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Dosimetric and Spectroradiometric Investigations of Glass-Filtered Solar UV†

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ABSTRACT

The aims of this study were to investigate how glass-filtered UV irradiances vary with glass thickness, lamination of the glass and the effect of solar zenith angle (SZA), and to measure the glass-filtered UV exposures to different receiving planes with a newly developed UVA dosimeter. Spectroradiometric and dosimetric techniques were employed in the experimental approach. The percentage of the glass-filtered solar UV compared to the unfiltered UV ranged from 59% to 70% and was influenced to a small extent by the glass thickness and the SZA. The laminated glass transmitted 11–12% and the windscreen glass transmitted 2.5–2.6%. The influence of the SZA was less for the thicker glass than it was for the thinner glass. The change in transmission was less than 14% for the SZA between 48° and 71°. There was a negligible influence due to the SZA on the glass-transmitted UV of the laminated and windscreen glass. The influence of the glass thickness in the range of 2–6 mm on the percentage transmission was less than 16%. The influence of the glass thickness and the SZA on the glass-transmitted UV has been incorporated in the use of a UVA dosimeter for the glass-transmitted UV exposures. The UVA dosimeter was employed in the field to measure the glass-filtered UV exposures to different receiving planes. The UVA dosimeter has the potential for personal solar UVA exposure measurements.

INTRODUCTION

Understanding UV exposures during occupational and recreational activities could substantially reduce the risk of developing skin cancers and sun-related eye disorders later in life. Information on the levels of solar UV exposures to humans during normal daily activities in different environments is essential to understand the solar UV environment. This is necessary in the formulation of guidelines for programs to optimize the solar UV exposures to humans and hence reduce the risks of skin cancer and sun-related eye damage.

Polysulfone dosimeters have been employed widely in the quantification of erythemal UV (1) and UVB (280–320 nm) exposures in a range of environments and during different human activities. Examples of these are the investigation of the exposures to outdoor workers (2,3), school children (4,5), exposures underwater (6), in aircraft (7), in a welding environment (8), during outdoor activities (9) and evaluation of the protection provided by hats (10,11), trees (12), stockings (13) and clothing (14).

During normal daily recreational and occupational activities, there are a number of environments where humans are subjected to solar UV that has been transmitted through glass. Examples of these environments are in offices and homes in the vicinity of a window, in vehicles with untinted windows wound up (15–18) and in glass greenhouses (19) and sunrooms. The spectrum of the solar UV transmitted through glass is substantially different from that of the unfiltered solar UV spectrum (20,21). For glass, this results in a change in the relative ratio of UVA (320–400 nm) to UVB irradiances and a consequent change in the biologically damaging UV exposures. Nevertheless, it is still possible to obtain biologically damaging UV through glass (22). Additionally, glass-filtered UV has been reported to have implications for photosensitive patients (20).

For these environments where the UVB wavelengths have been removed and the UVA wavelengths are still present, it is necessary to determine the UVA exposures. The World Health Organization (23) has recommended research to monitor personal UV exposures in order to establish the percentage of the ambient solar UV received by the population. For these environments where the solar UV is filtered through glass and the UVB wavelengths are not transmitted, polysulfone dosimeters are not suitable for the dosimetric measurements of solar UV. This is due to the polysulfone responding only to wavelengths shorter than 330 nm (1).

Several different types of dosimeters have been reported for the measurement of UVA exposures (15,24,25). This article will extend this previous research and employ the UVA dosimeter reported in Parisi *et al.* (25) for the dosimetric measurements of glass-filtered solar UV. The research questions that will be investigated are: How do the glass-filtered UV irradiances vary with glass thickness, whether or not the glass is laminated, the effect of solar zenith angle (SZA) and can the glass-filtered UV exposures to different receiving planes be measured with a newly developed UVA dosimeter.

