4350, Australia) for thirty minutes at a distance of 10 cm above the dosimeters. The lamp was powered by a current regulated power supply (model TPS 23010, manufactured by Topward Electric Instruments; supplied by Nilsen Instruments, 11 Ross St., Brisbane, 4006, Australia) at 9.5 A. The temperature during the exposures was maintained at 38 ± 2 °C. The optical absorbance of the dosimeters was measured immediately prior and post exposure.

Effect of Storage

The dark reaction or the stability following exposure to UV of the four dosimeter materials was investigated by exposing the dosimeters to UV from the QTH lamp and the optical absorbance measured prior to and immediately post exposure. In order to increase the reliability of measurements, the absorbance was measured at four sites over the dosimeter surface. The absorbance was also measured following intervals of 24 hours, 3 days and 7 days storage in the dark at room temperature.

Effect of temperature

The effect of temperature on the response of the dosimeter materials has been investigated by irradiating the materials with the QTH lamp for thirty minutes at three temperatures between 34.5 °C and 62.5 °C. The various temperatures were maintained by blowing either cool air or warm air across the materials. The temperatures were

measured with a thermocouple placed at the same site as the materials. The experiment was repeated three times to confirm the results.

Dose rate

In order for the materials to be suitable as UV dosimeters, the change in optical absorbance must be independent of dose rate. To investigate this, each material has been irradiated with five different dose rates to provide a total UV exposure of 1.45 J cm^{-2} . The exposures were obtained with the QTH lamp at distances of 8, 10, 12, 14 and 16 cm providing total UV dose rates of 1.2, 0.81, 0.63, 0.46 and 0.38 mW cm^{-2} respectively as previously measured with a calibrated spectroradiometer. A constant temperature of $45 \pm 1 \text{ }^\circ\text{C}$ was maintained during the exposure periods. The output of the lamp was measured with a double holographic grating spectroradiometer (12). The spectroradiometer was calibrated prior to use with a secondary standard lamp calibrated against a primary standard which had been calibrated with the Australian standard lamp housed at the CSIRO National Measurement Laboratory, Lindfield, Australia.

Dose Response

The materials were exposed for a series of exposure times to summer solar UV in Brisbane, Australia between 08:22 and 13:53 EST on 17 December, 1994 under a clear sky. The exposures were measured with a spectroradiometer scanning at intervals over the waveband 280 to 400 nm. The total UV dose over a period, T, is provided by:

$$\text{Dose} = \int_0^T \int_{\text{uv}} S(\lambda, t) d\lambda dt \quad \text{J cm}^{-2} \quad (1)$$

where $S(\lambda, t)$ is the spectral irradiance measured by the spectroradiometer and the wavelength integration interval covers the UV waveband of interest, in this case, 280 to 400 nm. The spectroradiometer measures the spectral irradiance in finite wavelength increments, $\Delta\lambda$, and employing $S(\lambda)$ as the time averaged spectrum between successive scans, Equation (1) becomes:

$$\text{Dose} = T \sum_{280}^{400} S(\lambda) \Delta\lambda \quad \text{J cm}^{-2} \quad (2)$$

Measurement of the UV doses in this manner along with the change in optical absorbance allows the dose response of each material to be determined.

Spectral Response

The spectral response, $R(\lambda)$, of a material gives the change in optical absorbance for the different materials due to unit irradiance in the wavelength interval λ to $\lambda + d\lambda$. The spectral response was measured by irradiating the material with a known monochromatic dose of UV radiation followed by measurement of the change in absorbance of the material at that wavelength. The doses applied were less than 0.6 J cm^{-2} and were within the region of linear dose response. The UV source was a fan cooled xenon mercury lamp powered by an LPS255 HR universal arc lamp power supply (supplied by Spectral Energy Co., 57 Woodland Ave., Westwood, NJ, 07675, USA). The lamp was powered by 23 A at 21 VDC. A monochromatic beam was produced by a monochromator (model GM252, Spectral Energy Co., 57 Woodland Ave., Westwood, NJ, 07675, USA). The input and output slits of the monochromator were set to 0.5 mm to provide a peak with a bandwidth of 2 nm at FWHM. The output of the monochromator at each wavelength setting was measured with a

spectroradiometer based on a dual grating monochromator (model H10DUV, Jobin Yvon Co., 16-18 rue du Canal, France) controlled by a Data Scan 2 controller.

