Diurnal Variations in Solar Ultraviolet Radiation at Typical Anatomical Sites[1]

LI-WEN HU#, QIAN GAO#, WEN-YING XU+, YANG WANG#, HUI-ZHI GONG#, GUO-QING DONG#, JING-HAI LI#, AND YANG LIU#,2

#Department of Environmental Health, School of Public Health,China Medical University, Shenyang, 110001, Liaoning, China; +Huzhou Entry-Exit Inspection and Quarantine Bureau, Huzhou 313000, Zhejiang, China

Objective Solar ultraviolet (UV) radiation is an important environmental factor that affects human health. The understanding of diurnal variations of UV radiation at anatomical sites may be helpful in developing ways to protect humans from the harmful effects of UV radiation. **Methods** In order to characterize the diurnal variations, the UV exposure values were measured at 30 min intervals by using Solar-UV Sensors and a rotating manikin in Shenyang city of China (41°51′N, 123°27′E). Measurement data for four representative days (in each of the four seasons respectively) were analyzed. **Results** The diurnal variations in solar UV radiation at the shoulder, the forehead and the chest were similar to those associated with a horizontal control measurement. However, the diurnal variations at the eye and the cheek exhibited bimodal distributions with two peaks in spring, summer and autumn, and a unimodal distribution in winter. The UV exposure peaks at the eye and the cheek were measured at solar elevation angles (SEA) of about 30° and 40°, respectively. **Conclusion** The protection of some anatomical sites such as the eye from high UV exposure should not be focused solely on the periods before and after noon, especially in the places and seasons with high SEA.

Key words: Ultraviolet radiation; Exposure; Monitors; Radiation dose

INTRODUCTION

Solar ultraviolet (UV) radiation is an important environmental factor that affects human health. It is likely that exposure to UV radiation among the people of the contemporary time is greater than that in previous generations[1]. Excessive solar UV radiation has various direct and indirect effects on human health, which may lead to skin cancer, cataracts, immune suppression, photoaging, and other ailments[2-4]. Based on the data from 2006, the World Health Organization reported that globally around 1.5 million Disability Adjusted Life Years (0.1% of the total global disease burden) are lost every year due to excessive UV exposure[4]. Skin cancer and cataracts are among the primary public health problems and consequently have aroused special concerns[4]. These conditions in particular have attracted wide interest of researches over the recent years.

Many scientists have investigated the dose-effect relationship between excessive solar UV exposure and its detrimental health impacts. In this regard, the ability to quantify individual UV exposure is especially important. However, it is difficult to accurately determine an individual's level of solar UV exposure in epidemiological and experimental studies.

In previous epidemiological studies, the personal UV exposure of each subject was assessed by monitoring the exposure at specific anatomical sites over time. These sites included the shoulders[5-8], the chest[6,8-10], the back[6,11-12], the arms[12-13], the wrist[14-17], the eyes (the bridge of a person's spectacles)[7, 18-19], and the neck[20-22]. The subjects in these studies included students, building workers, athletes, and indoor workers. However, because of the complexity of human morphology, diversity in individuals' activities, and limited monitoring duration, we believe that further efforts are needed to systematically and accurately establish the dose-effect relationship between solar UV radiation and human diseases. In various dosimetry studies,

[1]This research was supported by the National Natural Science Foundation of China (NSFC30700652, NSFC 30800895), which for the Doctoral Program of Higher Education of China (20070159022), and the Liaoning Provincial Science and Technology Development Fund (20062087).

[2]Correspondence should be addressed to Professor Yang LIU, Department of Environmental Health, School of Public Health, China Medical University, No. 92 Second Road Heping District Shenyang 110001, P. R. China. Tel: 86-24-23256666-5407. Fax: 86-24-23264417. E-mail: cmuliuyang@yahoo.com

Biographical note of the first author: Li-Wen HU, female, born in 1981, doctoral student at the School of Public Health, China Medical University, majoring in occupational and environmental health.

0895-3988/2010
CN 11-2816/Q

researchers have sought to improve the precision of human solar UV exposure assessment. These techniques included various inclined planes to simulate body posture[23-33] as well as stationary or rotating manikins[34-51]. Nevertheless, it is widely agreed that there is a need for more accurate quantification of UV radiation at representative anatomical sites of interest.

