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Ultraviolet radiation dosimetry with radiochromic film

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Abstract. Radiochromic film is tested for its broad-band response to ultraviolet (UV) B (290–320 nm) and A (320 nm–400 nm), visible and infrared radiation produced by a solar simulator and examined for dosimetry in ultraviolet radiation. Results show that MD-55-2 radiochromic film in solar and fluorescent light sources responds almost exclusively to broad-band UVA radiation with negligible colouration from UVB, visible and low level infrared radiation. A second order polynomial function approximates the change in optical density at 660 nm wavelength for film colouration with exposure to UVA from white light fluorescent and solar UV with exposures measured with a dedicated UVA dosimeter. Using a double exposure technique as used in radiation dosimetry where the film is firstly irradiated to a known UV dose, radiochromic film can be used as a quantitative measure of UVA exposure.

1. Introduction

Ultraviolet dosimetry has been performed with many types of detector. Broad-band radiometers measure the total irradiance over a selected waveband (Berger 1976, Wengraitis *et al* 1998). The biologically effective irradiance can be determined if suitable filters and sensors are selected to provide a spectral response similar to the action spectrum in consideration. Several passive detectors (Davis *et al* 1976, Diffey 1989, Wong *et al* 1989) have been developed for different purposes in ultraviolet dosimetry. One of them, polysulphone, has been used extensively for measurements of human exposure to skin and it has been calibrated for the erythemally effective exposure (Airey *et al* 1997, Kimlin *et al* 1998). Biological materials can be used for assessing UV exposure. Since the material is biological specimens, its spectral response follows that of other biological bodies. An example is the utilization of spore films (Horneck *et al* 1993). Studies (Quintern *et al* 1997) show that the uncertainties of this type of detector are comparable to that of chemical detectors.

Radiochromic film which has been used extensively in dosimetry of high energy x-rays and electron beams (McLaughlin *et al* 1991, Muench *et al* 1991, Butson *et al* 1998) has been used to adequately measure ultraviolet (UV) radiation. The radiochromic film, Gafchromic MD-55-2,

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consists of a colourless, transparent film which responds to ultraviolet radiation by changing to a blue colour with two main absorption peaks located at 610 and 670 nm (Niroomand-Rad *et al* 1998). The process does not require any optical, chemical or thermal development and responds directly to the UV radiation. As the absorption peaks are located in the visible, red region, a very simple and inexpensive optical densitometer can be used to measure the UV exposure, a process not achievable with other UV film dosimeters such as polysulphone film which require analysis in the UV region (Davis *et al* 1976, Diffey 1989, Parisi *et al* 1997). This film could prove to be extremely useful in areas of UV analysis where small unobtrusive detectors which can be analysed in the field are needed. Here we measure the response of MD-55-2 film to broad-band UVA, UVB, visible (V) and infrared (IR) radiation and show that UVA exposure can be measured to within an accuracy of ±5% of values measured by a broad-band ultraviolet UVA dosemeter.

2. Methods

Gafchromic MD-55-2 radiochromic film† detectors were placed in a solar spectral simulator to evaluate its response to broad-band UVA, UVB, V and IR radiation. The solar simulator (F3S) is comprised of a multiple lamp array configured to simulate the full spectrum of terrestrial sunlight at the equator at mid-summer noon and variable throughout each major spectral bandwidth. The area of uniform irradiance under the lamps is 1200 mm × 780 mm. The instrument is internally and externally air cooled. The spectral irradiance was measured from 250 to 400 nm using a computer-controlled McPherson triple grating monochromator with a prism disperser. A calibrated tungsten–halogen lamp was used as the reference source (Dissanayake *et al* 1993). The UVB levels below 300 nm are higher than sunlight by approximately a factor of three after filtering through a 0.025 inch Kodacel 407 cellulose triacetate film which only slightly photodegrades after 30 hours of use with this source. The F3S is monitored before and after every exposure using an International Light 1700 Research Radiometer combined with two sensor attachments: an SED240 with a SC280 UVB-1 filter and a W diffuser; and an SEE038 sensor, broad-band UVA filter and W diffuser.

Exposures were performed over multiple 2 minute periods. This was achieved by placing the MD-55-2 film approximately 30 cm from the solar simulator light sources. Separate testing was performed with UVA, UVB, visible and IR wavebands. Small amounts (less than 1%) UVB was present in the UVA source. No UVA was present in the UVB source. The UVA source also had small amounts of visible light present in its source. The film comes from the manufacturer in sheets of dimensions 12.5 cm × 12.5 cm approximately 280 μm thick. The sensitive layer of the film is located inside two polyester base films and is approximately 30 μm thick. The polyester layers provide a stabilized base for the film and also protect it from scratching and contamination. The protective layers also provide a water resistant barrier to the UV sensitive film. For experimental evaluation of UV radiation, the film was cut into 1 cm × 1 cm squares and the edge was attached to a paper strip for handling to avoid finger prints and other contamination on the film. The films optical density was analysed on a Photon Industries‡ spot densitometer whose light source is 660 ± 10 nm FWHM.