UV Measurements

For each type of dosimeter material exposed to a source spectrum of $S(\lambda)$ over a time interval, T , the change in optical absorbance, ΔA_i is given by:

$$\Delta A_i = T \int_{UV} S(\lambda) R_i(\lambda) d\lambda \quad i = 1, \dots, 4 \quad (3)$$

where $R_i(\lambda)$ is the spectral response or wavelength sensitivity of the material and the subscript designates one of the four different types of dosimeter material used. A predicted value for the change in absorbance, ΔA_i , for each dosimeter was calculated using an assumed function for the source spectrum of the form:

$$S(\lambda) = (\lambda - \lambda_0) * \left(\sum_{i=1}^n a_i \lambda^{i-1} \right) \quad (4)$$

where the parameters, a_i of the assumed $S(\lambda)$ were found by an iterative method (16) to minimise the least squares function, χ^2 , defined by:

$$\chi^2 = \sum_{i=1}^4 \frac{1}{\sigma_i^2} (\Delta A_i - \Delta A_i')^2 \quad (5)$$

where σ_i is the error in ΔA_i . The assumed function for $S(\lambda)$ was constrained to possess a root at λ_0 , the value of which was determined from a knowledge of the wavelength for which the source irradiance was zero. The value of n in Equation (4) was determined by an F test (16) which was used to calculate if there was a statistically significant improvement in χ^2 if the order of the fitted function was increased by one.

The four dosimeter materials have been placed in a single holder 30 mm x 30 mm. This has placed the materials in close proximity to one another and ensures that the possible errors due to spatial variation of the spectrum are eliminated. The holder is in the form of a sticky label folded in half and cut to size with four holes of 6 mm diameter with a different material in each of the holes as shown in Figure 2. The holes were punched with a specifically designed and constructed hole punch that used a positioning slot to ensure the holes were in the same position for every holder. The materials were handled with tweezers and mounted over the holes in subdued lighting and stored in the dark till used. This miniaturisation will also allow the dosimetric system to be applied at any site on objects with complicated topography.

The system of four dosimeters has been applied to evaluate the solar UV spectrum and the spectrum from the QTH lamp and the evaluated spectra compared to those measured with the calibrated spectroradiometer. For the solar spectrum the dosimeters have been exposed for five minutes to summer UV in Brisbane, Australia on 15 December, 1994. The period of five minutes is a compromise between producing a measurable change in optical absorbance and short enough to minimise the temporal variation in the solar spectrum. For the QTH lamp, the dosimeters have been exposed for 52.9 minutes with the lamp at a distance of 14 cm. The erythemal exposures calculated from these have been compared to those obtained with polysulphone dosimeters and with the spectra measured with the calibrated spectroradiometer. The polysulphone has been calibrated for erythemal exposure on 17 December, 1994 by

measuring the solar UV spectrum with the spectroradiometer and the erythema exposure calculated by:

$$UV_{ery} = \int_0^T \int_{uv} S(\lambda, t) A(\lambda) d\lambda dt \quad J \text{ cm}^{-2} \quad (6)$$

where $A(\lambda)$ is the erythema action spectrum shown in Figure 1.

In a similar fashion, the dosimetric system has been exposed at 10:36 and 12:36 EST in late autumn on 25 May, 1995 and the erythema exposure determined. This erythema exposure has been compared to that obtained with a single polysulphone dosimeter employing the calibration for erythema exposure on 17 December, 1994 and with the erythema exposure measured with the RB meter (model 2D, Solar Light Co., 6655 Lawton Ave., PA, 19126 USA) calibrated by the supplier.

RESULTS

Dosimeters

The absorption spectra of the four materials are plotted in Figure 3. These results show that for a given UV exposure, the phenothiazine undergoes the largest change in absorption. The phenothiazine film developed a yellowish hue that became more intense with increasing exposure whereas there was no visible change for the other materials. In the literature the values of ΔA are measured at 330 nm for polysulphone and NDA, 305 nm for 8-MOP and 280 nm for phenothiazine. The results in Figure 3 show that the maximum ΔA occurs at a wavelength corresponding approximately to these wavelengths. Consequently, these wavelengths will be used for the measurement of ΔA in this research. At the selected measurement wavelengths, polysulphone and phenothiazine undergo an increase in absorption and NDA and 8-MOP undergo a decrease.

