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Note: Calibration of EBT3 radiochromic film for measuring solar ultraviolet radiation

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Solar (UVA + UVB) exposure was assessed using the Gafchromic EBT3 film. The coloration change was represented by the net reflective optical density (*Net ROD*). Through calibrations against a UV-tube lamp, operational relationships were obtained between *Net ROD* and the (UVA + UVB) exposures (in $\mathrm{J\,cm^{-2}}$ or $\mathrm{J\,m^{-2}}$). The useful range was from ~0.2 to ~30 $\mathrm{J\,cm^{-2}}$. The uniformity of UV irradiation was crucial for an accurate calibration. For solar exposures ranging from 2 to 11 $\mathrm{J\,cm^{-2}}$, the predicted *Net ROD* agreed with the recorded values within 9%, while the predicted exposures agreed with the recorded values within 15%. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4898162]

Solar ultraviolet (UV) radiation can cause various detrimental effects to humans including skin cancer and degenerative effects for our eyes like cataracts.[1] The solar UV spectrum comprises different wavelength ranges, including UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm). The UV radiation reaching the Earth's surface is made up of mostly UVA and also with a small amount of UVB. The current work has focused on the use of film detectors for passive monitoring the solar (UVA + UVB) radiation on a relatively long-term basis.

Commercially available electronic UV dosimeters are expensive and most of these can only give instantaneous UV irradiances (e.g., in $\mathrm{W/cm^2}$) but not the exposure values (e.g., in $\mathrm{J\,cm^{-2}}$). The UVTEX A + B meter (SafeSun, Optix Inc., Washington, DC) we used before for exposure measurements[2] is no longer commercially available in the market. These limitations have made researches that have to rely on long-term measurements or relying on simultaneous measurements at many sites implausible. Film detectors which produce color changes on irradiation, e.g., the polyphenylene oxide film[3,4] and the polysulfone film,[5] have been found useful in these situations. However, color changes in these films occur in the UV region, which necessitate quantification using a photospectrometer device. Abdel Rehim *et al.*[6] purposely constructed a radiochromic dye film with color changes in the visible region for UV dosimetry.

Gafchromic film products which were primarily designed for clinical dosimetric applications[7] and produced color changes on irradiation, were found to be sensitive to ambient light sources[8] such as the solar radiation and fluorescent light sources, leading to permanent coloration.[9,10] Subsequently, Butson *et al.*[11] demonstrated that the MD-55-2 film could quantitative measure UVA exposures, while Butson *et al.* used the EBT film[2] and EBT2 film[12] for measuring solar (UVA + UVB) exposures.

The EBT film had been superseded first by EBT2 and then by the EBT3 films in the market. Aydarous *et al.*[13] studied the response of the EBT3 film to UV radiation with different wavelengths, namely, 365, 302, and 254 nm. The present work aimed to assess the feasibility of using the EBT3 film for measuring solar UV radiation and to provide information on calibration, and to verify the methodology using real-life solar UV irradiation data.

ISP Gafchromic EBT3 films (Lot No. A03181301) were used. All exposed EBT3 films had a size of about 1.5 × 1.5 $\mathrm{cm^2}$ and were exposed with the same black matte backing paper to maintain uniform scattering conditions. Subsequent to UV radiation, all the films were kept in light tight containers to avoid further UV radiation. After 24 h, a selected area (with a size of 0.75 × 0.75 $\mathrm{cm^2}$ or 0.25 × 0.25 $\mathrm{cm^2}$) on the films was scanned on an Epson Perfection V700 desktop flatbed scanner using the reflection mode with a resolution of 50 dots per inch (dpi).[2,14] No filters or correction functions were applied to raw pixel value results. The created images were 48 bit RGB color images, and the red component was analyzed using the ImageJ software (http://imagej.nih.gov/ij/). The coloration change in the scanned area of the irradiated films was represented by the net reflective optical density (ROD) which was defined as

$$Net\ ROD = \log(P_u/P_t), \tag{1}$$

where P_u and P_t were the pixel values of the reflected intensity through an unexposed film and an exposed film, respectively. This definition was also employed by Butson *et al.*[2] and a similar one was used by Ohuchi[15] for reflected optical density.