Following measurements of broad-band response, the film was tested for accumulative exposure to solar UV and fluorescent light sources. Solar UV exposures were performed in Wollongong, New South Wales, Australia, latitude 34° during winter and spring between the

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‡ Photon Industries, 30 Eastern Avenue, Mangerton, NSW 2500, Australia.

times of 9:00 am and 5:00 pm. Measurements were performed on cloudy and clear days. The UVA intensity varied from 15 to 85 $\mathrm{mW/m^2}$ during experiments. Accumulated exposure was measured in dose mode on a broad band UVTEX 3600idm UVA meter. Measurements were also made in front of an unfiltered 'white' light fluorescent 20W light source. The films were placed 5 cm from the source at which distance the UVA intensity was measured as 0.7 $\mathrm{mW/m^2}$. Accumulated exposure was measured with the UVA meter in dose mode. The white light source produces a range of UV output with mercury vapour peaks located at 313 nm, 334 nm and 365 nm. The 365 nm peak is the most intense of these three peaks. For solar and fluorescent exposures tests, various background colours were evaluated to see the effect of backscattered UV on dosimetry. Background material used consisted of papers with colours of white, green, red, blue, dark grey and black. The films were taped directly on these materials during experiments. Films from 3 different batches of MD-55 film were investigated for reproducibility and accuracy to ascertain any variation in dosimetry. The film batch numbers were 37350, 970116 and 941206.

3. Results and discussion

Figure 1 shows the measured response to broad-band UVA, UVB, V and IR radiation for MD-55-2 film. The errors shown on the curve are the variations in measured optical density on ten film samples placed in the light source. Errors associated with measurement include variations in film sensitivity and variations in solar simulator intensity during exposure. The results are normalized to 1 for the net optical density readout produced for the full spectrum exposure. This comprised all wavelengths possible. As can be seen, the film produces a negligible response to all UVB, visible and low level infrared radiation. A change in film opacity was seen with high level infrared which caused the film to degrade to an opaque colour and bubble rather than turning a blue colour. This is associated with the physical deterioration of MD-55-2 film with high temperatures (Niroomand-Rad *et al* 1998). It is assumed that the protective layer, or film base acts as a UVB absorber and does not allow UVB to penetrate down to the sensitive layer. The absorption spectra of the MD-55-2 film was tested using a GE spectrometer and results showed that the film produced a sharp, complete absorption at wavelengths below 315 ± 5 nm which lies at the edge of UVA–UVB.

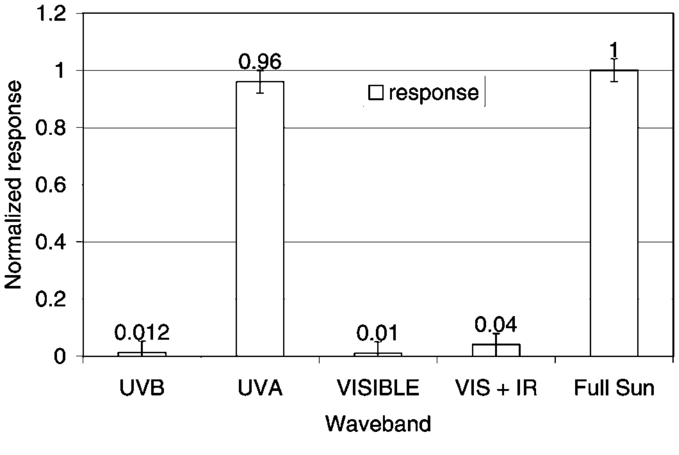

Figure 1. The response of MD-55-2 Gafchromic film to broad-band UVA, UVB, visible and infrared light.

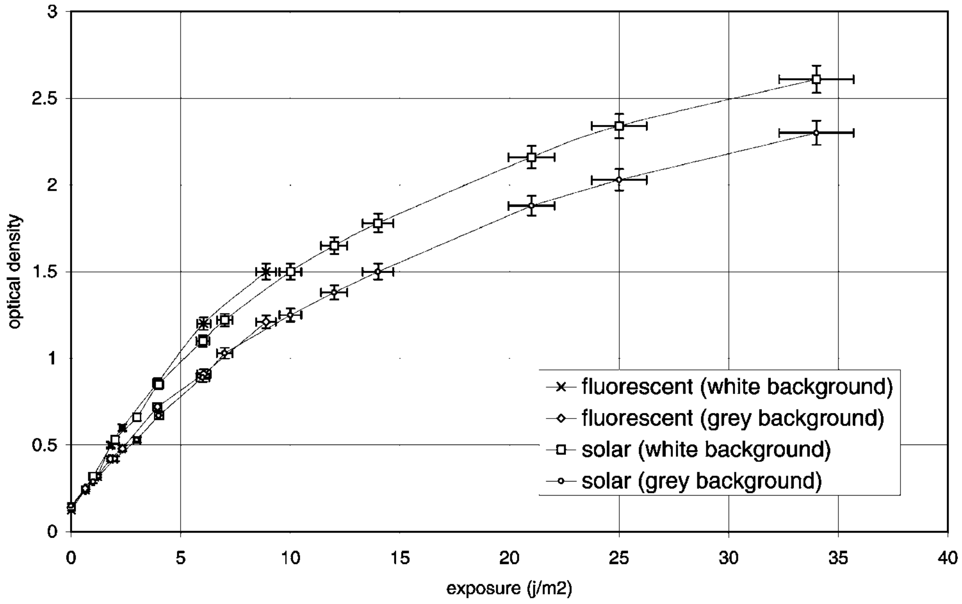

Figure 2. Shows the response of MD-55-2 to solar radiation and 'white light' fluorescent light sources with white and dark grey backgrounds.

