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Journal of Photochemistry and Photobiology A: Chemistry 101 (1996) 63-67

Journal of PHOTOCHEMISTRY AND PHOTOBIOLOGY A:CHEMISTRY

The use of Riso B3 film gamma dosimeter for monitoring ultraviolet radiation

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Received 21 December 1995; accepted 28 March 1996

Abstract

The Riso thin B3 plastic film, which is essentially a gamma radiation dosimeter, has been succesfully used for measuring integrated UV irradiance. The colorless flexible plastic film changed colour to red upon exposure to UV-irradiation. The radiation-induced colour was analyzed spectrophotometrically at the maximum of the absorption peaking at 554 nm wavelength. The film was found to respond faithfully to UV-B, UV-C and less sensitively to UV-A radiation, showing maximum sensitivities at 200, 298 and 366 nm wavelengths. Correlations were established between the absorbed dose of UV radiation and the change in absorbance (ΔA_{554}) at 254, 298 and 366 nm irradiation wavelengths. The data were analysed to determine the reproducibility of (ΔA_{554}) measured from films exposed to the same UV irradiance. The effect of post-irradiation stability on the dosimeter performance was discussed. The results demonstrate that B3 film has a maximum sensitivity and suitability for use as a personal dosimeter for biologically effective solar UV-B and UV-C radiation, where most acute and chronic effects of sunlight exposure on biological systems are believed to occur. Also, it can be used for monitoring of artificial ultraviolet radiation sources used for medical and industrial processes.

Keywords: Plastic film; Dosimetry; Spectral sensitivity; Ultraviolet radiation; Spectrophotometry

1. Introduction

Ultraviolet radiation occupies that portion of the electromagnetic spectrum from 100 to 400 nanometers (nm). This is commonly divided into three subregions: short wavelength (UV-C), varying from 100 to 280 nm; medium wavelength (UV-B), ranging from 280 to 315 nm; and long wavelength (UV-A), varying from 315 to 400 nm [1].

UV radiation is harmful to humans and ecosystems, the UV-A is relatively less harmful, but UV-B has many damaging effects, while UV-C is lethal to many forms of life. The biological effects of UV radiation in humans are limited to the skin and the eye because of its low penetrating properties in human tissues. The normal responses of the skin to UV radiation may be classified as either acute, e.g., erythema, melanin pigmentation, vitamin D production, or chronic e.g., skin ageing and skin cancer [2]. Erythema (e.g., the reddening of the skin in sun-burn) is a photochemical response of the skin normally resulting from overexposure to wavelengths in UV-C and UV-B regions (180–315 nm). Erythema induced by the longer UV-B wavelengths (295–315 nm) is more severe and persists for a longer period than that for shorter wavelengths [3].

Ultraviolet radiation sources are divided into two classes: natural and artificial. The sun is the most important natural source of UV light although much of its transmitted energy is in the longer wavelength subregion above 295 nm. The ozone layer in the stratosphere and troposphere around the earth acts as a protective shield by cutting off UV-C radiation and reducing the amount of UV-B radiation reaching the earth's surface. The reduction of the ozone layer results in an increase in UV-B radiation, within a narrow 25 nm waveband, between 290 and 315 nm [4]. Artificial UV radiation is used in a wide variety of industrial and medical processes and for cosmetic purposes. Industrial applications include photocuring of plastics and inks (UV-A and UV-B), solar simulation (all UV), fade testing (UV-A and UV-B) and wastewater disinfection (UV-C), etc. [1,5]. Clinical medicine include photochemotherapy, where proper UV-A radiation dosimetry is important in PUVA therapy, not only to prevent severe erythema, but also to determine the lowest effective radiant exposure to minimize long-term damage [6].

Many substances, in the form of dyed and undyed plastic films, exhibit a measurable change in their properties upon

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PII S1010-6030(96)04358-4

exposure to UV radiation and have been investigated in the search for a UV badge dosimeter, e.g., polysulohone film [7,8], diazo films [9] and polyvinyl chloride (PVC) films incorporating photosensitizing drugs [10,11]. Recently, we have developed several thin plastic films for UV radiation measurements [12–14]. To continue this work it was decided to study several photoactive chemicals incorporated into a polymeric matrix with a view to developing UV dosimeters.