The (UVA + UVB) irradiance (power per unit area, $\mathrm{W\,m^{-2}}$) and exposure (irradiance integrated over time, $\mathrm{J\,cm^{-2}}$ or $\mathrm{J\,m^{-2}}$) were measured. Two Solarmeter® Model 5.0 (UVA + UVB) Total UV meters from Solartech Inc. (MI, USA) (http://www.solarmeter.com/model5.html) were employed, which were designed for measuring the (UVA + UVB) irradiance. One of these two meters was modified and coupled to a data logger for measuring the (UVA + UVB) exposure, as described below. These instruments were calibrated on 12 March 2014 through the transfer of readings from a Standard Meter (Serial No. 03278) simultaneously and

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equidistant from a solar UV light source, while the Standard Meter had been calibrated according to NIST standards. According to the certificate of traceability, the accuracy of readings was ±5%.

The present work has a number of objectives. The first one is to demonstrate the feasibility of using the EBT3 film for UV dosimetry through irradiation from a UV bench lamp. The Cole Parmer 15 W UV bench lamp (9815-series), which had self-filtering low-pressure "black light" tubes, was used. We hereafter refer this UV lamp as the UV-tube lamp to differentiate it from the Arc Xenon lamp that we have also employed for our experiments. The films were placed at 1.2 cm from the UV-tube lamp. Operational relationships between *Net ROD* and the UV exposures would be determined to provide the required calibrations. The range usable for UV dosimetry was also established. Although Aydarous *et al.*[13] claimed that the response of the EBT3 film to UVA and UVB radiation tended to saturate at an exposure of about 60 $\mathrm{J\,cm^{-2}}$, this was not explicitly shown in their calibration curves.

The second objective is to check the effects of the uniformity of the UV irradiation on the accuracy of the calibration. The Newport 300 W ozone-free Arc Xenon lamp with an illumination area of 1.5 in. diameter and equipped with 90° beam turning assembly was used. A Hoya U-360 filter was attached to the end of the beam turning assembly used to block light with wavelengths smaller than 300 nm and larger than 400 nm. The films were placed at 9.1 cm from the filter. This setup was known to provide a non-uniform irradiation pattern, with more energy being deposited within a very small area (exposure peak) at the center of the illumination area.

The third objective is to verify the methodology using real-life solar UV irradiation data. The first task was to build a setup for measuring (UVA + UVB) exposures. As mentioned above, one Solarmeter® Model 5.0 (UVA + UVB) Total UV meter was modified for measuring (UVA + UVB) exposures. Briefly, the R6 load resistor on the circuit board was identified, which was clearly labeled on the component side of board and was close to the sensor connector. Two wires were connected and soldered across the R6 load resistor, and exited out the container of the meter. The wires were connected to a data logger (Measurement Computing, Model: USB-1208LS). The voltage signal out of the meter recorded by the data logger was linearly proportional to the LCD reading shown on the meter. Thus by using the unmodified meter as a reference we created a "calibration factor" so that the voltage signal recorded by the data logger could be converted to the irradiance with the unit $\mathrm{mW/cm^2}$. The data logger was then programmed to perform integration over time to give the exposure with the unit $\mathrm{J\,cm^{-2}}$. Regarding the real-life solar UV irradiation, five EBT3 films were exposed in Hong Kong (Lat 22.3° N, 114.2° E) on 26 May 2014, which was a very sunny day and had high UV intensities, so that the irradiation time could be shortened to minimize the uncertainties due to changes in the collection angle of the UV meters. The films were irradiated for 9, 14, 19, 29, and 44 min during the time period from 1315 to 1400.