The diurnal variation of solar UV radiation on a horizontal surface has been well understood, but little attention has been paid to the study of this variation at anatomical sites of interest. An improved understanding of solar UV exposure variation will be helpful in deriving recommendations for how to avoid excessive exposure to certain parts of the body. In order to measure and quantify realistic diurnal variations in solar UV radiation at typical anatomical sites, a rotating manikin that mimics the anatomical arrangement of forehead, eye, cheek, shoulder, and chest was used. The UV exposure to these anatomical sites was monitored. This study will enhance our understanding of diurnal variations in solar UV exposure at various anatomical sites. Furthermore, by quantifying the exposure doses at different anatomical sites, including the eyes, the dose-effect relationship between UV exposure dose and disease profile can be better understood.

MATERIALS AND METHODS

A Rotating Manikin

The rotating manikin consists of two parts. The upper part is the manikin and the lower part is a powered stage. The UV dose was measured by using a set of Solar-UV Sensors attached to anatomical sites of interest on the manikin, included the forehead, the right eye, the left cheek, the shoulders, and the chest, as shown in Fig. 1. The lower part supports and automatically rotates the manikin at a uniform rate (moving around a vertical axis). The rotational speed of the manikin was one round every six seconds in this study.

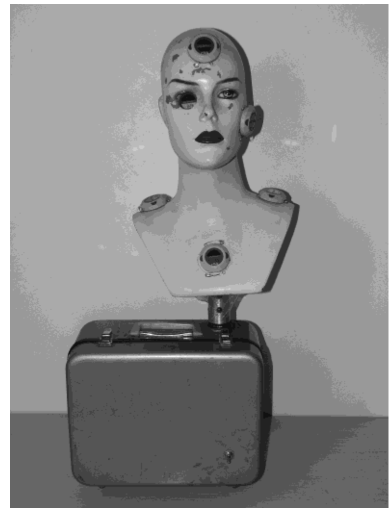

FIG. 1. The rotating manikin. The selected anatomical sites include 1) the forehead, 2) the right eye, 3) the left cheek, 4) the shoulders, and 5) the chest. Note that the UV sensor for the right eye is in the right orbit, and the UV sensors for the forehead, the cheek, the chest, and the shoulders are all attached to the corresponding surface areas.

Equipment Calibration

The chosen Solar-UV Sensor (Model: SUB-T, Toray Industries, Tokyo, Japan) had previously been used to monitor UV exposure[14]. The spectral sensitivity of this instrument covers a wavelengths of solar UV radiation of 280-390 nm, as plotted in Fig. 2. The sensor outputs cumulative UV exposure over any period of time. When the SUB-T device was set under the visible light (longer than 400 nm), there was no intensity reading. When the environmental temperature was below 50 ℃, its relative sensitivity was nearly 100%, when the environmental temperature was 70 ℃, its relative sensitivity was not less than 95%. As far as its angular response is concerned, the relative sensitivity versus the incident angle over [-90°, 90°] is very close to the theoretical cosine relationship. In the factory, each UV sensor was calibrated to meet the requirements of the National Bureau of Standards.

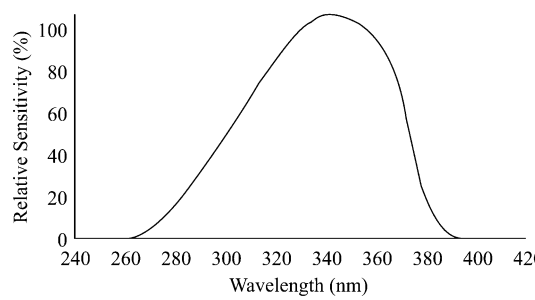

FIG. 2. Spectral sensitivity of the Solar-UV Sensor, SUB-T.

In order to monitor and reduce the system error, all the UV sensors were exposured on a horizontal surface at the same time and incidence angle of the solar radiation for 8 h to take readings on the first sunny day of each season before the experiment. The means in the ultraviolet exposure were computed and the means were used as true values to find the calibration coefficient for each UV sensor. All sensors coincide well within the means of ±5%. These coefficients were used to calculate exposure dose values from raw readings.

Geographic and Meteorological Conditions

The chosen monitoring location was in Shenyang city, the provincial capital of Liaoning of China

(41°51′N, 123°27′E), at a mean altitude of 50 m. Seasonal changes are significant at this location. All of the measurements were acquired on sunny days with clear skies or minimal cloud cover. Whether to collect a measurement depended upon the local weather forecast. The measurements were conducted when the mornings were sunny, but the measurement plans were aborted in the event of inclement weather during the day.