The present work evaluates the B3 film as an UV radiation detector in terms of colour response range, spectral sensitivity down to short wavelengths, post-irradiation stability and uncertainties associated with dose measurement. Possible application of the B3 film for monitoring artificial and environmental UV radiation are also reported.

2. Experimental

The thin plastic film (0.025 mm) used in this investigation was the Riso B3, batch 343510 (made by Beiersdorf AG). The plastic film (polyvinyl butyral) contains leucocyanide (pararosaniline), which can be made radiochromic upon exposure to ultraviolet light or ionizing radiation [15]. Before use, all dosimeters were stored in the laboratory and protected against exposure to daylight and light from fluorescent lamps. Relative humidity in the laboratory was between 25 and 40% and the temperature was 21 ± 2 °C.

For calibration purposes and irradiation of samples, three UV radiation sources were utilized: (a) A standard 8 W mercury lamp (Desaga 131200) and monochromatic filters with a bandwidth of 5 nm (Oriel Corporation, Stradford, Ct, U.S.A) were used to provide the required irradiation wavelength. Intensity meters for short and long wave ultraviolet lamps Model J-225x, UVP and J-221, UVP were used to measure the intensity of ultraviolet light of the mercury lamp. (b) UVP ultraviolet Crosslinker model: CL-1000 was also used for irrdiation of B3 films at 302 nm wavelength. The UVP Cl-1000 is designed to measure and control the ultraviolet radiation within the exposure chamber. It is equipped with a UV sensor to measure the UV energy and automatically adjusts to variations in UV intensity that occur as the UV lamp ages. (c) A XENOTEST 150 S (Heraeus Instruments), light and weatherfastness tester, where solar and global radiation is simulated by xenon arc radiation. A radialux UV meter (Heraeus Instrument) was used to measure the irradiance and dose in the wavelength range 300–400 nm in the weathering device.

A Perkin Elmer UV/VIS spectrophotometer Lambda 3B and UVIKON 860 spectrophotometer were used to measure the absorbance and absorption spectra of the irradiated and unirradiated films.

3. Results and discussion

3.1. Radiation-induced absorption spectra

Upon UV irradiation, the colorless B3 films showed a significant colour change to red. The red colour developed and the intensity of this colour increases with increasing doses of incident UV radiation. Fig. 1 shows spectrophotometric scans of unirradiated film and films irradiated to a series of doses in the range from 0.75 to 0.55 kJ/m^2, using the Desaga 131200 lamp. The radiation-induced absorbtion spectra show that the largest change in absorbance occurs at 554 nm wavelength. Therefore, this wavelength was subsequntly used to quantify the UV-induced changes in the film.

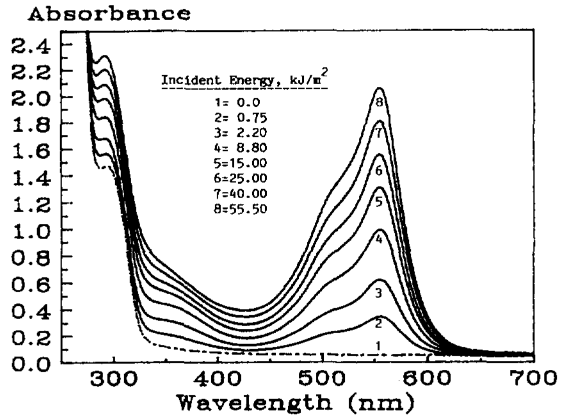

Fig. 1. Variation in the absorption spectra with incident UV dose using UVP ultraviolet crosslinker.

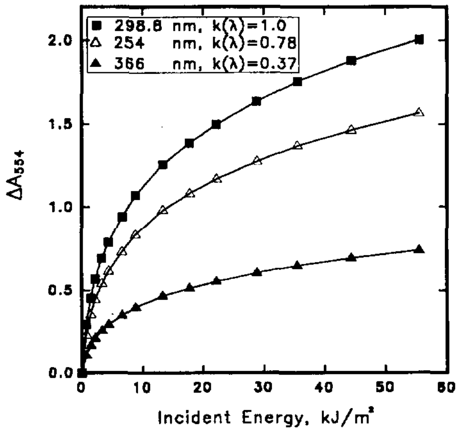

Fig. 2. Variation in ΔA_{554} with incident UV dose at different irradiation wavelengths.