Figure 1 shows the comparison between the responses of EBT3 Gafchromic film to UV radiation exposures with different scanned field sizes, namely, 0.75×0.75 cm^2 and 0.25×0.25 cm^2. The error bars to the data points represented the standard errors obtained from 3 repeated measurements. The data points for the two scanned field sizes almost completely overlapped with one another. Figure 1 also shows a sigmoidal relationship between (*Net ROD*) and log(*Exposure*), so we fit the data points for the scanned field size of 0.75×0.75 cm^2 with the equation

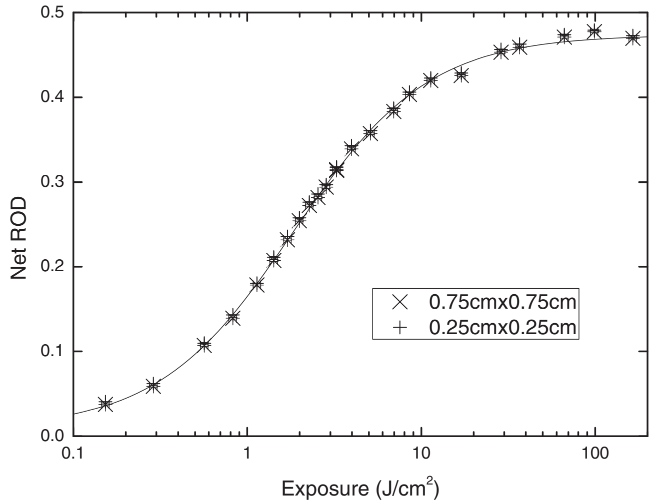

FIG. 1. Comparison between the responses of EBT3 film to UV radiation exposures provided by a UV-tube lamp with different scanned field sizes (crosses: 0.75×0.75 cm^2; pluses: 0.25×0.25 cm^2). Data points represent mean ± SEM ($n = 3$). The solid line is the best-fit line given by Eq. (3).

$$Net\ ROD = A + (B - A)/\{1 + 10^{[C(D - \log(Exposure))]}\} \quad (2)$$

using Origin 8 SRO v8.0725 (OriginLab Corporation, Northampton, MA, USA). The best fitted parameters (± standard error) were $A = 0.0080 \pm 0.0043$, $B = 0.474 \pm 0.002$, $C = 1.12 \pm 0.02$, and $D = 0.265 \pm 0.010$, with the adjusted $R^2 = 0.99932$. As such, the best fit line is given by

$$Net\ ROD = 0.00880 + 0.465/\{1 + 10^{[1.12(0.265 - \log(Exposure))]}\}, \quad (3)$$

which is also plotted as solid line in Figure 1. Conversely, for an experimentally measured *Net ROD* value, the (UVA + UVB) exposure could also be computed using

$$Exposure = 10^{0.265 - \{\log[0.465/(Net\ ROD - 0.0088) - 1]\}/1.12}. \quad (4)$$

The useful range was observed as from ∼0.2 to ∼30 $\mathrm{J\,cm^{-2}}$.

Figure 2 shows the comparison between the response of EBT3 Gafchromic film to UV radiation exposures provided by the UV-tube lamp with a scanned field size of 0.75×0.75 cm^2 given by Eq. (3), and that provided by the Arc Xenon lamp, with scanned field sizes of 0.75×0.75 cm^2 and 0.25×0.25 cm^2. While the two sets of data for the Arc Xenon lamp with different scanned field sizes were close to each other, there was a significant discrepancy between the data and that corresponding to the UV-tube lamp. The discrepancy could be explained by the non-uniform irradiation by the Arc Xenon lamp, as well as the nonlinear response of the EBT3 film to the UV exposure as shown in Figure 1. In particular, saturation of the (*Net ROD*) occurred at large UV exposure values. In other words, the sensitivity defined as the ratio of (*Net ROD*) to the UV exposure would be smaller at large UV exposure values.