The results of the absorbance of 25 of the four dosimeter materials are provided in Table 1 with the error represented as one standard deviation. This range is due to variations in the film. The variation in the absorbance of the unexposed film will be greater between batches and is due to a number of parameters such as variation in film thickness, composition and a number of other variables. This variation is taken into account by measuring the absorbance of each dosimeter prior to exposure.

Reproducibility

The results of exposing seven films of polysulphone, NDA, 8-MOP and phenothiazine to the same exposure are presented in Table 2. From the results, the variations are: polysulphone, 4%, NDA, 7%, 8-MOP, 5% and phenothiazine, 13%. Phenothiazine displays the largest variation for the same exposures. In the literature (17), the variation for polysulphone was 1.4% with no data available for the other materials.

Effect of Storage

The results of the effects of storage on the change in optical absorbance for each material are presented in Table 3. The columns A1 and A2 represent the absorbances pre and post exposure. These are the means of the four readings over the dosimeter surface. The final four columns are the ΔA values as a function of storage time. Each ΔA value and associated error represents the average and the standard deviation of the

change in optical absorbance measured at four sites over the dosimeter material. The experiment has been repeated with similar results

From the results, polysulphone undergoes a dark reaction or change in absorbance with storage. In this case, the absorbance increased by 4% after 24 hours and 5.5% after 7 days. This is in agreement with the results previously reported in the literature, namely, an increase in absorbance by 4% after 24 hours and 5% after 7 days (3,18). The results indicate that NDA and 8-MOP also undergo a dark reaction. An increase in absorbance of less than 10% for several weeks storage at room temperature has previously been reported for NDA (13). The dark reaction for 8-MOP has not been investigated in the literature. The results show that phenothiazine does not undergo a dark reaction. The dark reaction of phenothiazine has not been investigated in the literature.

In order to overcome errors due to these dark reactions, standardisation of the read-out time following exposure is necessary (17). For this paper, all of the optical absorbances for the materials are measured immediately prior and post exposure. An alternate read-out time may be employed provided it is maintained as constant.

Effect of Temperature

The results of the effects of temperature are presented in Table 4. The results are the means over the three experiments with the error represented as one standard deviation. Over the temperature range investigated, no significant effect was detected in dose response for polysulphone and 8-MOP. The results of polysulphone confirm literature findings (17,19) where polysulphone was irradiated at temperatures between -4°C and 85°C with no detected variation in film response. The results for phenothiazine show that there is no effect up to 50°C , but there is a repeatable increase in dose response at higher temperatures. The effects of temperature on 8-MOP and phenothiazine have not been reported in the literature. For NDA there is an increase in dose response with temperature over the temperature range investigated. A linear least squares regression fitted to the NDA data provides an increase with temperature in the change in absorbance of $0.001^{\circ}\text{C}^{-1}$. The temperature effects on NDA have been investigated by storing dosimeters at 50°C and -15°C prior to exposure (13). However, the effects of variations in temperature during exposure have not been reported. The temperature effects on NDA can be minimised by usage of the material at temperatures in the mid thirties. These can be maintained by performing the irradiation in the open or in well ventilated conditions.

Dose Rate

The results for dose rate independence are presented in Figure 4. The errors associated with each value of ΔA are represented as 10%. This value was obtained by consideration of the reproducibility of the change in absorbance discussed above and other research in the literature with polysulphone (5). The dose responses of the materials are independent of dose rates between 0.38 and 1.2 mW cm^{-2} . This is consistent with results previously reported in the literature for polysulphone (3), phenothiazine (15) and 8-MOP (14). No dose rate experiments have been reported for NDA.