3.2. Dose response

In order to study the response of the B3 film to UV radiation, irradiations were carried out using the Desaga 131200 lamp and the monochromatic filters to provide the required irradiation wavelength. The UV irradiations were carried out at exposure wavelengths of 254 ± 5, 298.8 ± 5 and 366 ± 5 nm. The change in absorbance of the irradiated film ($\Delta A = A_i - A_o$, where A_0 is the absorbance before irradiation and A_i is that after irradiation), were measured at 554 nm wavelength as a function of UV incident energy. The recorded variations in ΔA_{554} as a function of UV exposure energy at different irradiation wavelengths are shown in Fig. 2. It is observed that the response at all three irradiation wavelengths is non-linear and tends to saturate at high doses. Statistical analysis of the results indicates that the radiation-induced changes in the B3 film may be expressed by the following general empirical relationship

$$K(\lambda)D=0.031+0.074X+7.74X^2-3.5X^3+3.24X^4 \quad (r=0.99995), \qquad (1)$$

where $K(\lambda)$ is the wavelength response of the film normalized to unity at an irradiation wavelength $\lambda=298.8$, X represents the change in absorbance measured at 554 nm ($\Delta A_{554}(D,\lambda)$) for a UV exposure energy D (kJ/m^2) at wavelength λ. The expressions given by Eq. (1) are represented by the full lines in Fig. 2. These curves agree fairly well with experimental data points within 2.5% and so Eq. (1) may be used to quantify the UV dose received by a B3 film for a given ΔA_{554}.

3.3. Spectral sensitivity

The wavelength response of the B3 film was established by applying a dose of 0.65 kJ/m^2 at various irradiation wavelengths in the range from 200 to 400 nm (3 films at each wavelength) and the radiation-induced absorbance was measured for all films at 554 nm wavelength (A_{554}). The relative responses $K(\lambda)$ were evaluated at each wavelength by employing Eq. (1) and setting D equal to 0.65 kJ/m^2. The resulting $K(\lambda)$ values were normalized to unity at the most effective irradiation wavelength (298.8 nm) and plotted as a function of irradiation wavelengths Fig. 3. It can be seen that the maximum sensitivity of the B3 film lies between 295 and 320 nm wavelength in the UV-B region, where most significant adverse health effects of exposure to UV radiation have been reported [16]. This region of the spectrum has a relatively high penetrating power and can cause severe burns of the eyes and skin. Although maximum sensitivity occurs at 310 nm, there is still an easily measurable response at 254 and 366 nm. For wavelengths longer than 330 nm, extremly long exposure times would be necessary in order to reach a film response. It is clear from the work reported in this paper that B3 film can be used down to shorter wavelengths. Our results show that sensitivity at 254 nm is still useful, but when used at shorter wavelengths, careful filtering would be required to exclude the much more reactive and longer wavelengths. Compared to the spectral sensitivity (action spectrum) of the well known polysulphone plastic film dosimeter for biologically effective solar UV-B radiation [7], both films show a similar action spectrum in the important wavelength region between 295 and 315 nm, which is important for monitoring devices designed for natural ultrviolet radiation (see Fig. 4).

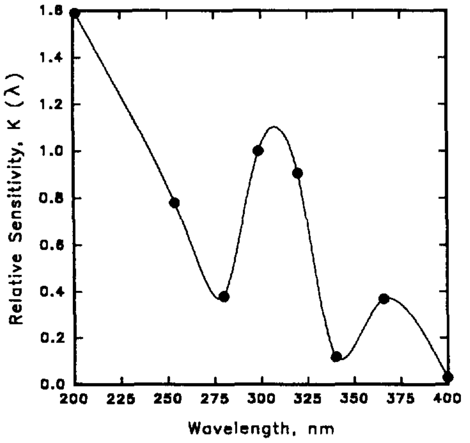

Fig. 3. Relative spectral sensitivity for B3 plastic film.