MATERIALS AND METHODS

Horizontal plane. A series of glass-filtered solar UV spectra for a horizontal plane were undertaken in late autumn at each of 10.00 EST (Australian Eastern Standard Time) and 12.00 EST on 25 May 2006

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and 8.15 EST on 26 May 2006 (in Toowoomba, Australia, 27.5°S, 151.9°E, 693 m above sea level). The SZA for each series of measurements were 55°, 48° and 71°, respectively. The glass was placed over the input optics of a calibrated UV spectroradiometer employed to scan the solar UV spectrum between 280 and 400 nm in 0.5 nm increments. Each scan took approximately 1 min to initialize and 2 min for the data collection. The types of glass tested were clear window glass with thicknesses of 2, 3, 4, 5 and 6 mm, laminated glass (Downs Quick-Fix Glass, Toowoomba, Australia) and windscreen glass. The laminated glass consists of two pieces of 3 mm thick glass bonded together. For each series of measurements, the sequence undertaken was to measure the unfiltered solar spectrum followed by the glass-filtered spectrum for each of the seven glass types and finally another measurement of the unfiltered solar spectrum.

The UV spectroradiometer (Bentham Instruments, Reading, UK) employed to measure the glass-filtered UV spectrum has been described elsewhere (26). Briefly, the spectroradiometer is based on a monochromator (model DTMc300F) with double holographic gratings with the input optics provided by a diffuser (model D6) that is connected by a 4 mm diameter, 1 m long fiber optic. The irradiance calibration of the system was undertaken at the site against a 150 W quartz tungsten halogen lamp calibrated to the National Physical Laboratory, UK standard and the wavelength calibration was against the UV spectral lines of a mercury lamp.

Dosimetric measurements. The glass-filtered dosimetric measurements were undertaken with a previously described UVA dosimeter (25). Briefly, this dosimeter consists of the chemical phenothiazine cast in thin film form (27) and filtered by mylar film with a thickness of approximately 0.13 mm (Cadillac Plastics, Australia). The dosimeter is made up in a holder with an overall size of 3 cm × 3 cm and with an opening of 1.2 cm × 1.6 cm. This UVA dosimeter is sensitive to the UVA wavelengths only and the UVA-induced photodegradation in the dosimeter is quantified by the measurement in a spectrophotometer (model 1601; Shimadzu Co., Kyoto, Japan) of the change in optical absorbance at 370 nm. This measurement wavelength has been selected as it is in the wavelength range where the largest change in optical absorbance occurs.

The dosimeters were calibrated to broadband solar UVA by exposing a series of dosimeters on a horizontal unshaded plane to a range of UV exposures between 9.50 EST and 12.50 EST on a relatively clear day on 26 May 2006. The resulting exposures varied from 5 min to 3 h. The SZA over this period ranged from 48.6° to 56.5°. Concurrently, the UVA exposures were measured with a broadband meter (model 501; Solar Light Co., PA) located on an unshaded roof. The UVA meter is temperature stabilized to 25°C and it records the horizontal plane UVA exposures every 5 min. The meter was calibrated against the UV spectroradiometer described previously.

The preexposure and immediate postexposure absorbances of each dosimeter were measured in the spectrophotometer at 370 nm to allow calculation of the change in absorbance (ΔA). This calibration relates the UVA exposures to the changes in optical absorbance. For each dosimeter the absorbance was measured for four sites over the dosimeter in order to account for any minor variations over the dosimeter. The four sites were obtained by rotating each dosimeter by 90° between each measurement about an axis parallel to the spectrophotometer beam.

A set of four dosimeters were exposed on a horizontal plane under each of the 3 mm glass, the laminated glass and the windscreen glass. Each set was exposed for 1.5 h exposure for SZA between 49° and 56°. The resulting changes in absorbance and the calibration curve obtained were employed to determine the UVA exposures transmitted through each type of glass.