Dose Response

The results of measuring the change in optical absorbance as a function of UV exposure for each material are provided in Figure 5. The dose response for phenothiazine indicates that total UV exposures above 10 J cm^{-2} produce a negligible change in absorbance. For all of the materials, the slope of the calibration curve decreases at higher doses. The error associated in using the materials for doses where the slope of the calibration curve is small becomes larger. Consequently the dosimeters should be utilised only for doses where the dose response curve is monotonically increasing. In this paper, the dosimeters have been exposed to five minutes summer and autumn sunshine, a dose of less than 2 J cm^{-2} which is in the region of linear dose response.

Spectral Response

The results are plotted in Figure 6 and show that NDA has a peak response at approximately 325 nm and is sensitive to wavelengths up to 350 nm, 8-MOP responds to wavelengths up to 370 nm, polysulphone has a high spectral response in the UVC and UVB with a rapid drop for wavelengths longer than 320 nm and phenothiazine responds to all UV wavelengths with a peak at approximately 320 nm. Notice also that the same dose produced a different peak response for each material. Phenothiazine is the most sensitive and 8-MOP is the least sensitive.

Table 5 provides a summary of the wavelength characteristics of each of the materials. Column 2 is the wavelength for measuring the change in absorbance for each material. Column 3 is the approximate wavelength at which a peak occurs in the spectral response and column 4 is the wavelength band to which the material responds.

UV Measurements

The UV spectra evaluated with the system of four dosimeters for a solar exposure at 10:23 EST on 15 December, 1994 and for the QTH lamp at 14 cm are shown in Figure 7 along with the respective spectra measured with the calibrated spectroradiometer. The 'integrated difference' between the evaluated and measured spectra was calculated by summing in 1 nm steps the absolute difference between the measured and evaluated spectra and dividing by the summed irradiance of the measured spectrum. This difference is less than 20% for the solar spectrum and less than 10% for the lamp spectrum. The erythemal irradiances calculated from the evaluated spectra for the solar exposures on 15 December, 1994 and 25 May, 1995 and for the QTH lamp are provided in Table 6. These differ by less than 11% from the erythemal exposures calculated from the spectra measured with the spectroradiometer. The values obtained by employing polysulphone dosimeters calibrated on 17 December to measure erythemal irradiances are shown in the third column. The data collected with the RB meter is provided in the next column. No data was collected with the RB meter on 15 December, 1994.

The data collected on 25 May, 1995 and for the QTH lamp illustrates the necessity of calibrating polysulphone dosimeters and RB meters to the source spectrum they will be exposed to and highlights the advantage of the method used in this paper. For the solar exposures, the results obtained employing polysulphone dosimeters and the RB meter differ by up to 24% compared to the spectroradiometer data. In contrast, the erythemal irradiance evaluated with the four dosimeters is within 11% of the

spectroradiometer data. For the QTH lamp, the erythema exposure calculated with the evaluated spectrum (Table 6) provides an improvement by a factor of five compared to the erythema exposure obtained with the polysulphone dosimeter calibrated for summer solar UV. The usage of the system of four dosimeters eliminates the requirement to calibrate the dosimeters with the UV source that will be employed.

CONCLUSION

The properties of a composite dosimetric system comprising of polysulphone, NDA, 8-MOP and phenothiazine for the evaluation of the UV spectrum have been investigated. The four materials were found to possess suitable properties and allowed evaluation of the solar UV spectrum at a number of times along with the spectrum from an artificial source. The method can be applied to measure personal biologically effective (e.g. erythema) exposure to UV radiation due to a source with any type of source spectrum with an accuracy of better than 20%. The process of the dosimetric system is similar to that of polysulphone and the resulting spectrum is deduced by entering the measured changes of absorbance into a computer program. The entire procedure requires only several minutes to complete. Unlike the polysulphone dosimeters, the composite system does not require calibration against a specific source of UV in order to maintain a high degree of accuracy in the collected data. The system of dosimeters is sensitive to the entire UV waveband. The variation in the source spectra was greater than the differences between the measured and evaluated spectra of 20% for the solar spectra and 10% for the lamp spectrum. The errors with the polysulphone dosimeters and the RB meters change as the source spectrum varies and can become unacceptably large. In the examples provided in this paper, the errors due to changes in the solar spectrum were 24% for polysulphone and the RB meter. The error when polysulphone calibrated for summer solar UV was employed to measure the erythema exposure due to a QTH lamp was unacceptably high at 89%. The authors suggest that the errors would be as high for other artificial sources such as welding arcs and suntanning lamps. The method presented in this paper has been shown to overcome this problem and as a result the method provides a more accurate method for measurements of exposures from all types of UV sources, including artificial UV sources such as suntanning devices.