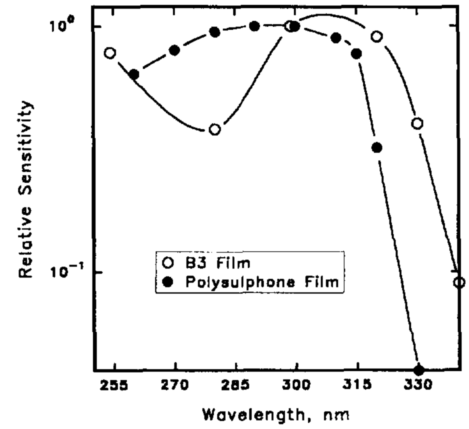

Fig. 4. Relative spectral sensitivity for both B3 and polysulphone films.

The principal limitation of the new dosimeter in the form used here is its sensitivity which extends to wavelengths of up to 340 nm, with a less sensitive region between 340 and 400 nm, where the biological effectiveness of UV radiation is negligible at wavelengths above 315 nm. This difference in spectral response can lead to significant errors in estimates of the biologically effective UV-B dose when the B3 film is used to monitor natural UV radiation, due to the rapid increase in the intensity of the solar spectrum between 315 and 350 nm. Similar effects have been reported for the polysulphone dosimeter. In this case, the response of polysulphone was related to erythermally effective UV-B radiant exposure by carrying out correction calculations which involve estimates of the action spectrum, the spectral sensitivity of polysulphone film and the relative spectral power distribution of the incident radiation [6]. Similarly, the B3 film spectral response bears a resemblance to the erythema action spectrum, although it does extend too far into the UV-A. However, using appropriate filters in combination with the B3 film, the relative sensitivity of the film (without UV-A sensitivity) can be adjusted for erythema induction [17].

3.4. Post-irradiation stability

B3 films irradiated to a dose of 1.13 kJ/m^2 were stored immediately after irradiation in the dark at a temperature of ~22.7 °C and relative humidity of 30.6% (normal laboratory storage conditions). The films were read spectrophotometrically at 554 nm and at different intervals of time during the post-irradiation storage period of 200 h. They were found to experience an increase in absorbance of ~6% by the end of the storage period (see Fig. 5).

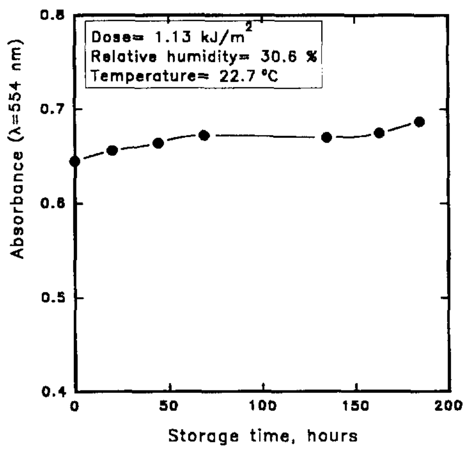

Fig. 5. Post-irradiation stability of the B3 film. Films were given a UV dose of 1.13 kJ/m^2 using UVP crosslinker CL-1000 UV lamp.

3.5. *Assessment of uncertainties*

The reproducibility of the measured (ΔA_{554}) of the films exposed to the same UV irradiance was determined by considering two uncertainties. The first uncertainty is associated with the measuring process and the second is concerned with the measurements resulting from different films exposed to the same UV irradiance.

The uncertainty associated with the measuring process was detemined by taking into consideration multiple readings of ΔA_{554} of the same film (a hundred readings per film). From the data obtained, it was found that the average uncertainty was 0.7%, reflecting the precision associated with a single ΔA_{554} measurement. However, the percentage uncertainty associated with the mean readings of different films exposed to the same dose varied from 0.6 to 2% with the mean of 1.3%. The combined effect of both errors was reflected by the uncertainty of all the measured ΔA_{554} values for all films exposed to a given dose. The obtained combined percentage uncertainties of ΔA_{554} values after irradiation (3 films at each dose point) over the useful dose range was found to be $\pm 2.2\%$. In other words, it can be said that the error associated with a single measurement of any film that has been exposed to radiation and the variations arising from the measuring process, as well as those from the manufacturing of the film material, were taken into consideration.