UV Exposure Measurement

The dose measurement data were collected during one week around the equinoxes and solstices from March 2004 to June 2007. The rotating manikin was placed horizontally and unobstructedly in a clearing at the chosen measurement location. One UV sensor was also placed on the ground in an exposed, unobstructed area near the rotating manikin. This sensor was activated over the same experimental period in order to measure the ambient solar UV dose in the locality of the manikin. UV exposure was measured during 7:30-16:00 China Standard Time (CST) in spring and autumn, 6:30-17:30 CST in summer, and 8:00-16:00 CST in winter. The cumulative data were recorded at 30 min intervals. The unit of measurement was kJ m^{-2}. In this study, the measurements across both shoulders were averaged in order to obtain a result for that site.

RESULTS

Out of a possible maximum of 196 measurement days, the results were legitimate for only 67 days due to weather and other inclement conditions as mentioned above in the section Methods and Materials. On certain days, no measurements could be acquired due to rapidly changing weather patterns. Four representative measurement days were chosen, respectively in each of the four seasons. The solar positions at different time points on these four days are listed in Table 1.

Representative seasonal diurnal variations in solar UV exposure at five different anatomical sites and at the horizon are plotted in Fig. 3. In Shenyang, the diurnal variations in horizontal UV dose were bell-shape curves with peaks at 11:30-12:00 CST across all four measurement days. The diurnal variations in solar UV exposure at the forehead, the

TABLE 1

Solar Positions Associated with the Four Chosen Measurement Days in Shenyang City(°)

Time (CST)	14 Sept, 2005 (Autumn)		14 Dec, 2006 (Winter)		17 Mar, 2007 (Spring)		14 Jun, 2007 (Summer)	
	SAA[a]	SEA[b]	SAA	SEA	SAA	SEA	SAA	SEA
06:30	95.47	11.34	115.31	-	97.09	5.61	78.87	23.18
07:00	100.68	16.84	120.12	-	102.23	11.05	83.46	28.69
07:30	106.15	22.25	125.16	3.21	107.58	16.43	88.22	34.25
08:00	112.01	27.52	130.48	7.50	113.26	21.66	93.28	39.83
08:30	118.40	32.56	136.12	11.53	119.37	26.67	98.82	45.38
09:00	125.48	37.30	142.13	15.16	126.05	31.37	105.12	50.84
09:30	133.42	41.60	148.51	18.33	133.42	35.67	112.57	56.13
10:00	142.37	45.34	155.27	20.96	141.59	39.45	121.75	61.10
10:30	152.40	48.35	162.38	22.97	150.63	42.57	133.55	65.53
11:00	163.46	50.44	169.75	24.31	160.50	44.90	148.98	69.04
11:30	175.24	51.47	177.30	24.94	171.04	46.28	168.37	71.09
12:00	187.26	51.34	184.89	24.83	181.92	46.63	189.79	71.18
12:30	198.92	50.07	192.40	23.99	192.72	45.93	209.48	69.29
13:00	209.76	47.75	199.71	22.45	203.07	44.22	225.27	65.88
13:30	219.56	44.57	206.72	20.25	212.67	41.61	237.35	61.52
14:00	228.26	40.68	213.37	17.46	221.42	38.25	246.72	56.59
14:30	235.99	36.27	219.64	14.15	229.31	34.28	254.29	51.32
15:00	242.90	31.45	225.53	10.39	236.44	29.84	260.68	45.87
15:30	249.16	26.35	231.08	6.27	242.92	25.03	266.28	40.33
16:00	254.92	21.04	236.31	1.94	248.88	19.94	271.37	34.75
16:30	260.31	15.59	241.27	-	254.44	14.66	276.15	29.19
17:00	265.47	10.07	246.03	-	259.71	9.26	280.75	23.67
17:30	270.50	4.57	250.65	-	264.81	3.84	285.28	18.24

Note. [a] SAA is solar azimuth angle, [b] SEA stands for solar elevation angle.

