PERSONAL EXPOSURE DISTRIBUTION OF SOLAR ERYTHEMAL ULTRAVIOLET RADIATION IN TREE SHADE OVER SUMMER

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ABSTRACT

The personal radiant exposure distribution of solar erythemal UV in tree shade for an upright posture was measured, with measurements over the whole summer for a total of seventeen trees. For each tree, the personal radiant exposure distribution was measured for both the morning and afternoon periods. The exposure ratios averaged over all the trees and over the morning and afternoon periods ranged from 0.16 to 0.49 for the different anatomical sites. A numerical model was employed to estimate the UV radiant exposure to humans in the tree shade over the entire summer. The body sites with the higher exposure ratios in the tree shade were the vertex of the head, shoulders and forearms with radiant exposures over the summer of 1,300 MED to the vertex of the head and 1,100 MED to the shoulders and forearms. These radiant exposures in the shade are substantially higher than the ambient erythemal UV measured in full sun on a horizontal plane over a full summer at a more temperate Northern Hemisphere latitude. The average radiant exposures per day to each anatomical site for a complete day in the tree shade ranged from 4.6 to 14.6 MED. The research has provided new data that is essential to quantify the human UV exposure during outdoor activities.

Key words: non-ionizing; ultraviolet; trees; erythema; dosimeters; shade

1. INTRODUCTION

Research on the health effects to humans due to solar ultraviolet (UV) radiation requires the quantification of the UV exposure to humans. The World Health Organization (WHO, 1994) recommend research monitoring personal UV exposures to determine the fraction of the ambient solar UV received by the population. The solar ultraviolet radiant exposure to specific body sites on humans requires the usage of personal passive UV dosimeters (Diffey, 1989, Wong et al., 1992) to the selected body sites. Personal monitoring allows the quantification of the distribution and the fraction of the ambient UV radiant exposure on a horizontal plane (Webb, 1997). Polysulphone (Davis et al., 1976) has been used extensively as a personal UV dosimeter.

In Queensland, Australia, the solar UV radiant exposures have been measured by using polysulphone dosimeters on infants and small children, (Moise et al., 1999), outdoor workers (Wong et al., 1996, Gies et al., 1995, Kimlin et al., 1998a), school children (Kimlin et al., 1998a, Gies et al., 1998), home workers (Kimlin et al., 1998a, 1998b) and during recreational activities (Herlihy et al., 1994). However, little is known about the anatomical distribution of the natural solar UV in tree shade. Previous research has measured the solar UV in tree shade on a horizontal plane (Grant, 1997, Parisi et al., 1999a, 1999b, Parsons et al., 1998) and to a human form in the shade of two different trees (Parisi et al., 1999a). For the summer season, the diffuse component was measured to comprise 56% to 60% of the solar UV radiation in the tree shade (Parisi et al., 1999c). This high diffuse UV component may result in high UV radiant exposures in the tree shade to parts of the body that are not protected from UV radiation that are at all orientations and inclinations, including the vertical. No database exists on the radiant exposure to specific human body sites in tree shade. Consequently, this paper extends the previous research to measure the anatomical distribution of solar erythemal UV in tree shade and the protection factor (ratio of radiant exposure in shade to that in sun) at the anatomical sites for an upright posture, with measurements over the whole summer, and to employ a numerical model to estimate the UV radiant exposure in the tree shade over an entire summer.

2. MATERIALS AND METHODS

2.1 Measurement of Personal UV in Tree Shade

Polysulphone dosimeters were employed to monitor the erythemal UV radiant exposure to selected anatomical sites to a model of a human in tree shade. The polysulphone film was cast at the University of Southern Queensland (USQ) and fabricated into dosimeters. Each of the dosimeters has an active area of approximately 1 cm^2 and an overall size of 3 cm x 3 cm. The pre and post exposure optical absorbency of the polysulphone dosimeters was measured at 330 nm in a spectrophotometer (Shimadzu Co., Kyoto, Japan). It was not practical nor convenient to use human subjects wearing the dosimeters in the tree shade over the period of a day. Consequently, the well-established method of deploying the dosimeters on rotating manikins to average out the directional variation was employed (for example, Airey et al., 1995, Kimlin et al., 1998a). Previous research has compared the difference between human and manikin UV radiant exposure measurements and found a difference on average of 30% (Meldrum, 1998). These differences are probably due to a tendency of humans to stoop forward, outstretch the arms and a preference to turn away from the direct sun (Holman et al., 1983).