3.6. *Application for monitoring environmental and artificial UV radiation*

In order to test the efficiency of the B3 film for measurement of ultraviolet radiation emitted from artificial UV sources, two sets of B3 films were exposed to increasing doses of UV radiation from two different lamps. The first lamp was a type commonly used in weather fastness (XENOTEST 150 S). In this UV source, solar and global radiation (out-door sunlight) is simulated by xenon arc radiation (see UV spectral distribution, Fig. 6). The second lamp (CL-1000 Crosslinker), in which the irradiation wavelength was set to 302 nm and the spectral emission of the lamp, according to the manufacturer, is shown in Fig. 7.

B3 film sets were exposed to different irradiation doses of UV radiation in the two lamps and the change of absorbance (ΔA_{554}) was measured for each film at each dose. The irradiance and irradiation doses were measured using the RADIALUX UV sensor (range 300–400 nm). The obtained responses of the B3 film are presented in Figs. 8 and 9 for

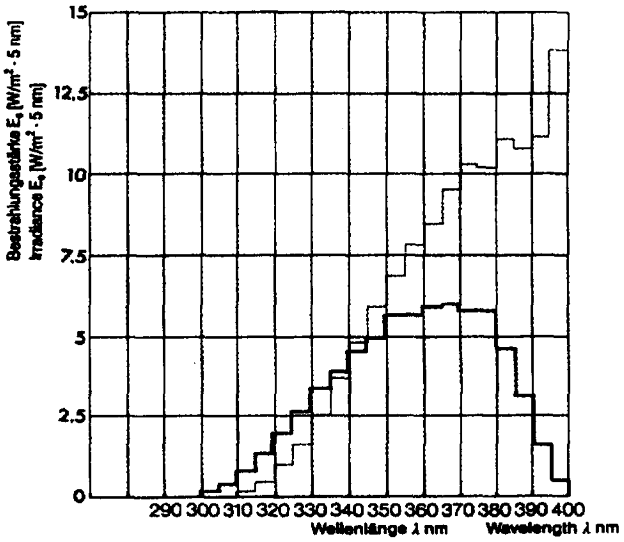

Fig. 6. Spectral output of the XENOTEST lamp in the UV region.

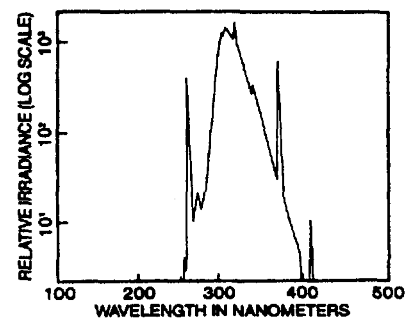

Fig. 7. Spectral output of the UVP ultraviolet crosslinker CL-1000 lamp.

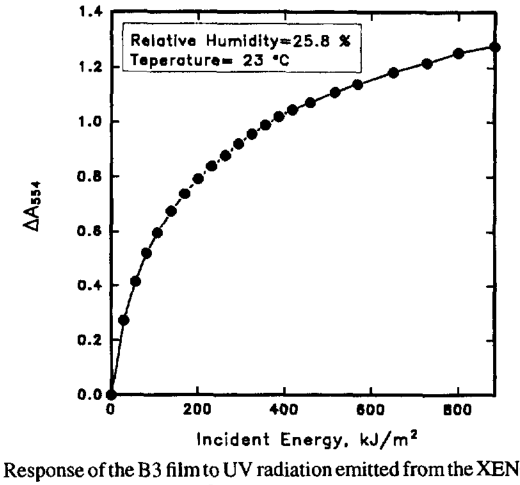

Fig. 8. Response of the B3 film to UV radiation emitted from the XENOTEST lamp. (Irradiance = 71.4 W/m^2).

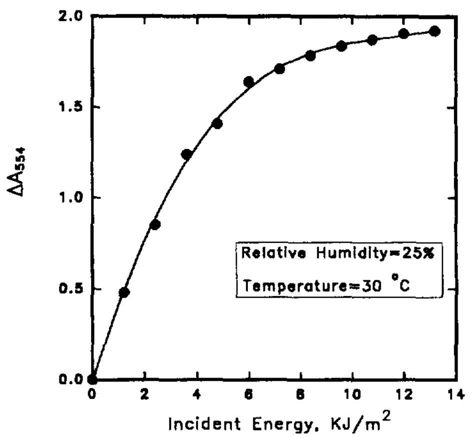

Fig. 9. Response of the B3 film to UV radiation emitted from the UVP ultraviolet crosslinker Cl-1000. (Irradiance = 4 W/m^2).