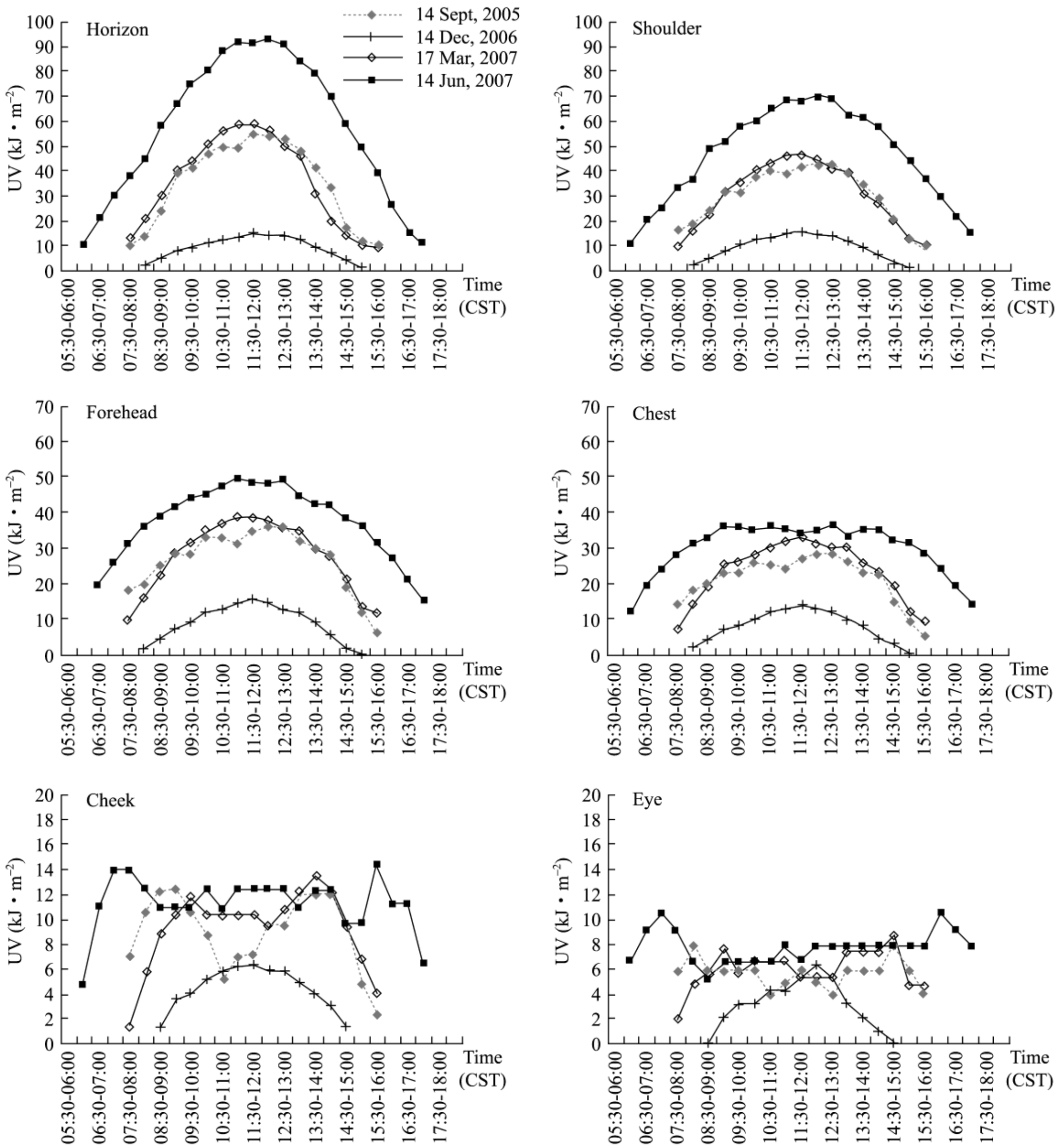

FIG. 3. Representative seasonal diurnal variations in solar UV exposure at typical anatomical sites.