Another advantage of this method of measuring UV exposures is that it produces an evaluation of the spectrum. This represents an improvement over the RB meter and single dosimeters such as polysulphone and CR-39. A knowledge of the spectrum also allows the biologically effective irradiance to be calculated for any action spectrum other than for erythema.

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REFERENCES

1. Stolarski R, Bojkov R, Bishop L, Zerefos C, Staehelin J, Zawodny J. Measured trends in stratospheric ozone. *Science* 1992; **256**: 342-349.
2. Frederick JE, Diaz SB, Smolskaia I, Esposito W, Lucas T, Booth CR. Ultraviolet solar radiation in the high latitudes of South America. *Photochem Photobiol* 1994; **60**: 356-362.
3. Davis A, Deane GHW, Diffey BL. Possible dosimeter for ultraviolet radiation. *Nature* 1976; **261**: 169-170.
4. Wong CF, Fleming R, Carter SJ. A new dosimeter for ultraviolet-B radiation. *Photochem Photobiol* 1989; **50**: 611-615.
5. Wong CF, Fleming RA, Carter SJ, Ring IT, Vishvakarman D. Measurement of human exposure to ultraviolet-B solar radiation using a CR-39 dosimeter. *Health Phys* 1992; **63**: 457-461.
6. Herlihy E, Gies PH, Roy CR, Jones M. Personal dosimetry of solar UV radiation for different outdoor activities. *Photochem Photobiol* 1994; **60**: 288-294.
7. Parisi AV, Wong CF. A dosimetric technique for the measurement of ultraviolet radiation exposure to plants. *Photochem Photobiol* 1994; **60**: 470-474.
8. CIE (International Commission on Illumination) Technical Report. Personal dosimetry of UV radiation. 1992: Publication No. CIE **98**.
9. CIE (International Commission on Illumination) Research Note. A reference action spectrum for ultraviolet induced erythema in human skin. *CIE J* 1987; **6**: 17-22.
10. DeLuisi J, Wendell J, Kreiner F. An examination of the spectral response characteristics of seven Robertson-Berger meters after long-term field use. *Photochem Photobiol* 1992; **56**: 115-122.
11. Diffey BL. Possible errors involved in the dosimetry of solar UV-B radiation. In Worrest RC, Caldwell MM, ed. *Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life*. Berlin: Springer-Verlag, 1986: 75-86.
12. Wong CF, Toomey S, Fleming RA, Thomas BW. UV-B radiometry and dosimetry for solar measurements. *Health Phys* 1995; **68**: 175-184.
13. Tate TJ, Diffey BL, Davis A. An ultraviolet radiation dosimeter based on the photosensitising drug, Nalidixic Acid. *Photochem Photobiol* 1980; **31**: 27-30.
14. Diffey BL, Davis A. A new dosemeter for the measurement of natural ultraviolet radiation in the study of photodermatoses and drug photosensitivity. *Phys Med Biol* 1978; **23**: 318-323.
15. Diffey BL, Davis A, Johnson M, Harrington TR. A dosimeter for long wave ultraviolet radiation. *Br J Derm* 1977; **97**: 127-130.
16. Bevington PR, Robinson DK. *Data Reduction and Error Analysis for the Physical Sciences*. New York: McGraw-Hill, 1992: 141-167.
17. Diffey BL. Ultraviolet radiation dosimetry with polysulphone film. In: Diffey BL, ed. *Radiation measurement in photobiology*. New York: Academic Press, 1989: 136-159.
18. Diffey BL. A comparison of dosimeters used for solar ultraviolet radiometry. *Photochem Photobiol* 1987; **46**: 55-60.
19. Diffey BL. Personal ultraviolet radiation dosimetry with polysulphone film badges. *Photoderm* 1984; **1**: 151-157.

