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Long-term Passive Monitoring of Solar UV Radiation Using Radiochromic Films

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ABSTRACT

The solar ultraviolet (UV) spectrum spans over a range of wavelengths, namely, UVA (315–400 nm), UVB (280–315 nm) and UVC (100–280 nm). The UV radiation reaching the surface of the Earth comprises of mainly UVA, a small amount of UVB and essentially no UVC. Solar UV can affect the human health. An under-dose will lead to diseases such as rickets and osteoporosis, while an over-dose will cause sunburns, skin cancers and cataracts. It is therefore pertinent to design methods for integrated long-term measurements of UV radiation (e.g., over 1 day). Recently, we succeeded in demonstrating the feasibility of using the Gafchromic EBT3 radiochromic film to quantify solar (UVA+UVB) exposures (in Jcm^{-2}). These radiochromic-film products were originally developed for clinical dosimetric applications, with visible-light absorption changes upon X-ray irradiation, but were understood to be also responsive to UV radiations. We found that the usable range of UV exposures for the EBT3 film was from ~0.2 to ~30 Jcm^{-2}. However, the maximum UV exposure could reach 50 Jcm^{-2} per day, so we need a wider usable range. The current work proposed modifications to the EBT3 film for longer-term measurements (e.g., over 1 day). We explored the UV responses of EBT3 films covered with 2 and 5 barriers, each barrier being a blue polypropylene film with a thickness of 0.3 mm. The usable range for the film with 2 barriers was from ~4 to ~40 Jcm^{-2}, while the usable range for the film with 5 barriers was from ~30 to ~300 Jcm^{-2}. Using both EBT3 films covered with 2 and 5 barriers will give a continuous usable range from 4 to 300 Jcm^{-2}, which will be useful for a consecutive 6-d UV exposure measurement.

INTRODUCTION

The solar ultraviolet (UV) spectrum spans over a range of wavelengths, namely, UVA (315–400 nm), UVB (280–315 nm) and UVC (100–280 nm). The UV radiation reaching the surface of the Earth comprises of mainly UVA, a small amount of UVB and essentially no UVC.

Solar UV radiation is the single most important UV source for the general public. It has been established that an over-dose or under-dose can have adverse impacts on human health. On one hand, UV is necessary to prevent diseases including rickets and osteoporosis, etc. On the other hand, UV can cause sunburns, skin cancers and cataracts. It is therefore necessary to have a good understanding on UV exposures in different environments.

There were already comprehensive studies on UV irradiances (in power per unit area, e.g., W/cm^2) and exposures (in energy per unit area, e.g., Jcm^{-2}) for different environmental settings, but unfortunately many of these could only perform instantaneous or short-term measurements (e.g., over a few hours) using commercially available electronic UV dosimeters which required batteries or electricity for operation. Apparently, longer-term measurements (e.g., over 1 day) have their merits in that they can avoid artefacts due to short-term fluctuations and can thus provide more accurate and representative information. One possible solution is to employ passive detectors which do not rely on batteries or electricity for operation. Moreover, most commercially available electronic UV dosimeters are relatively expensive, which have made detailed studies on spatial variations of UV levels implausible, due to the high cost of a large number of dosimeters for the measurements to be made simultaneously at many sites. Passive detectors are much less costly and can facilitate such simultaneous measurements.

Radiochromic film detectors are passive detectors whose light-absorption changes upon irradiation and are much less costly than the electronic dosimeters. As such, these film detectors can be useful in the situations described above. The polyphenylene oxide film[1,2] and the polysulfone film[3] are examples of such film detectors. Nevertheless, for these films, the light-absorption changes in the UV region, which requires a photospectrometer for quantification. To simplify the procedures, Abdel Rehim *et al.*[4] designed a radiochromic film with visible-light absorption changes upon UV irradiation.