The dosimeters were attached on upright manikins, each on a platform rotating at 1 to 2 revolutions per minute in the tree shade to simulate a human in a predominantly upright position. For each of the manikins the rotating platform had a height above the ground of 65 to 70 cm with the manikin on top of that. The heights of the manikins above the platforms were 1.78 m with the head upright. The arms on the manikins between the shoulder and elbow were approximately vertical with the forearms at different angles between the vertical and horizontal. The legs were either vertical or at an angle of up to 30 degrees to the vertical. This setup was designed to simulate a human in the tree shade that is resting, talking or a spectator at a sports event. Each manikin was maintained within the visible shade boundary throughout the day by moving it as the tree shadow shifted. This was to simulate humans who move to stay in the tree shade as the shade shifts throughout the day. The dosimeters were affixed on the manikins at the sites as follows: vertex of head, left and right ear, nose, left and right cheek, chin, forehead, lumbar spine, lower sternum, left and right shoulder, left and right forearm, right thigh front and back, left thigh front and back, right shin front and back, left shin front and back, right ankle front and back and left ankle front and back. All of these sites were selected to provide a thorough coverage of the human body and to assess the effect of shade on the UV distribution over a human.

The measured change in optical absorbance at 330 nm, ΔA, of the dosimeters due to UV radiant exposure is related to the erythemal UV radiant exposure, UV_{ery}, by (Diffey, 1989, Airey et al., 1995):

$$UV_{ery} = K(\Delta A + \Delta A^2 + 9\Delta A^3) \qquad (1)$$

where K is a constant determined in the calibration. The value of K varies for different thicknesses of polysulphone film. This is overcome by calibrating each individual batch of film. For an individual batch of film, the error in UV_{ery} from a measured ΔA is of the order of 10% (Diffey, 1989). The exposure ratio, ER, of a particular anatomical site was calculated as the ratio of the erythemal radiant exposure to that site in the shade to the ambient erythemal radiant exposure on a horizontal plane in full sun over the same time period. This ambient UV was measured by two dosimeters deployed on a horizontal plane in full sunlight over the same time period of radiant exposure as the dosimeters on the manikins. In Equation (1), the constant K cancels in the calculation of the exposure ratio.

2.2 Measurement Parameters

The UV radiant exposures to the anatomical sites were measured in the Southern Hemisphere summer (December to February) in the shade of evergreen Australian trees in the grounds of the University of Southern Queensland, Toowoomba (27.5 °S), Australia. The trees were mainly a range of types of gum trees. Seventeen trees whose shadow did not interfere with the shadow of neighbouring trees or surroundings were selected. The tree canopy transmission in the visible waveband was previously measured and ranged from 0.45 to 0.94 (Parisi et al., 1999b). Cloud cover during the measurement periods over the summer ranged from 1 to 7 out of a possible 8 okta (okta meaning one-eight of the sky dome as seen by an observer) with 8 okta representing complete coverage of the sky dome with cloud. Measurements were not undertaken if there was no visible shade boundary due to cloud. The manikins with the polysulphone dosimeters were deployed between 09:00 Australian Eastern Standard Time (EST) and 15:00 EST and the erythemal UV radiant exposures measured over this period. To prevent saturation of the dosimeter response all of the dosimeters were changed at noon. The radiant exposure period of 09:00 to 15:00 EST was selected in order to cover the highest UV irradiance period of the day.