Planes at any orientation. The glass-transmitted UVA exposures to receiving planes at different inclinations and orientations was investigated by employing five pieces (150 mm × 150 mm) of the 3 mm glass to form a horizontal plane and four vertical planes with each one facing north, east, south and west, respectively. These were arranged to form a cube and two dosimeters placed on the inside of each of the vertical planes and on the underside of the horizontal plane. Nonreflective and opaque tape was used as a backing material in order to prevent the dosimeters receiving UVA radiation on their reverse sides. This ensured that the dosimeters received the UVA exposures to the horizontal plane facing upward and the vertical planes facing north, east, south and west, respectively. The same setup was employed for the laminated glass. The dosimeters for both sets of glass were exposed to solar UV between 8.45 EST and 10.15 EST on 21 June 2006 for the SZA range of 68.3° to 56.2°. The solar azimuth over this time ranged from 46.4° to 24.5°.

RESULTS

Horizontal plane

Two unfiltered solar UV spectra on a horizontal plane at 10.00 EST on 25 May 2006 for a SZA of 55° collected over 2 min periods approximately 25 min apart, prior to and immediately after the glass-filtered spectra were recorded are provided in Fig. 1. The SZA changed by less than 3° over this time. The solar UV spectrum filtered through 2, 3, 4, 5 and 6 mm glass (from left to right) are provided as a comparison. The same figure provides the solar UV spectrum filtered through laminated glass and filtered though windscreen glass. For the glass of different thicknesses, the UVB waveband has been removed and the effect of the increasing glass thickness is to shift the cutoff wavelength to longer wavelengths. The difference in the spectral irradiance is larger at the shorter wavelengths compared to the longer wavelengths. For example, the spectral irradiances at 330 nm are 123.4, 98.8, 71.9, 46.8 and 33.4 mW m^{-2} nm^{-1}, respectively, for the 2, 3, 4, 5 and 6 mm glass. In comparison, the spectral irradiances at 385 nm are 415.8, 411.7, 409.2, 403.6 and 398.5 mW m^{-2} nm^{-1}. The glass-filtered spectral irradiance at 330 nm for the 6 mm glass is approximately one quarter of that for the 2 mm glass. However, at 385 nm, the difference is of the order of 4%. At this wavelength, the UV transmission of the laminated glass and windscreen glass is reduced by a factor of 7 and 218, respectively, compared to the window glass. The bonding material used in the laminated and windscreen glass filters a significant proportion of the UV without significantly influencing the visible transmission (28).

The irradiances to a horizontal plane on a relatively clear day due to the unfiltered solar spectrum and the spectrum filtered through the five thicknesses of glass, the laminated glass and the windscreen for the SZA of 48°, 55° and 71° were employed to calculate the ratios of the glass-filtered UV to the

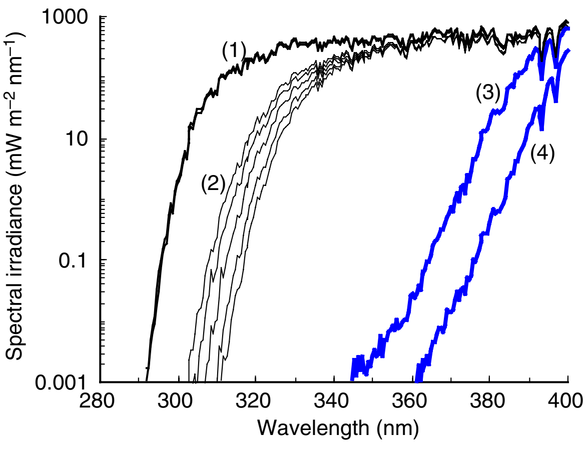

Figure 1. The unfiltered solar UV spectrum (1), the solar UV spectrum filtered through 2, 3, 4, 5 and 6 mm glass (from left to right) (2), the solar UV spectrum filtered through laminated glass (3) and filtered through windscreen glass (4).