Incidentally, radiochromic-film products have been developed and are commercially available in the market for clinical dosimetric applications[5], with visible-light absorption changes upon X-ray irradiation. As something undesirable in the original design, these films were also sensitive to ambient light sources[6] such as the solar radiation and fluorescent light sources[7,8]. Interestingly, our group has previously succeeded to demonstrate that the feasibility of using the Gafchromic MD-55-2 film to quantify UVA exposures[9], and the Gafchromic EBT film[10], EBT2 film[11] and EBT3[12] film to quantify solar (UVA+UVB) exposures. It is remarked that the EBT and EBT2 films had already been superseded by the EBT3 film in the market. In particular, we found that the usable range of UV exposures for the EBT3 film (i.e., the UV exposures corresponding to coloration changes of the film far from saturation) was from ~0.2 to ~30 $\mathrm{Jcm^{-2}}$ [12]. From our own preliminary studies, the maximum UV exposure recorded during summer time could reach 50 $\mathrm{Jcm^{-2}}$ per day. As such, the EBT3 film still needs further modifications to become suitable for longer-term measurements (e.g., over 1 day). The present work was devoted to such modifications.

NOMENCLATURE

UVA	[-]	Electromagnetic radiation with wavelengths in the range 315–400 nm
UVB	[-]	Electromagnetic radiation with wavelengths in the range 280–315 nm
UVC	[-]	Electromagnetic radiation with wavelengths in the range 100–280 nm
UV irradiance	[$\mathrm{W/cm^2}$]	UV irradiance
UV exposure	[$\mathrm{J/cm^2}$]	UV exposure
Net ROD	[-]	net reflective optical density
P	[-]	pixel values of the reflected intensity through an EBT radiochromic film

Subscripts

u	through an unexposed film
t	through an exposed film

MATERIALS AND METHODS

In the present investigation, we explored the possibility to extend the usable range of UV exposures by covering the EBT3 radiochromic films with "barriers" to reduce the UV irradiance on the films. The UV responses of the covered films would be different from those of the bare (uncovered) films. In the current study, we examined the responses of EBT3 films covered with 2 and 5 barriers, each barrier being a blue polypropylene (PP) film with a thickness of 0.3 mm (Easy Mate Blue PP Cover Sheet PJ29721040B). The EBT3 films covered with the barriers were supported on another PP film which was black in color (Easy Mate Black PP Cover Sheet PH29721040BK).

ISP Gafchromic EBT3 films (Lot no A03181301) were used in the present study, and were cut into smaller films with a size of about 1.5×1.5 $\mathrm{cm^2}$ to be covered with either 2 or 5 barriers. The films with the barriers were subjected to UV exposure using a Cole Parmer 15 W UV bench lamp (9815-series) in the laboratory. The films were placed at 1.2 cm from the lamp during the UV exposure. The (UVA + UVB) irradiance ($\mathrm{Wm^{-2}}$) from the UV bench lamp was measured using a Solarmeter® Model 5.0 (UVA + UVB) Total UV meter from Solartech Inc. (MI, USA). The instrument was calibrated by the manufacturer on 12 March 2014, and the accuracy of readings was estimated to be ±5%.

After UV irradiation, the EBT3 films were kept in light tight containers for 24 h. A selected 0.75×0.75 $\mathrm{cm^2}$ area on the films was then scanned using an Epson Perfection V700 desktop flatbed scanner in the reflection mode with a resolution of 50 dots per inch[10,12,13]. No filters or correction functions were applied to raw pixel value results. The red component of the 48-bit RGB color images was analyzed using the free ImageJ software (http://imagej.nih.gov/ij/). The coloration change due to UV irradiation was characterized by the net reflective optical density (*Net ROD*) defined as

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

where P_u and P_t were the pixel values corresponding to the reflected intensity from the unexposed film and the exposed film, respectively. This definition was previously employed by our group[10,12] while a similar one was used by Ohuchi[14] for reflected optical density.

The relationships between *Net ROD* and the UV exposures for the EBT3 films covered with both 2 and 5 barriers were plotted, from which the mathematical forms of the relationships as well as the usable ranges of UV exposures were found.