Table 1. Normalized response of Gafchromic film to UV with various background materials.

Colour	Normalized response
White	1.00
Bottle green	0.89
Sky blue	0.87
Scarlet red	0.92
Dark grey	0.83
Black	0.81

Figure 2 shows the optical density of MD-55 radiochromic film as a function of ultraviolet exposure for solar UVA and fluorescent light UVA as measured with a UVTEX 3600idm dosimeter. The errors shown for MD-55 radiochromic film for measurement of UV solar radiation is two standard deviations of the mean over all film measurements conducted in June and July 1999. Fluorescent light experiments were performed over the same time period. The optical density to UV exposure ratio is approximated by a second order polynomial fit with a standard error in measurement as $\pm 3\%$. Shown in the results is the variation in response curves for the films depending on the type of background material used during exposure. Results for dark grey and white backgrounds produce approximately 15% difference in measured exposure. This effect is assumed to be associated with backscattered UVA which is reflected off the backing material. Table 1 shows the results normalized to 1 for white background of various colours which have received the same exposure. Smaller optical densities are measured for black and dark grey material and the highest for white. Thus the colour and most likely the texture of the experimental conditions effect the optical density recorded by the Gafchromic film.

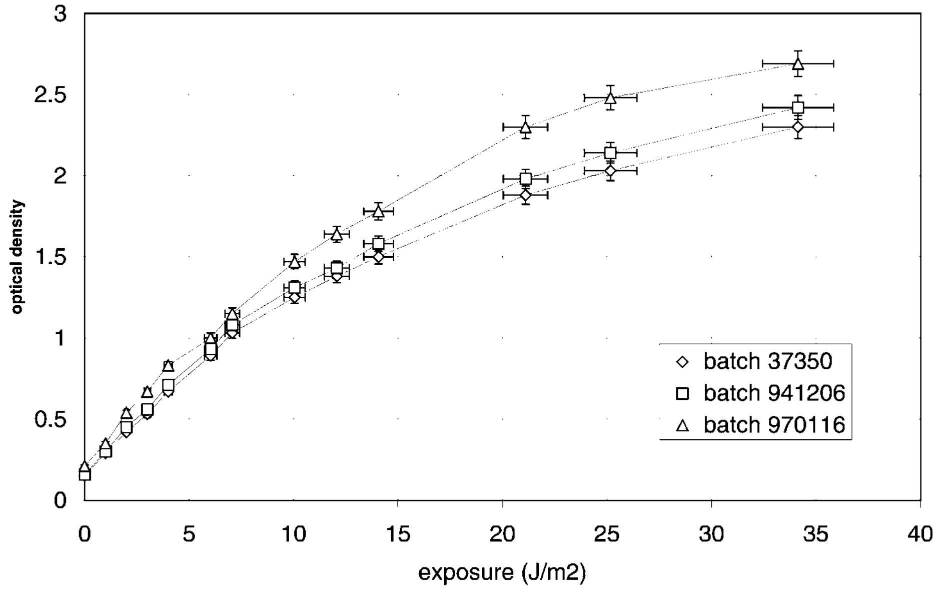

Figure 3. The response of three different batches of MD-55 film to solar radiation.

Variations in response to UV for various film batches and samples were noticed and examples are shown in figure 3. Results show that three batches produce a variation in response by 20% when exposed to the same UV source and having the same background material, however each batch produces reproducible results within ±3% for solar radiation. The variation or batch dependence is probably most likely a manufacturer effect and does not effect the accuracy of UV exposure measurements provided a calibration is performed on each new film before use. These variations could also be associated with film non-uniformity (Meigooni *et al* 1996). A calibration can be performed however on each film piece by a few small exposures on the film in question before experimental use to determine a sensitivity factor.

4. Conclusion

Gafchromic MD-55-2 film can be a useful dosimeter for UVA radiation provided a pre-experimental calibration is performed in the source in question. It may be necessary to calibrate the film with background material matched to the colour and texture of the experimental exposures. Due to the physical characteristics of radiochromic film, such as its physical toughness, water resistance and the ability to produce results measured with inexpensive visible light densitometers, it has the potential for measurement of UVA dose. The film by itself does not provide a measure of absolute UV exposure. However, the film can be calibrated against a primary standard and used in the field to an adequate level of accuracy.

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