2.3 Calculation of UV in Tree Shade over Summer

A numerical model was employed to incorporate measurements of the ambient erythemal UV radiant exposure in full sun and ratio of the UV radiation to a body site to the ambient UV on a horizontal plane. This research considers the UV radiant exposure in a Southern Hemisphere summer (December to February) when the highest UV radiant exposures are expected to occur. The erythemal UV radiant exposure, UV_S, to anatomical site S over the summer, is:

$$UV_S = \sum_{m=1}^{3} N(m) \sum_{h=0}^{23} AE(h).ER_S \qquad (2)$$

where N(m) is the number of days in each of the three months, AE(h) is the ambient erythemal UV radiant exposure in full sun on a horizontal plane and ER_S is the exposure ratio for site S calculated as explained in section 2.1. The exposure ratios are expected to vary with the change in solar zenith angle throughout the summer along with the changes throughout the day due to the variations in the ratio of diffuse to direct UV. This has been addressed by employing the polysulphone dosimeters to measure the integrated UV between 09:00 and 15:00 EST and taking the average of the exposure ratios for each site measured for the seventeen trees during the entire summer. The AE(h) was measured in 15 minute intervals with an erythemal UV Biometer (model 501, Solar Light Co., Philadelphia, USA) permanently mounted outdoors on an unshaded roof and whose spectral response approximates that of human skin. The Biometer was calibrated against a spectroradiometer based on a double holographic grating monochromator (model DH10, Jobin-Yvon Co., France), 15 cm diameter integrating sphere (model OL IS-640, Optronics Laboratories, Orlando, USA) and UV sensitive photomultiplier tube (model R212, Hamamatsu Co., Japan) with calibration traceable to the National Measurement Laboratory (Parisi et al., 1999d).

3. RESULTS

3.1 Ambient Radiant Exposures

The ambient erythemal UV radiant exposures in full sun on a horizontal plane for each 15 minute interval and averaged over all days of the three months are shown in Figure 1. The unit of MED is defined as the minimum erythemal dose and is the amount of biologically effective UV required to produce barely perceptible erythema after an interval of 8 to 24 hours following UV exposure of unacclimatized white skin (Diffey, 1992). In this research, a MED is equivalent to 210 J m^{-2}. The effect of cloud can be seen with the deviation from the bell shaped curve. The cumulative ambient erythemal UV radiant exposure for December, January, February and the total for summer are 972, 959, 752 and 2,683 MED respectively. The cumulative total for February is 23% less than that for December. This drop in the radiant exposures may be due to the combined effects of increasing solar zenith angle and increased cloud cover for February.

3.2 Tree Shade Exposure Ratios

The exposure ratios, ER, to each anatomical site in the tree shade are shown in Figure 2. These ER values also provide information on the protection factor provided by the shade for each anatomical site. The highest value is 0.49 for the vertex of the head. A comparison between the measurements of the exposure ratios in the period before noon and the period after noon found no statistically significant difference ($P < 0.05$) according to Student's t-test. Additionally, there was no statistically significant difference according to the Student's t-test in the exposure ratios for trees with tree canopy transmission in the visible waveband in each of the categories of 0.4-0.59, 0.6-0.79 and 0.8-1.0. Consequently, the results shown are the average of the morning and afternoon measurements for all of the trees and the error bars are one standard error in the mean.

In Figure 2, the right ankle and shin have a higher ER than the corresponding sites on the left leg. This may be due to each of the legs on the manikins being at different angles to the vertical. The exposure ratio may depend on the solar elevation angle and the values presented in this research are the average exposure ratios for the range of solar elevation angles between 09:00 EST and 15:00 EST. In comparison, previous research at a similar latitude in summer (Wong et al., 1992) has found the exposure ratios in full sun to be higher with values for the vertex, nose, cheek and forehead of 1, 0.36, 0.25 and 0.66 respectively.

3.3 UV in Tree Shade over Summer

The results of the exposure ratios and the ambient erythemal UV measured with the Biometer were employed in Equation (1) to calculate the UV to each of the anatomical sites for the complete summer with the results shown in Figure 3. The highest radiant exposures in the tree shade are to the vertex of the head with approximately 1,300 MED over the summer and to the shoulders and forearms with approximately 1,100 MED. Additionally, the UV radiant exposure over the summer has been divided by the number of days in the season to provide in Table 1 the average erythemal UV radiant exposure per day to each of the anatomical sites. The range of radiant exposures per day in the tree shade is 4.6 to 14.6 MED. In comparison, employing the exposure ratios in full sun for the vertex, nose, cheek and forehead of 1, 0.36, 0.25 and 0.66 respectively (Wong et al., 1992) provides summer radiant exposures per day in the full sun of 29.8, 10.7, 7.5 and 19.7 MED to the respective sites. The overall error in these exposure ratios for full sun could be up to 20% (Wong et al., 1992).

4. DISCUSSION

This paper has provided the first extensive set of quantitative data of the anatomical distribution of the solar erythemal ultraviolet in tree shade and the protection factors for the different anatomical sites for an upright posture during summer at a sub tropical Southern Hemisphere location. The research has provided new data that is essential to quantify the human UV exposure during outdoor activities. Previous research investigated the anatomical distribution in the shade of two trees (Parisi et al., 1999a), however, this research has provided a more extensive data set using seventeen trees with measurements over the complete summer in the morning and afternoon periods to calculate the exposure ratios in the tree shade. The solar zenith angles encountered over the summer were 4^{o} to 21^{o} at noon and 30^{o} to 54^{o} at 09:00 and 15:00 EST. The exposure ratios may change with solar zenith angle and changes in the ratio of diffuse to direct UV, however the measurement with the polysulphone dosimeters between 09:00 and 15:00 EST provided the average of the exposure ratios for these solar zenith angles. The UV irradiances in the tree shade are expected to change with different atmospheric conditions, such as cloud cover. This has been addressed by taking the measurements through the summer for the range of atmospheric conditions encountered.

The exposure ratios were used with the measured ambient erythemal UV in full sun to calculate the erythemal UV radiant exposures over the summer to each anatomical site in the tree shade. The measured ambient erythemal UV over the summer at the latitude of this research was 2,683 MED, whereas, previous research (Diffey, 1992) has measured the ambient erythemal UV at Durham (55 ^{o}N) over the Northern Hemisphere summer June to August months of 985 MED. The ambient UV radiant exposures measured in this research are higher by a factor of 2.7 and highlight the importance of the research in this paper at locations with high UV irradiances such as Queensland, Australia.

The estimates in this paper are for radiant exposures in the tree shade over the whole day, seven days a week over the complete summer with the assumption of no protective measures. The body sites with the higher exposure ratios in the tree shade were the vertex of the head, shoulders and forearms with the radiant exposures to these sites over the summer in excess of 1,100 MED. This is higher than the ambient erythemal UV measured in full sun over a summer on a horizontal plane at a latitude of 55 ^{o}N (Diffey, 1992). The average radiant exposures per day to each anatomical site for a complete day in the tree shade ranged from 4.6 to 14.6 MED. This exceeds the daily occupational UV exposure limit specified for Australia (NHMRC, 1989).

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REFERENCES

Airey D K, Wong J C F and Fleming R A 1995 A comparison of human- and headform-based measurements of solar ultraviolet B dose *Photodermatol. Photoimmunol. Photomed*. **11** 155-158

Davis A, Deane G H W and Diffey B L 1976 Possible dosimeter for ultraviolet radiation *Nature,* **261** 169-170

Diffey B L 1989 Ultraviolet radiation dosimetry with polysulphone film *Radiation Measurement in Photobiology* ed B L Diffey (Academic Press: New York) pp 136-159

Diffey B L 1992 Stratospheric ozone depletion and the risk of non-melanoma skin cancer in a British population *Phys. Med. Biol.* **37** 2267-2279

Gies P, Roy C, Toomey S, MacLennan R and Watson M 1995 Solar UVR exposures of three groups of outdoor workers on the Sunshine Coast, Queensland *Photochem. Photobiol.* **62** 1015-1021

Gies P, Roy C, Toomey S, MacLennan R and Watson M 1998 Solar UVR exposures of primary school children at three locations in Queensland *Photochem. Photobiol.* **68** 78-83

Grant R H 1997 Biologically active radiation in the vicinity of a single tree *Photochem. Photobiol.* **65** 974-982

Herlihy E, Gies P H, Roy C R and Jones M 1994 Personal dosimetry of solar UV radiation for different outdoor activities *Photochem. Photobiol.* **60** 288-294

Holman C D J, Gibson I M, Stephenson M and Armstrong B K 1983 Ultraviolet irradiation of human body sites in relation to occupation and outdoor activity: field studies using personal UVR dosimeters *Clin. Exp. Dermatol.* **8** 269-277

Kimlin M G, Parisi A V and Wong J C F 1998a Quantification of the personal solar UV exposure of outdoor workers, indoor workers and adolescents at two locations in southeast Queensland *Photodermatol. Photoimmunol. Photomed*. **14** 7-11

Kimlin M G, Wong J C F and Parisi A V 1998b Simultaneous comparison of the personal UV exposure of two human groups at different altitudes *Health Phys.* **74** 429-434

Meldrum L R 1998 Estimate of lifetime UV exposure for selected workers in south east Queensland *MAppSc thesis* (Queensland University of Technology, Brisbane)

Moise A F, Gies H P and Harrison S L 1999 Estimation of the annual solar UVR exposure dose of infants and small children in tropical Queensland, Australia *Photochem. Photobiol.* **69** 457-463

NHMRC (National Health and Medical Research Council) 1989 Occupational standard for exposure to ultraviolet radiation *Radiation Health Series No.29.* (Canberra: NHMRC).

Parisi A V, Willey A, Kimlin M G and Wong J C F 1999a Penetration of solar erythemal UV radiation in the shade of two common Australian trees *Health Phys.* **76** 682-686

Parisi A V, Kimlin M G, Wong J C F, Wilson M 1999b Solar ultraviolet exposures at ground level in tree shade during summer in south east Queensland *submitted Internat. J. Biometeorol.*

Parisi A V, Kimlin M G, Wong J C F, Wilson M 1999c Diffuse component of the solar ultraviolet radiation in tree shade *2nd Internet Photochem. Photobiol. Conf. July 16 – Sept 7, 1999.*

Parisi A V, Wong J C F, Kimlin M G and Meldrum L 1999d Errors in determining broadband ultraviolet irradiances from spectral measurements *Rad. Prot. Australas.* **16** 10-15

Parsons P, Neale R, Wolski P and Green A 1998 The shady side of solar protection *Med. J. Aust.* **168** 327-330

Webb A R 1997 Changes in stratospheric ozone concentrations and solar UV levels *Rad. Prot. Dos.* **72** 207-216

WHO (World Health Organization) 1994 *Environmental Health Criteria 160: Ultraviolet Radiation* (Geneva: World Health Organization) p 256

Wong C F, Fleming R A, Carter S J, Ring I T and Vishvakarman D 1992 Measurement of human exposure to ultraviolet-B solar radiation using a CR-39 dosimeter *Health Phys.* **63** 457-461

Wong C F, Airey D K and Fleming R 1996 Annual reduction of solar UV exposure to the facial area of outdoor workers in Southeast Queensland by wearing a hat *Photodermatol. Photoimmunol. Photomed.* **12** 131-135

Table 1 – The erythemal UV radiant exposure per day to each of the anatomical sites.

Site	Exposure/day (MED)	Site	Exposure/day (MED)
Vertex	14.6	R Forearm	12.4
L Ear	5.6	R Thigh Front	6.8
R Ear	4.6	R Thigh Back	5.3
Nose	10.0	L Thigh Front	6.7
L Cheek	5.9	L Thigh Back	6.1
R Cheek	4.9	R Shin Front	7.5
Chin	6.0	R Shin Back	5.5
Forehead	7.6	L Shin Front	5.7
Lumbar Spine	5.3	L Shin Back	7.8
Lower Sternum	8.3	R Ankle Front	10.0
L Shoulder	12.1	R Ankle Back	6.8
R Shoulder	12.2	L Ankle Front	8.4
L Forearm	11.6	L Ankle Back	7.8

FIGURE CAPTIONS

Figure 1 – The ambient erythemal UV in full sun for each 15 minute interval averaged over all days for each of the summer months.

Figure 2 – The exposure ratios in the tree shade for each of the anatomical body sites. The error bar is represented as one standard error in the mean.

Figure 3 – The erythemal UV radiant exposures to each anatomical site in the tree shade over the entire summer.

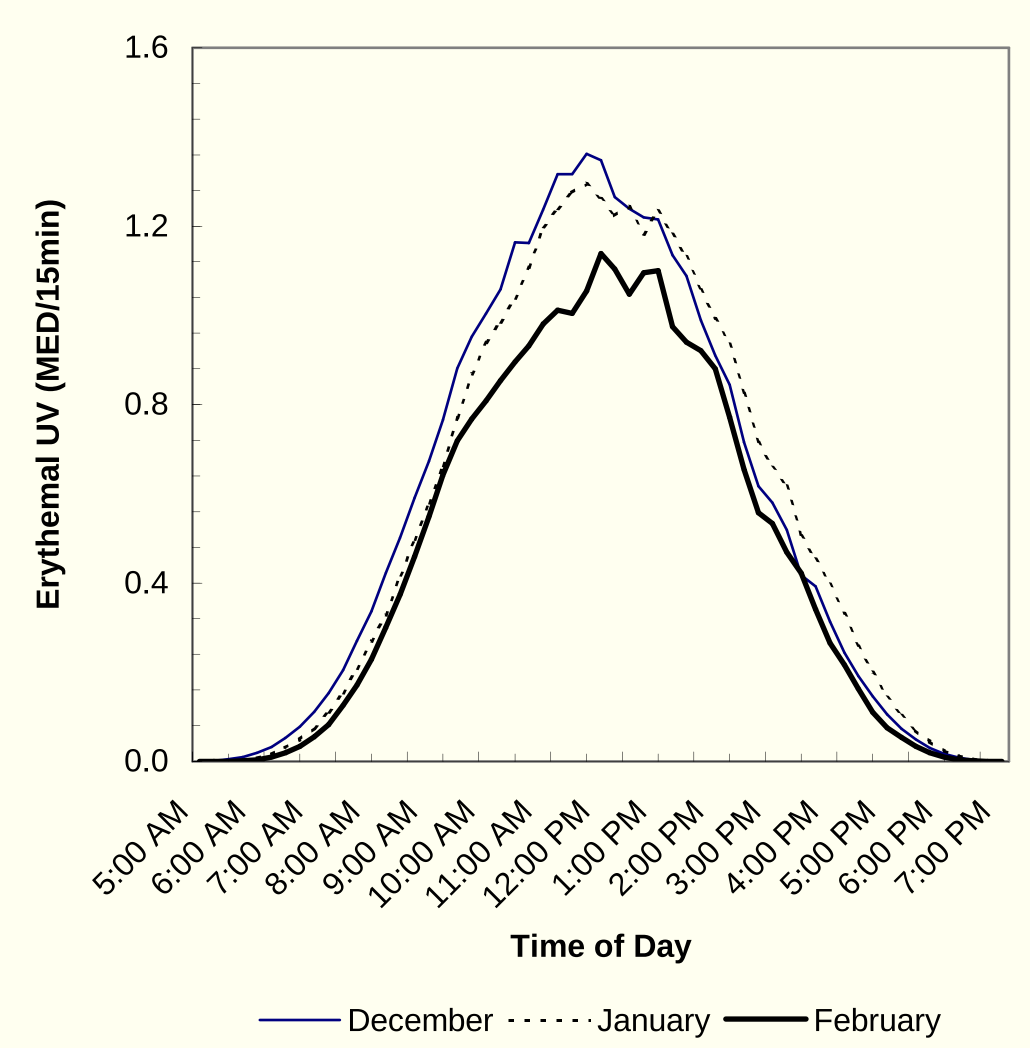

Figure 1 – The ambient erythemal UV in full sun for each 15 minute interval averaged over all days for each of the summer months.

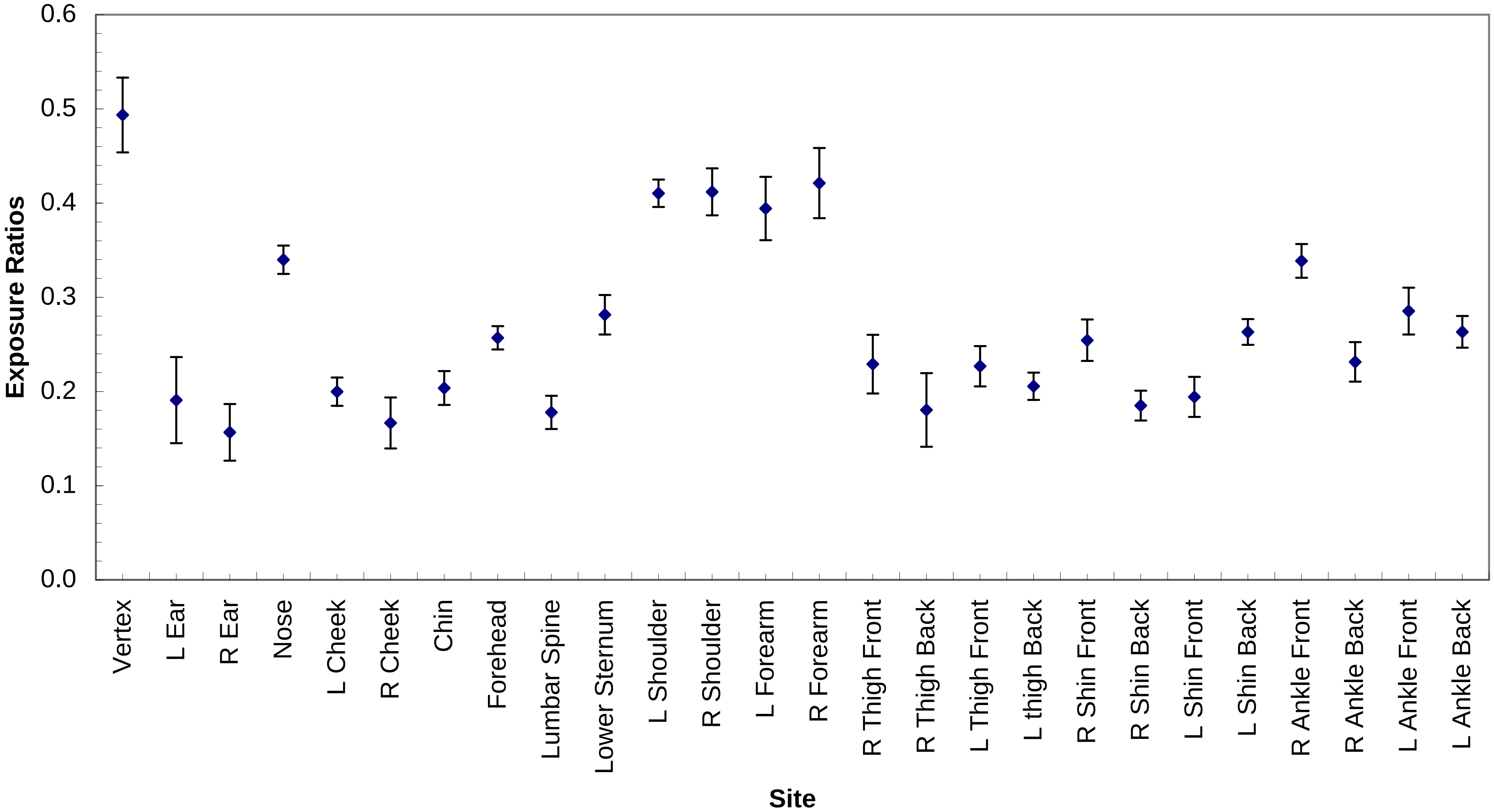

Figure 2 – The exposure ratios in the tree shade for each of the anatomical body sites. The error bar is represented as one standard error in the mean.