Table 1 - Variation of the absorbance prior to exposure of a batch of dosimeters

Polysulphone	NDA	8-MOP	Phenothiazine
0.235 ± 0.008	1.475 ± 0.116	1.085 ± 0.133	0.525 ± 0.038

Table 2 - Reproducibility of the change in absorbance for the same UV exposure.

Exposure	Polysulphone ΔA_{330}	Nalidixic acid ΔA_{330}	8-MOP ΔA_{305}	Phenothiazine ΔA_{280}
1	0.051	0.041	0.060	0.306
2	0.055	0.041	0.062	0.295
3	0.052	0.046	0.062	0.322
4	0.050	0.046	0.056	0.395
5	0.050	0.038	0.061	0.329
6	0.053	0.041	0.065	0.382
7	0.050	0.045	0.059	0.286
Mean \pm 1 SD	0.051 \pm 0.002	0.042 \pm 0.003	0.061 \pm 0.003	0.331 \pm 0.042

Table 3 - Change in ΔA with storage time.

Material	A1	A2	Storage time (days)			
			0	1	3	7
Polysulphone	0.268	0.328	0.060±0.001	0.072±0.001	0.074±0.001	0.078±0.002
NDA	1.529	1.483	0.046±0.002	0.043±0.003	0.042±0.003	0.039±0.002
8-MOP	1.323	1.260	0.063±0.002	0.054±0.003	0.053±0.002	0.047±0.002
Phenothiazine	0.467	0.833	0.366±0.009	0.357±0.010	0.361±0.011	0.362±0.011

Table 4 - The effects of temperature during the UV exposure.

Material	Change in absorbance ΔA at each temperature		
	34.5 \pm 1.3 °C	48.0 \pm 0.7 °C	61.3 \pm 0.9 °C
Polysulphone	0.061 \pm 0.003	0.064 \pm 0.005	0.065 \pm 0.003
NDA	0.035 \pm 0.004	0.055 \pm 0.006	0.068 \pm 0.005
8-MOP	0.016 \pm 0.003	0.016 \pm 0.002	0.018 \pm 0.002
Phenothiazine	0.37 \pm 0.05	0.42 \pm 0.02	0.62 \pm 0.04

Table 5 - Summary of the wavelength characteristics of the materials.

Material	λ_{measure} (nm)	Peak response (nm)	Response waveband
Polysulphone	330	280 to 310	Up to 340 nm
NDA	330	325	Up to 350 nm
8-MOP	305	280	Up to 370 nm
Phenothiazine	280	310 to 325	All UV wavelengths

Table 6 - Results of erythemat irradiances obtained with the four dosimeters compared to those with a polysulphone dosimeter, RB meter and spectroradiometer (SR).

Source	Erythemat Irradiance ($\mu\text{W cm}^{-2}$)			
	Four dosimeters	Polysulphone	RB meter	SR
Solar 15/12/94 at 10:23	24.3	25.2	-	23.7
Solar 15/12/94 at 11:53	25.2	28.1	-	25.3
Solar 25/05/95 at 10:36	8.6	7.8	7.4	9.7
Solar 25/05/95 at 12:36	8.6	6.7	8.0	8.8
QTH lamp at 14 cm	18.5	2.5	-	22.6

Figure 1 - (1) Erythema action spectrum, (2) spectral response of polysulphone, (3) spectral response of CR-39 and (4) response of the RB meter.

Figure 2 - Dosimetric system of the materials NDA, polysulphone, 8-MOP and phenothiazine.

Figure 3 - Absorption spectra (1) pre and (2) post exposure to UV for NDA, polysulphone, 8-MOP and phenothiazine.

Figure 4 - The change in optical absorbance for various dose rates.

Figure 5 - Change in optical absorbance, ΔA as a function of the total UV exposure for NDA, polysulphone, 8-MOP and phenothiazine.

Figure 6 - Spectral responses obtained with the irradiation monochromator for (1) polysulphone, (2) NDA, (3) 8-MOP and (4) phenothiazine.

Figure 7 - The (1) measured and (2) evaluated spectrum for a summer solar exposure and the (3) measured and (4) evaluated spectrum for the QTH lamp at a distance of 14 cm.