shoulder, and the chest were similar to those associated with the horizontal measurement. The anatomical data also exhibited bell-shape curves, with the maximum 30 min UV exposure metrics recorded around noon each day. However, diurnal patterns at the eyes and the cheeks were significantly different from the horizontal control measurement. The UV exposure doses at the eye and the cheek sites not only decreased, but also exhibited more interesting diurnal variations in solar UV exposure. In spring, summer, and autumn, the diurnal variations in solar UV exposure at the eye and the cheek sites featured two peaks, one in the morning and the other in the afternoon, while the diurnal variations at these sites in winter were simple bell-shape curves with a single peak at noon. In spring, the peak UV doses per 30 min were received by the eye during 9:00-9:30 CST and during 14:30-15:00 CST, and by the cheek during 9:30-10:00 CST and during 13:30-14:00 CST. In summer, these time frames were 7:00-7:30 CST and 16:00-16:30 CST for the eye, and 7:30-8:00 CST and 15:30-16:00 CST for the cheek. In autumn, these time frames were 8:00-8:30 CST and 14:30-15:00 CST for the eye, and 9:00-9:30 CST and 14:00-14:30 CST for the cheek.

As shown in Fig. 4, the daily UV exposure doses (8:00-16:00 CST) at the shoulder, the forehead, and the chest on the four measurement days were significantly different, with exposure ordered across seasons as follows: winter < autumn < spring < summer. The daily UV exposure doses at the eye and the cheek in spring, summer, and autumn were clearly higher than those in winter. However, the differences between spring, summer, and autumn were relatively small for the eye. The anatomical sites could be placed in a descending order of UV exposure on the selected four days as follows: eye < cheek < chest < forehead < shoulder. The one exception was that the dose at the forehead was slightly higher than that at the shoulder during the winter.

Fig. 5 showed that in Shenyang the UV exposure doses per 30 min at the shoulder, the forehead, and the chest as well as on the horizontal plane increased with greater Solar Elevation Angle (SEA). Moreover, the peak of the UV exposure dose per 30 min occurred approximately at SEA of 30 ° for the eye site and at about 40 ° for the cheek site. In winter, the highest SEA in Shenyang was approximately 25 °, and the 30 min UV exposure doses at the eye and the cheek sites increased along with the increase of SEA. When SEA was small, such as in the morning and afternoon or in winter, UV exposure varied little at different anatomical sites. As SEA became larger, the discrepancy at different anatomical sites grew and reached a maximum when SEA was at its highest value of about 71 ° in summer.

In this study, the UV exposure doses per hour were derived and the proportion of UV exposure associated with different time windows as a percentage of the total daily exposure (8:00-16:00 CST) at all the anatomical sites was calculated (see Table 2).

The solar UV exposure on the horizontal plane was strongest in the 4 hours of midday period. During this period, the horizontal plane received 60.17% (in summer) to 73.53% (in winter) of the total 8 hours of UV exposure. Variations in exposure at the shoulder, the forehead, and the chest sites were similar to those on the horizontal plane, and during the 4 hours of midday period with the greatest exposure, they all received more than 50% of the daily UV dose. In all of the seasons except winter, the solar UV exposure doses at the eye and the cheek during the aforementioned 4 hour period were smaller than those on the horizontal plane and at other anatomical sites. These two sites received 84.21% and 76.66% of the daily UV dose, respectively, in winter. As shown in Table 2, the cumulative solar UV exposure from 1 hour in the morning (9:00-10:00 CST) and 1 hour in the afternoon (14:00-15:00 CST) was often approximately equal to that of the 2 hour period included at noon, and was sometimes even higher than the value at noon. Especially in summer, the UV exposure received at the eye during the 2 hour period of both 7:00-8:00 CST and 16:00-17:00 CST (34.09%) was higher than that during the 2 hour period of 11:00-13:00 CST (26.14%). The data from the cheek site showed features similar to those recorded at the eye site.

As shown in Table 3, the daily (8:00-16:00 CST) exposure ratios (the ratio between the UV exposure at a particular anatomical site and the horizontal dose) were computed to compare the results against other published reports. While the daily UV exposure ratios in summer were lowest, the daily ratios in winter were highest at various anatomical sites. The shoulder exhibited the highest daily exposure ratios and the eye was associated with the lowest. The cheek ratios were higher than the eye ratios, while the forehead and the chest ratios were around the median