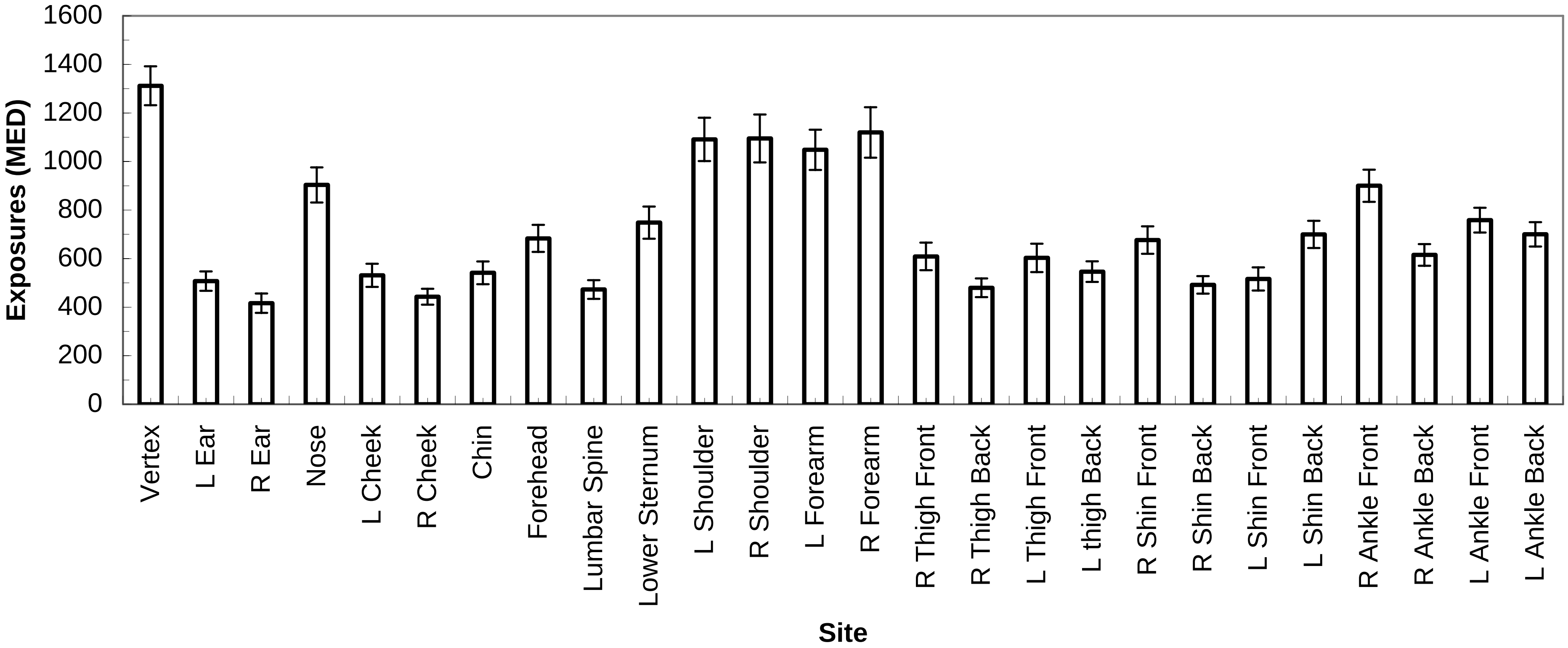

Figure 3 – The erythemal UV radiant exposures to each anatomical site in the tree shade over the entire summer.