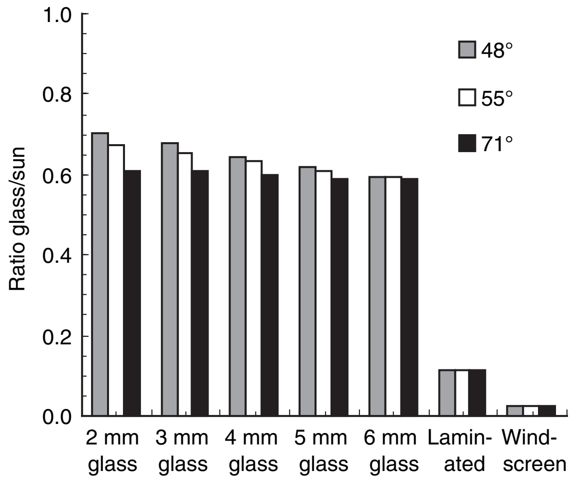

Figure 2. The ratio of the glass-filtered UV to the unfiltered UV for the different types of glass and the three solar zenith angles.

unfiltered UV for the different types of glass and the three SZA as provided in Fig. 2. This shows the influence of the different thicknesses and the SZA on the glass-filtered solar UV. The irradiances for the sun or unfiltered columns have been obtained by averaging the irradiances from the unfiltered spectra measured at the start and end of each series of spectral measurements.

Dosimetric measurements

The regression curve fitted to the calibration data of the UVA dosimeters (Fig. 3) is: UVA = $1.66e^{22.72\Delta A}$ kJ m^{-2}, where ΔA is the change in absorbance at 370 nm. The R^2 for the fitted curve is 0.99. The x-axis error bars are the standard deviation of the four ΔAs measured for each dosimeter.

The glass-filtered UVA exposures measured on a horizontal plane with the dosimeters are 167.7, 7.9 and 5.0 kJ m^{-2} for the 3 mm window glass, laminated glass and windscreen glass, respectively. The exposures through the 2, 4, 5 and 6 mm glass were within the error margin of the exposures for the 3 mm glass. The exposure through the laminated glass is significantly less than the exposure through the 3 mm window glass. Similarly, the UVA exposure through the windscreen glass is less than the exposure through the laminated glass.

Planes at any orientation

The glass-filtered solar UV exposures to the receiving planes at different orientations, measured with the UVA dosimeter are shown in Fig. 4 for the 3 mm glass and the laminated glass. The unfiltered UVA exposures on a horizontal plane measured over the same period was 113 kJ m^{-2}. The receiving plane with the highest exposure is the north vertical plane and for the 3 mm glass, the glass-filtered UV is approximately one-half of the horizontal plane unfiltered UVA exposure. The horizontal plane and the east facing vertical plane received approximately one-third of the unfiltered UVA exposure. The south and west vertical planes received approximately one-fifth of the horizontal plane unfiltered UVA exposure.

DISCUSSION

This article has reported on how the glass-filtered UV irradiances vary with glass thickness, lamination of the glass and the effect of SZA, and how the glass-filtered UV exposures to different receiving planes can be measured with a newly developed UVA dosimeter. The percentage of the glass-filtered solar UV compared to the unfiltered UV or the percentage of transmitted UV ranged from 59% to 70% and was influenced to a small extent by the glass thickness and the SZA. The laminated glass transmitted 11–12% and the windscreen glass transmitted 2.5–2.6%. This is comparable to the percentage transmission of 62.8% for nonlaminated glass and the range of 9.7–0.6% for clear laminated glass and gray laminated glass, respectively, found by Hampton *et al.* (20). For the UVA waveband, transmittances of 67–2.1% were measured for different vehicle windscreens and glass (29).

This study has extended previous research to investigate the influence of SZA on the glass-filtered UV. For the SZA range of 48° to 71° investigated, there was minimal influence due to the SZA on the percentage of transmitted UV. Similarly, the influence of the SZA was less for the thicker glass than it was for the thinner glass. For the thinner glass, the larger SZA causes a longer path through the glass and reduces the percentage transmission. For the thicker glass,

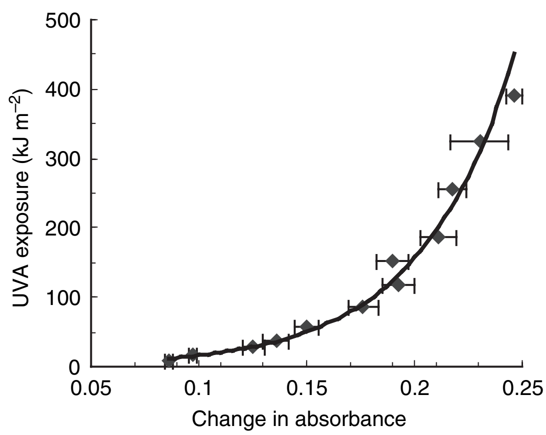

Figure 3. Calibration of the UVA dosimeter in winter for a solar zenith angle range of 48.6° to 56.5°.

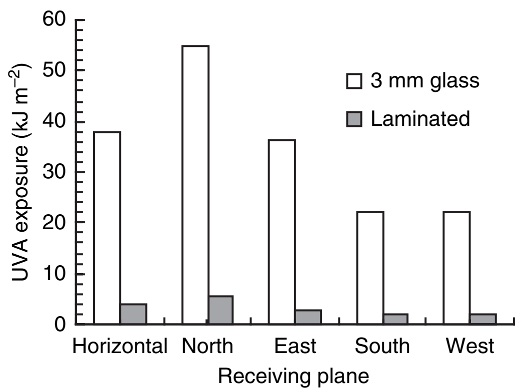

Figure 4. The glass-filtered solar UV exposures to the receiving planes at different orientations, measured with the UVA dosimeter.

the path through the glass is longer by a factor of approximately 3 due to the thicker glass and consequently, the glass thickness is a larger influencing factor in the amount of attenuation than the SZA. The change in percentage transmission was less than 14% for SZA between 48° and 71°. In comparison, the change in the unfiltered irradiance was more than doubled from 16.2 to 38.2 W m^{-2} for the respective SZAs of 71° and 48°. The influence of the glass thickness in the range of 2–6 mm on the percentage transmission was less than 16%. The bonding material in the laminated glass and windscreen glass significantly reduces the glass-transmitted UV to approximately 11% and 2.5%, respectively. This has been previously reported in Tuchinda *et al.* (28). This research has built on this and considered the influence of SZA on the UV transmitted through laminated glass and windscreen glass. There is negligible influence due to the SZA on the glass-transmitted UV of the laminated glass and windscreen glass.

The measurement of the influences of the glass thickness and the SZA on the glass-transmitted UV has been incorporated in the dosimetric measurement of the glass-transmitted UV exposures. The calibration of the UVA dosimeter provided in this study is for glass-filtered solar UV for SZA between 48.6° and 56.5°. The response of the UVA dosimeters starts to saturate after approximately 30–40 kJ m^{-2} exposure to UVA. Previous results with the calibration of polysulfone dosimeters employed for the measurement of erythemal exposures show that the dosimeters need to be calibrated with the range of solar spectra that will be encountered during the measurement campaign and it is expected that this will also apply to the UVA dosimeters. The UVA dosimeter has been employed in the field to measure the glass-filtered UV exposures, both on a horizontal plane and on different receiving planes. Due to the solar azimuth angles of 46.4° to 24.5° throughout the exposure period, the exposures to the south- and west-facing planes were due solely to the diffuse UV. In comparison, the exposures to the planes facing in the other directions were due to both the direct and diffuse UV. The exposures to each plane will vary for different solar zenith and azimuth angles, along with changes for planes at different inclinations and azimuths. Results for orientation will alter in the northern hemisphere due to the position of the sun in the sky, however such results presented are still important as they indicate the variability of UVA exposures through glass in different orientations. The UVA dosimeter reported can be employed to measure the UVA exposures to planes at any orientations for any solar zenith and azimuth angles and has the potential for use as a reliable dosimeter for personal solar UVA exposure measurements. Additionally, the UVA dosimeter could be calibrated against a weighted UV response as more knowledge is gained on the action spectra for various health effects. Further research will follow to investigate the use of the UVA dosimeter employed in this research to other situations and environments for the range of receiving planes on humans behind windows and in cars.

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