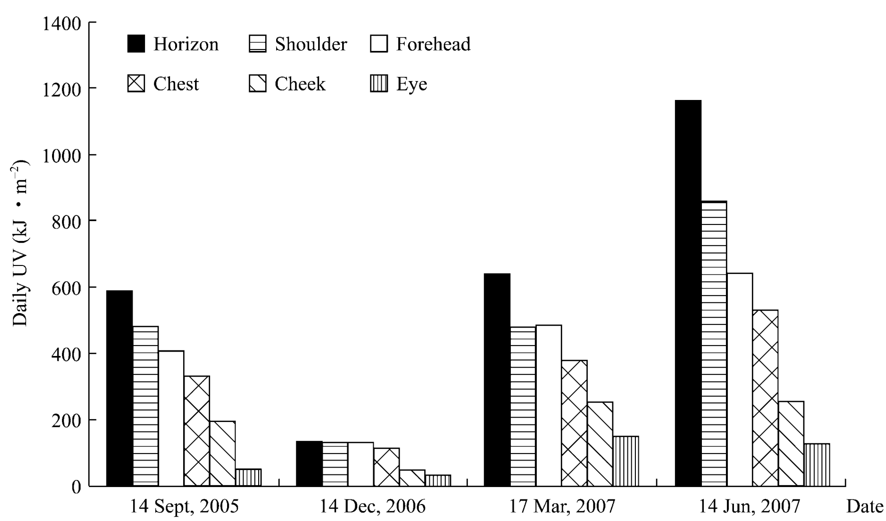

FIG. 4. Daily UV exposure doses (8:00-16:00 CST) at the five anatomical sites and on the horizontal plane across the four measurement days.