XENOTEST and CL-1000 UV irradiations, respectively. The results indicate that the B3 film shows a higher sensitivity to the emitted UV radiation from the CL-1000 source compared to the other UV source.The higher sensitivity of the B3 film towards the spectral output of the CL-1000 can be explained by the similarity of the spectral response of the B3 film and the lamp emission spectrum (see Figs. 3 and 7). In fact, determination of UV dose or irradiance is usually subject to some degree of uncertainty, depending on both the UV sources and UV detectors used for monitoring the output of UV sources. Therefore, it is desirable to use a dosimeter which matches the UV source emission spectrum.

4. Conclusion

Riso B3 thin plastic films (0.025 mm) prepared from polyvinyl butyral and pararosaniline cyanide, as the radiation sensitive element are investigated for UV radiation measurement. When the colourless B3 films are exposed to UV radiation between 200 and 400 nm wavelengths, they exhibit a colour change to red and the optical absorption of the films at 554 nm wavelength increases with the UV dose. The overall uncertainty associated with the measurement of dose response of B3 film dosimeter at different UV doses over the entire response range, when ΔA_{554} values are calculated, was found to be ±2.2%. The dosimeter has a maximum sensitivity and suitability for use as a personal dosimeter for biologically effective solar UV-B and if suitably filtered it can provide the bases for a UV film badge with many medical and industrial applications in the UV-A and UV-C regions of the spectrum.

References

[1] CIE70 International Commission on Illumination, International Lighting Vocabulary, 3rd Edn., Publication CIE No. 17 (E-1.1) (Paris: CIE), 1970.
[2] B.E. Johnson, F. Daniels Jr. and I.A. Magnus, in *Photophysiology, 4* (1968) 139-202.
[3] K.W. Hausser, *Strahlentherapie, 28,* (1928) 25–44.
[4] *Environmental UV radiation*, prepared by the Services of the European Commission, Directorate-General XII for Science, Research and Development, The ENVIRONMENT R&D Programme, Sep. 1993.
[5] D. Morse, *Civil Eng., 59* (1989) 64–66.
[6] B.L. Diffey, *Br. J. Dermatol., 98* (178) 703–706.
[7] A. Davis, G.H.W. Deane and B.L. Diffey, *Nature (London), 261* (1976) 169–170.
[8] A. Davis, B.L. Diffey and T.K. Tate, *J. Photochem. Photobio., 34* (1981) 283–286.
[9] S.A. Jackson, *J. Biomed., 2* (1980) 63.
[10] B.L. Diffey, A. Davis, M. Johnson and T.R. Harrington, *Br. J. Dermatol., 97* (1977) 127–130.
[11] B.L. Diffey and A. Davis, *Phys. Med. Biol., 23* (1978) 318–323.
[12] F. Abdel Rehim, M.M. Abdel-Aziz and A.M. El-Naggar, *J. Photochem. Photobiol. A: Chem., 56* (1991) 369–374.
[13] F. Abdel Rehim, A.S. Abdel-Gawad and A.A. Abdel-Fattah, *J. Photochem. Photobiol. A: Chem., 64* (1992) 123–131.
[14] F. Abdel Rehim, S. Ebrahim and A.A. Abdel-Fattah, *J. Photochem. Photobiol. A: Chem., 73* (1993) 247–251.
[15] A. Miller, W. Batsberg and W. Karman, *Radiat. Phys. Chem., 31* (1988) 491–496.
[16] H. Mosely, *Non-Ionizing Radiation Microwaves, Ultraviolet and Laser Radiation* (Medical Physics Handbooks 18), published under the Adam Hilger Lmptint by Jop Publishing Ltd., 1988.
[17] L.E. Quintern, G. Horneck, U. Eschweiler and H. Bucker, *J. Photochem. Photobiol. 55* (1992) 389–395.