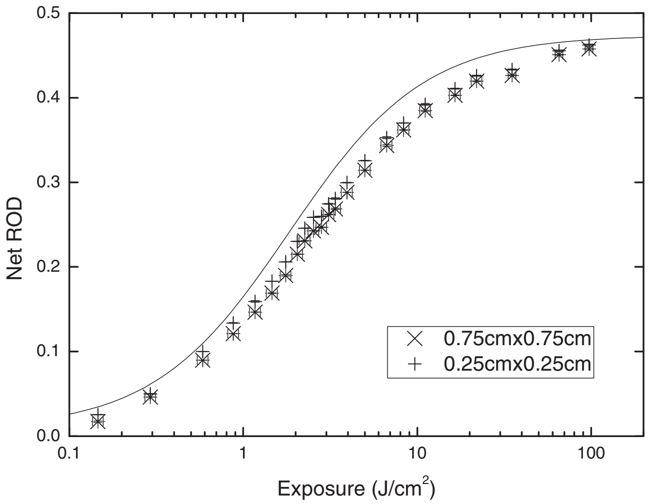

FIG. 2. Comparison between the response of EBT3 film to UV radiation exposures provided by the UV-tube lamp with a scanned field size of 0.75 × 0.75 cm^2 (solid line) given by Eq. (3), and those provided by the Arc Xenon lamp, with a scanned field size of 0.75 × 0.75 cm^2 (crosses) and with a scanned field size of 0.25 × 0.25 cm^2 (pluses).

As such, considering the exposure peak in the irradiation area of the Arc Xenon lamp, the overall sensitivity of the EBT3 film would be reduced. As a result, for the same UV exposure, the (*Net ROD*) would be smaller for the non-uniformly irradiated film when compared to the uniformly irradiated film. These results highlighted the importance of the uniformity of UV irradiation on the accuracy of the calibration.

Figure 3 shows the comparison between the UV exposures recorded on the data logger coupled to the modified Solarmeter® Model 5.0 (UVA + UVB) Total UV meter, and the prediction by the response of EBT3 Gafchromic film to UV radiation exposures provided by the UV-tube lamp with a scanned field size of 0.75 × 0.75 cm^2 as given by Eq. (4). The irradiance values for the five data were similar and the average was (39.9 ± 0.8) W m^{-2}, and the solar exposures ranged from 2 to 11 J cm^{-2}. For these exposures, the predicted color change in terms of the *Net ROD* (based on the recorded exposure values) agreed with the recorded values within 9%, while the predicted exposure values (based on the *Net ROD* of the EBT3 films) agreed with the recorded values within 15%.

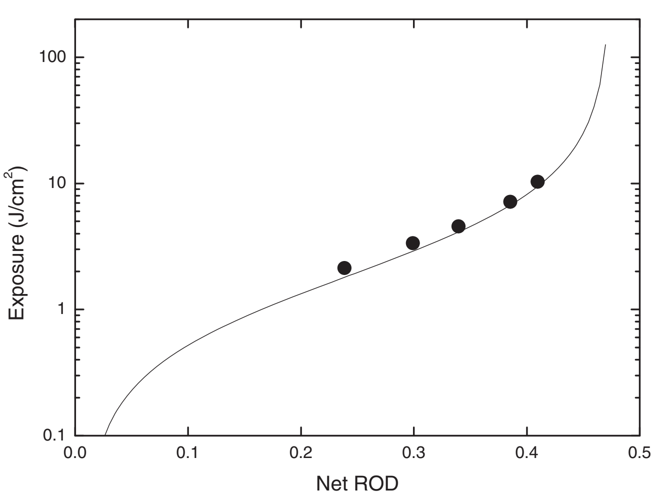

FIG. 3. Comparison between the UV exposures recorded on the data logger coupled to the modified Solarmeter® Model 5.0 (UVA + UVB) Total UV meter (solid circles), and the prediction using Eq. (4) (solid line).

As explained in the Introduction, the choice of the EBT3 film for the present study stemmed from our previous works on the EBT and EBT2 films. It would be interesting to compare a number of different radiochromic films with the same technique in future, which would further demonstrate the reliability of our calibration technique.

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