RESULTS AND DISCUSSION

Figure 1 shows the responses of EBT3 films covered with 2 and 5 barriers to UV exposures. The data appeared to show sigmoidal relationships between (*Net ROD*) and log(*Exposure*), which was also found in our previous work[12]. We therefore fitted the sigmoidal relationship to the data points using Origin 8 SRO v8.0725 (OriginLab Corporation, Northampton, MA, USA). The best fitted relationships were:

For 2 barriers:

$$Net\ ROD = -0.000830 + (0.494)/\{1 + 10^{[0.879(1.06\,-\,\log(Exposure))]}\} \tag{2}$$

For 5 barriers:

$$Net\ ROD = 0.0108 + (0.439)/\{1 + 10^{[1.06(1.84\,-\,\log(Exposure))]}\} \tag{3}$$

which were plotted as solid curves in Figure 1. The usable range for the EBT3 film with 2 barriers as shown by the region contained by the red dashed lines is from ~4 to ~40 $\mathrm{Jcm^{-2}}$. The usable range for the EBT3 film with 5 barriers as shown by the region contained by the green solid lines is from ~30 to ~300 $\mathrm{Jcm^{-2}}$.

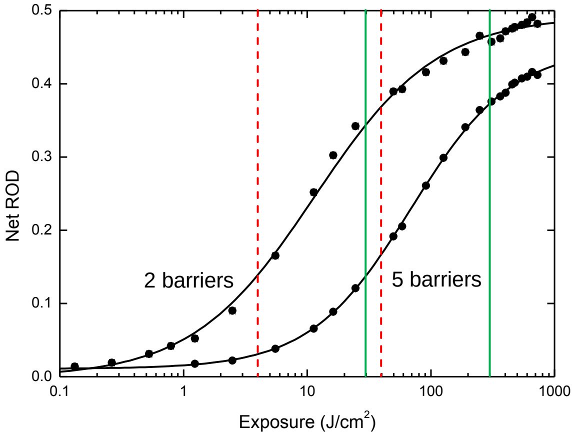

Figure 1 Responses of EBT3 films covered with 2 and 5 barriers supported on a black backing. Data points represent mean and error bars represent the SEM (n = 3). The curves are best-fit sigmoidal relationships given by Eqs. (2) and (3). The usable ranges for 2 and 5 barriers are represented by regions contained by the red dashed lines and green solid lines, respectively.

As described in the Introduction, our preliminary studies showed that the maximum UV exposure recorded during summer time could reach 50 Jcm^{-2} per day. Based on this, the EBT3 film covered with 5 barriers could be useful for a consecutive 6-d UV exposure measurement. As such, our objective of the present work to modify the EBT3 film for longer-term measurements was fulfilled. The trade-off was the sacrifice of the capability to measure low UV exposure levels (<30 Jcm^{-2}). A simple strategy to take care of both high and low UV exposure levels at the same time is to use both EBT3 films covered with 2 and 5 barriers for one measurement, which will be able to cover a continuous usable range from 4 to 300 Jcm^{-2}.

The present work was only a start to optimize the setup using EBT3 films for UV dosimetry. In future, different materials can be further explored as barriers and backings. Combination of more EBT3 films (covered with different numbers of barriers) can also be explored, which can further expand the usable range of UV exposures. However, we will also have to bear in mind that the larger number of EBT films will be more costly and will also lengthen the time taken to scan the films and analyze the images.

CONCLUSION

We examined the (UVA + UVB) responses of EBT3 films covered with 2 and 5 barriers, each barrier being a blue polypropylene film with a thickness of 0.3 mm. The usable range for the film with 2 barriers was from ~4 to ~40 Jcm^{-2}, while the usable range for the film with 5 barriers was from ~30 to ~300 Jcm^{-2}. Using the EBT3 films covered with 2 and 5 barriers together will give a continuous usable range from 4 to 300 Jcm^{-2}, which will be useful for a consecutive 6-d UV exposure measurement.

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