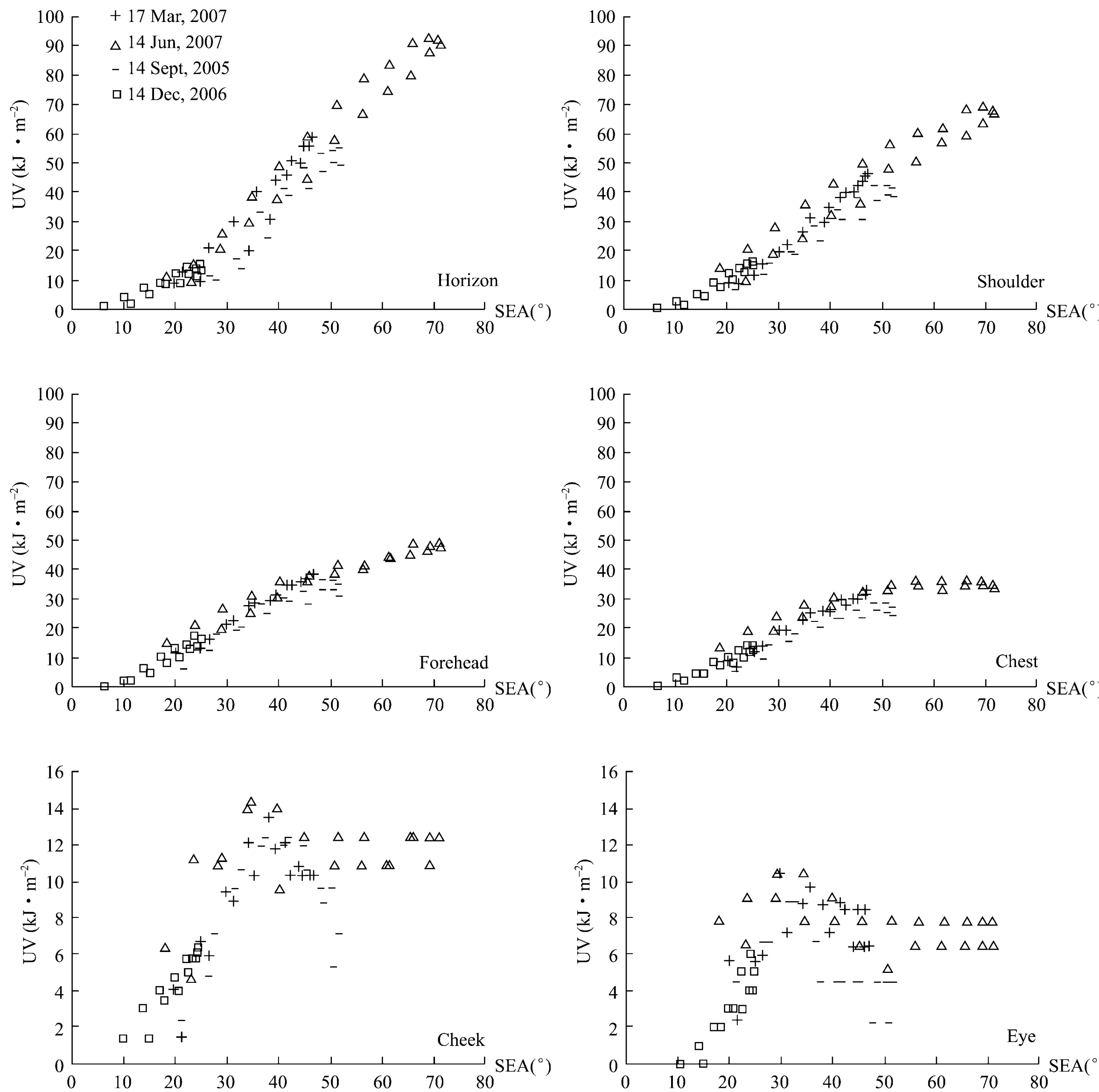

FIG. 5. UV exposure doses per 30 min at the horizon and at the five anatomical sites versus the SEA. The vertical axis represents cumulative UV dose per 30 min, while the horizontal axis shows the SEA of the measurement time interval. The changes in SEA over 30 min are shown in Table 1.

except on 14 December 2006, when the daily exposure ratio of the forehead was slightly higher than the ratio of the shoulder.

DISCUSSIONS

The results of the present study showed that diurnal variations in solar UV radiation at typical anatomical sites (especially the eye and the cheek) were significantly different. Since SEA found its maximum at around noon, the UV exposure doses per 30 min at the shoulder, the forehead and the chest reached their peaks at around solar noon, and were similar to the doses recorded by the horizontal control sensor. However, it was observed that the doses at the eye and the cheek exhibited bimodal distributions with two peaks in spring, summer and autumn, one in the morning and the other in the afternoon. The UV exposure doses per 30 min for the eye and the cheek were at their maximum approximately at SEA values of about 30 ° and 40 °, respectively, in all of the seasons except winter. The diurnal variations in UV exposure to the eye and the cheek on the manikin are different from those of ambient solar UV. This may

TABLE 2

UV Exposure per Hour as a Percentage of the Total Daily (8:00-16:00 CST) UV Exposure

Date	Hourly Interval	Percentage of the Daily UV (%)					
		Horizontal	Shoulder	Forehead	Chest	Cheek	Eye
14 Sept, 2005	08:00-09:00	6.48	8.69	10.39	11.11	15.70	15.16
	09:00-10:00	13.65	12.73	13.16	13.45	15.70	13.12
	10:00-11:00	16.55	15.76	15.24	14.91	9.66	10.93
	11:00-12:00	17.75	16.57	15.24	14.91	9.75	12.03
	12:00-13:00	18.26	17.58	16.63	16.37	13.11	9.84
	13:00-14:00	15.19	14.95	14.32	14.33	16.39	13.12
	14:00-15:00	8.53	9.90	10.85	10.82	14.75	15.05
	15:00-16:00	3.58	3.84	4.16	4.09	4.92	10.75
	total	100.00	100.00	100.00	100.00	100.00	100.00
14 Dec, 2006	08:00-09:00	5.15	4.33	4.79	5.00	2.36	0.00
	09:00-10:00	12.50	12.64	12.33	12.50	13.29	13.16
	10:00-11:00	16.91	18.41	18.49	18.33	19.05	18.42
	11:00-12:00	20.59	22.38	22.60	22.50	21.71	23.68
	12:00-13:00	20.59	20.94	20.55	20.83	20.38	28.95
	13:00-14:00	15.44	15.16	15.75	15.00	15.51	13.16
	14:00-15:00	8.09	5.78	5.48	5.83	7.68	2.63
	15:00-16:00	0.74	0.36	0.00	0.00	0.00	0.00
	total	100.00	100.00	100.00	100.00	100.00	100.00
17 Mar, 2007	08:00-09:00	8.56	7.55	8.38	8.53	9.43	10.46
	09:00-10:00	14.09	13.27	13.06	13.18	14.15	13.32
	10:00-11:00	17.95	16.50	15.59	14.99	13.21	13.32
	11:00-12:00	19.80	18.45	16.76	16.80	13.21	12.01
	12:00-13:00	17.79	16.94	15.98	15.76	12.93	10.71
	13:00-14:00	12.92	13.81	14.04	14.47	16.38	14.73
	14:00-15:00	5.70	9.28	10.72	10.85	13.79	16.07
	15:00-16:00	3.19	4.21	5.46	5.43	6.90	9.37
	total	100.00	100.00	100.00	100.00	100.00	100.00
14 Jun, 2007	07:00-08:00	5.86	6.35	8.39	9.61	14.93	17.05
	08:00-9:00	8.88	9.36	11.05	11.83	12.44	10.23
	09:00-10:00	12.24	12.04	12.52	13.31	11.61	11.36
	10:00-11:00	14.48	13.77	13.55	13.12	12.44	11.36
	11:00-12:00	15.78	15.11	14.29	12.75	13.27	12.50
	12:00-13:00	15.86	15.33	14.29	13.12	13.27	13.64
	13:00-14:00	14.05	13.66	12.67	12.57	12.44	13.64
	14:00-15:00	11.12	11.87	11.78	12.38	11.75	13.64
	15:00-16:00	7.59	8.86	9.87	10.91	12.77	13.64
	16:00-17:00	3.53	5.52	7.07	7.95	11.92	17.05
	Total[c]	109.40	111.87	115.46	117.56	123.82	134.09

Note. [c] The total values are higher than 100% because UV exposure per hour is calculated proportional to the total daily UV exposure (8:00-16:00 CST).

TABLE 3

Daily UV Exposure Ratios Measured at Typical Anatomical Sites (8:00-16:00 CST)

Date	Anatomical Sites (%)				
	Shoulder	Forehead	Chest	Cheek	Eye
14 Sept, 2005	81.91	73.89	58.36	24.90	15.41
14 Dec, 2006	94.78	97.79	86.49	42.26	29.32
17 Mar, 2007	83.34	76.89	64.93	26.26	16.80
14 Jun, 2007	77.33	58.53	46.64	16.17	9.90

be explained by the fact that the two anatomical sites are close to the vertical plane (slightly forward or backward). Besides, the eye in the orbit may be blocked by the eye crack, the superciliary arch and the nose, and the cheek may be blocked by the head etc.

As shown in this study, UV exposure doses during the two high-UV periods in the morning and afternoon to the eye are often comparable to or even higher than those during the 2 hour period including noon. Both this relatively uniform distribution and the bimodal distribution of the 30 min UV exposure to the eye indicate that when the SEA is about 30°, the eye may potentially receive maximal exposures. At the cheek site, when SEA is about 40°, similar conclusions apply. This is to be true for the unweighted total solar UV radiation. It should be emphasized that there are periods other than during the middle of the day when UV exposure to the eye may be equally dangerous, or even more dangerous than the exposure at noon. However, taking into account the effectiveness of the incident UV radiation early and late in the day, when the sun is low in the sky, the UVB content of the incoming solar UV is lower, and whether the eye may be potentially at the similar risk around solar noon needs to be proven by further experiments. Changes in the solar spectrum incident on the UV sensors and the effectiveness of the incident UV radiation are needed to be adequately measured. Nevertheless, with further appropriate data processing, the results of this study can potentially be helpful in preventing the UV-induced eye diseases. Thus, they may encourage individuals to plan their outdoor activities so as to prevent excessive UV exposure, especially to the eyes.

To quantify the effects of solar UV radiation on the human body, researchers have previously studied the UV radiation received on inclined planes (especially the sun-normal and vertical planes)[23-24]. They have found that the human body may receive higher UV exposure on certain inclined planes, especially if the plane is in a sun-normal direction. This holds true particularly at times of smaller SEA (early and late in the day), as compared to the UV dose on a control horizontal surface. Offering a similar conclusion with more realistic experiments, these studies have also explained why UV exposures at the forehead and the shoulder are greater than that at horizon in the early and late hours as well as that around winter noon when SEA is small in the present study.

The assessment of individual UV exposure is typically conducted by using the daily UV exposure ratios. In addition to experimental studies with inclined planes, a considerable amount of work have been performed by using manikins, especially upper body units. The daily UV exposure ratio to the forehead in summer in this study is higher than that measured by Gies[40,50], Holman CD[47], Cheese man[42], and Airey[36]. Our data are close to those measured by Diffey[51], but is lower than that reported by Wong *et al*.[41]. The daily UV exposure ratio at the cheek in summer in this study is close to that of Gies[40], but lower than that of Holman[47], Diffey and Cheeseman[42, 51], