Mean Exposure Fractions of Human Body Solar UV Exposure Patterns for Application in Different Ambient Climates

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ABSTRACT

In this research, the erythemally effective UV measured using miniaturized polysulphone dosimeters to over 1250 individual body sites and collected over a four year period is presented relative to the total exposed skin surface area (SSA) of a life-size manikin model. A new term is also introduced, the Mean Exposure Fraction (MEF). The MEF is used to weight modeled or measured horizontal plane UV exposures to the total unprotected SSA of an individual and is defined as the ratio of exposure per unit area received by the unprotected skin surfaces of the body relative to the exposure received on a horizontal plane. The MEF has been calculated for a range of solar zenith angles (SZA) to provide a sunburning energy data set weighted to the actual SSA of a typically clothed individual. For this research the MEF was determined as 0.15, 0.26 and 0.41 in the SZA ranges 0^o-30^o, 30^o-50^o and 50^o-80^o providing information that can be used in a variety of different ambient, latitudinal and seasonal climates where total human body UV exposure information is not available.

INTRODUCTION

Measurements and modelled predictions of the solar ultraviolet (UV) incident upon a horizontal plane are presented frequently in the literature (1,2,3). These results provide enough information to show geographical trends in solar ultraviolet exposure distributions, providing information on local ultraviolet climates to which population groups are exposed. However, for research that requires detailed information on localized patterns in human exposure distribution these studies can only provide limited information. This is largely due to an inherent difficulty in transforming the ambient horizontal plane solar ultraviolet exposure to the equivalent exposure received by the human body. Many studies have been conducted using ultraviolet sensitive dosimeters to estimate the proportion of exposure received by the body (4,5,6). The limitations of these studies are the total number of measurements that are available to be used to estimate the exposure received by unprotected skin surfaces.

To transform the ambient ultraviolet to the human form, factors such as the inclination and orientation of each portion of the unexposed skin, the shading provided by other body parts, the amount of skin covered by clothing, the amount of protection provided by hats, and the skin type of the individual need to be considered. Additional techniques employed in solving this problem have involved numerical modeling of the light distribution received by the human form (7,8) or other geometrical models (9,10). The positive side of using such a method is that the exposure received by the whole body can be considered at once. The difficulty however with these techniques is that they do not often take the shading caused by the body itself into account. Furthermore, they are not based on actual measurements of personal solar UV exposures.

To overcome this, a solution combining high density miniaturised ultraviolet sensitive dosimeter measurement and model exposure weighting was developed (11,12). This previous research resulted in the production of a large set of high density exposure measurements taken for a range of solar zenith angles (SZA). This data set is manipulated in this research and reduced into a single value, the Mean Exposure Fraction (MEF) for three specific SZA ranges that can be used to express the horizontal plane ambient ultraviolet exposure relative to the exposed skin surface area of an individual.

MATERIALS AND METHODS

Miniaturized polysulphone dosimetry: Miniaturized polysulphone dosimeters were used to measure the eythemally effective solar ultraviolet (UVe) (13). These dosimeters were used in preference to conventional polysluphone dosimeters due to their flexibility for fitting to complex human surface topography, and their ability to be deployed in high density.

To simulate the random movement of an individual in the sun, a turntable, rotating approximately two times in every minute was used to deploy two upright manikin models under changing SZA and low cloud cover conditions over a four year period (Figure 1). Miniaturized polysulphone dosimeters were attached in high density on each manikin model to measure specific body site UVe exposures. The number of dosimeters employed was based on using the technique of a series of horizontal and vertical contours spaced at 0.5 cm over the face, 1 cm on the neck, arms and hands and 2 cm on the legs (12). These spacings were used to take into account the variation in topography of the human body. The miniaturized dosimeters have been previously developed and tested for the measurement of UV exposures over a range of situations (11). Each miniaturized dosimeter was made using a flexible card frame measuring approximately 10 mm by 15 mm with a clear circular aperture of 6 mm over which polysulphone film of an approximate thickness of 40 μm was adhered. Each dosimeter was deployed to a mapped grid location plotted on each of the face, neck, arm, hand or leg manikin model body sites. The positions were plotted with a laser and a translation stage. The collected UVe exposure dataset is used here to determine the MEF of an individual for changing SZA under typically low cloud cover conditions. This data is extracted from the published supplementary results of Downs and Parisi (12).

>FIGURE 1<

The polysulphone film dosimeter used has a spectral response that approximates the erythemal action spectrum (14). Pre- and post- exposure absorbance measurements of the polysulphone film adhered to the UV dosimeter holders were made at 330 nm using a spectrophotometer (model 1601, Shimadzu Co., Kyoto, Japan) and subsequent exposures expressed relative to the horizontal plane exposure measured in proximity to the manikin models over the same exposure period. The exposure measured at any skin surface site and expressed relative to the horizontal plane ambient UVe exposure was determined as:

$$ER_s = \frac{E_{site}}{E_{hor}} \qquad (1)$$

where ER_s is the exposure ratio of the UV exposure measured at any given body site, E_{site}, and expressed relative to the horizontal plane UVe exposure, E_{hor}. Here, E_{site} and E_{hor} were determined using the polysulphone approximation of Diffey (15) for which only the change in polysulphone absorbency is required when determining ratios of exposure.

Local considerations: Body site ER_s measurements collected previously (12), were categorized within the SZA ranges of 0^o-30^o, 30^o-50^o and 50^o-80^o. The changing position of the sun within each SZA range introduces uncertainty due to variation in the exposure received primarily caused by changes in atmospheric absorption with changing solar position. These limitations must be recognized as inherent to the dosimeter measurement method which requires a minimal exposure duration to cause a change in the polysulphone film absorbency and thus the solar position varied during the minimal exposure intervals set by the three ranges presented here. All measurements were taken at the University of Southern Queensland Toowoomba campus, Australia, (152^o E, 28^oS). The range of SZA for which the measurements were taken will allow use of the presented dataset over an extended latitudinal gradient.

The total cloud coverage at the time of exposure, the type of cloud, atmospheric absorption by dust and anthropogenic particulates, altitude above sea level, and the SZA will each influence the total UV exposure received. These factors also influence the ratio of direct to diffuse irradiance and will influence the ER_s for the measured SZA ranges presented here. To minimize the influence of these factors the results presented here are for low cloud cover conditions and relatively unpolluted skies. The factors can be accounted for in any local environment of interest by either direct measurement of the UV exposure or the use of ambient UV modeling software, for which a number of models are readily available.

For the individual, the type of clothing worn, hatwear, eyewear and hair cover influence the total skin surface area that will be exposed. The total exposure received by the body is also strongly influenced by body posture during each exposure event (16). For this research, the case of an individual's exposure is considered for an upright position and the type of clothing worn is taken to be a t-shirt, short pants, and shoes leaving the face, neck, arms, hands and legs exposed to ambient solar ultraviolet. The technique developed applies to an upright adult individual and low cloud cases. The work is taken to represent a reasonable approximation of the exposure likely to be received by an individual for most cases. For children and for different body postures the technique presented can be repeated by high density dosimeter measurements for the individual activity and SZA range of interest.

Skin Surface Area: The mean UV exposure received by unprotected skin surfaces of the body is proportional to the body surface area exposed for any given body orientation. Each mankin body model surface including the face, neck, arms, hand and leg were considered separately for the purpose of calculating an exposed skin surface area (SSA). The face, neck, arm, hand and leg body surfaces were divided into a grid pattern consisting of 709 measurement points for the face, 98 for the neck, 166 for the arm, 74 for the dorsum of the hand and 233 for the leg (12). These points were used to define vertices for individual quadrilateral surface planes consisting of 4 vertex points in each plane. The area of each plane was calculated as the product of mean horizontal length and their respective vertical spacing (quadrilateral height).

Figure 2 illustrates the positions of vertex points marked on the manikin headform for facial exposure measurement. The figure also illustrates the surface grid pattern, and the SSA for a single quadrilateral surface plane. The surface plane shown in the figure is one of 633 surface planes used to determine the SSA for the human face. The grid network shown in Figure 2 was developed and tested in previous preliminary studies (11,12) to represent UVe exposure patterns but is modified here by weighting to the relative SSA of each body model.

The total SSA of the human face was determined as the sum of each individual surface plane. Due to the symmetry of the face and the back of the neck, only half of the surface area was marked on the manikin headform model. SSA for the face and neck were calculated by doubling the marked SSA. The SSA for a single arm and leg model was doubled to represent the exposure received by both arms and legs of an individual. The SSA for the back of the hand was measured and also doubled to represent the exposure received by both hands. Table 1 lists the total number of quadrilateral surface area planes and the calculated total area for each of the face, neck, arm, hand and leg body surfaces used in developing the MEF presented in the results.

>FIGURE 2<

>TABLE 1<

Mean Exposure Fraction: The mean exposure fraction is calculated using equation 2:

$$MEF = \sum ER_s A_s / \sum A_s \qquad (2)$$

Where the summation is performed for the face, neck, arms, hands and legs, and is determined for each mean ER_s determined for a skin surface plane quadrilateral having an area given by A_s. The MEF allows measured or modelled exposures to be weighted relative to the unprotected surface area of an individual for different SZA ranges.

RESULTS AND DISCUSSION

Table 2 presents the calculated MEF for exposure measurements made in each 0^o-30^o, 30^o-50^o and 50^o-80^o SZA range. The MEF is a dimensionless index which holds for any UVe exposure. Body surfaces with larger areas of unprotected skin collect the greatest amount of solar energy, however the exposure received by each body surface is also dependent upon the orientation of the surface with respect to the sun. The MEF as shown in table 2 varies with SZA and can be calculated for individual body surfaces. The measurements presented in this research are slightly lower than the geometry conversion factor ratios of Pope and Godar (10). This is likely due to the measurements used in this research accounting for shadowing effects on the whole body.

>TABLE 2<

Given the MEF for the three SZA ranges presented in table 2, any measured or modeled ambient UVe exposure can be expressed relative to the exposed SSA of the human body. As an example, table 3 presents the modelled ambient UVe exposure for Brisbane, Australia (27^o30'S 153^o0'E) on a single clear sky day in Summer, Autumn and Winter. The exposures presented here are modelled estimates. The UV irradiance model used to calculate the results presented in table 3 is a hybrid model employing the numerical algorithms of Green et al. (17), Green et al. (18), Schippnick and Green (19) and Rundel (20). This model has been used previously and is discussed in detail in previous research (21). The weighted MEF influences the exposure received by the total exposed skin surfaces of the body for the changing position of the sun for each day.

>TABLE 3<

Due to changing solar elevation with the season at Brisbane's latitude, the total exposure received by the unprotected SSA of the body changes from 20% of the ambient horizontal plane UVe exposure on 1 January, to 28% on 1 April, to 41% on 1 July. For an individual dressed for leisure who experiences low cloud cover conditions, this effectively results in that individual receiving approximately 30% of the ambient exposure to the exposed skin surfaces of the body when averaged over the entire year. Using the MEF, the fractional exposure received by the body can be determined from modeled or measured horizontal plane ambient UVe exposures over a wide latitudinal gradient.

CONCLUSIONS

A method has been presented from measured ER results recorded at over 1250 individual body sites to determine for the first time a measured weighting for the exposed SSA of the human body standing in an upright position. Although limiting, the data presented provides an approximation that can be applied to individuals using outdoor environment for many cases. The presented MEF information determined for each of three SZA ranges can be used as an evaluation of the actual UVe exposure received by individuals using an outdoor environment. Further research investigating the influence of body posture approximating the various activities individuals might partake in while outdoors will improve the presented MEF information determined for this research work. It is expected that the results presented will be useful for the prediction of annual and lifetime UVe cumulative exposures. This information will assist in epidemiological modeling of CMM and NMSC incidence with weighted UVe exposure data sets.

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TABLES

Table 1. Total area of exposed skin surfaces calculated by quadrilateral surface plane area summation for the face, neck, arm, hand and leg

Model	Quadrilateral surface planes	Total Surface Area (cm^2)
face	633	650
neck	77	186
arm	135	952
hand	56	176
leg	257	3746

Table 2. The Mean Exposure Fraction for the entire exposed skin surface area and each of the unprotected skin surfaces of the face, neck, both forearms, both hands and both legs calculated in the SZA ranges 0^o-30^o, 30^o-50^o, and 50^o-80^o. The MEF holds for any UVe exposure received on a horizontal plane.

SZA	Face MEF	Neck MEF	Forearms MEF	Hands MEF	Legs MEF	Total MEF
0^o-30^o	0.29	0.23	0.16	0.47	0.10	0.15
30^o-50^o	0.38	0.37	0.19	0.54	0.24	0.26
50^o-80^o	0.49	0.55	0.33	0.58	0.40	0.41

Table 3. Body weighted exposure calculated for different days of the year expressed by application of the MEF for each respective SZA range. The results presented are for Brisbane, Australia.

Date	Time of day	SZA range	Ambient UVe exposure (Jm^{-2})	Body weighted UVe exposure (Jm^{-2})
1 January 2011	5:50 am - 8:10 am	80^o-50^o	287	118
	8:10 am - 9:40 am	50^o-30^o	847	220
	9:40 am - 2:00 pm	30^o-4^o-30^o	4431	665
	2:00 pm - 3:35 pm	30^o-50^o	887	231
	3:35 pm - 5:55 pm	50^o-80^o	269	110
			Total = 6721	Total = 1344
1 April 2011	6:45 am - 9:10 am	80^o-50^o	284	116
	9:10 am - 11:50 am	50^o-32^o	1521	395
	11:50 am - 2:30 pm	32^o-50^o	1547	402
	2:30 pm - 4:55 pm	50^o-80^o	304	125
			Total = 3656	Total = 1038
1 July 2011	7:35 am - 11:50 am	80^o-51^o	661	271
	11:50 am - 4:10 pm	51^o-80^o	679	278
			Total = 1340	Total = 549

FIGURES

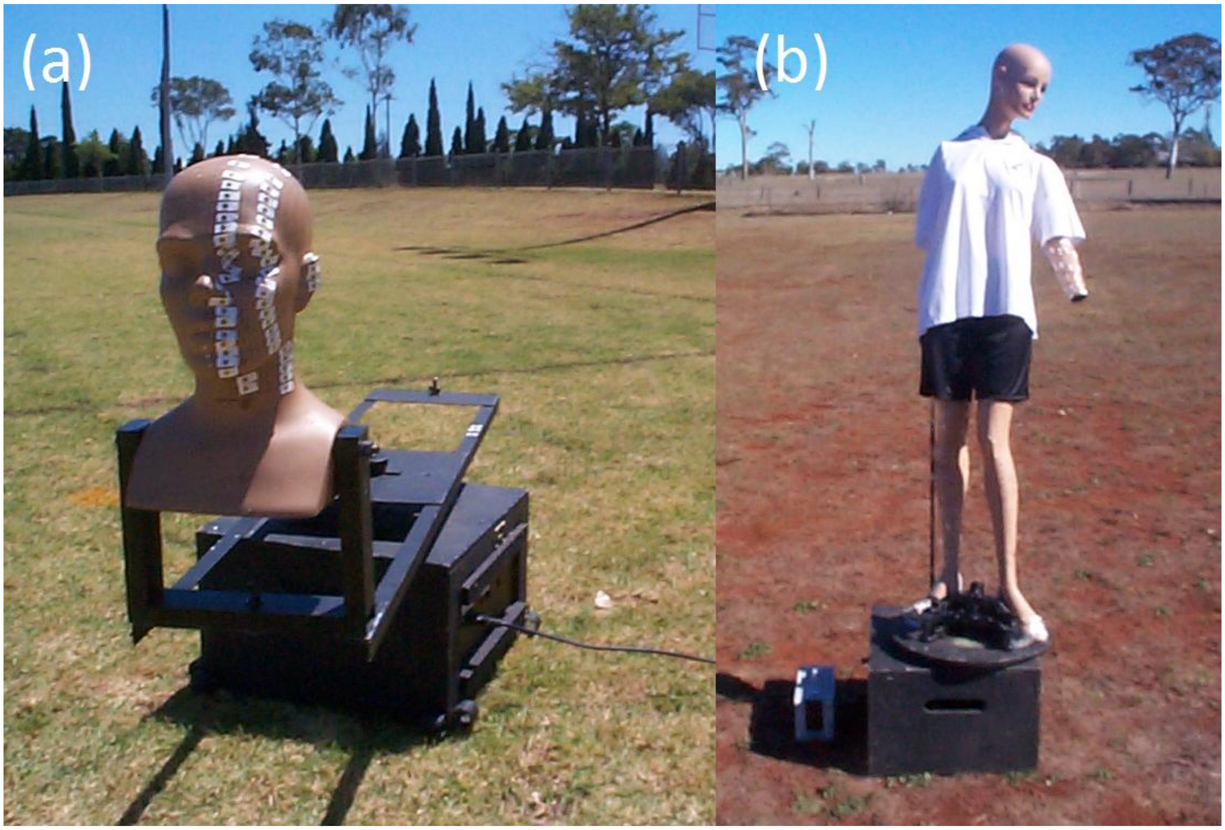

Figure 1. A headform (a) and full body (b) mankin model was used to collect UV exposure data to exposed skin surface areas over a four year period in the SZA ranges 0^o-30^o, 30^o-50^o and 50^o-80^o.

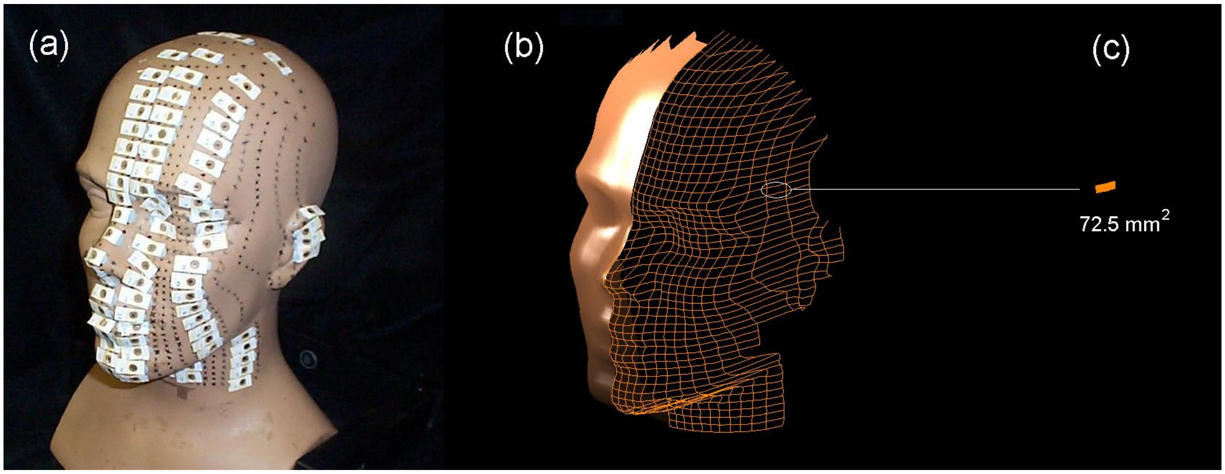

Figure 2. Marked vertex positions on the manikin headform (a), the computer generated exposure grid (b), and the quadrilateral surface area of a single surface plane (c). The summation of the area of each surface plane approximates the surface area of the face.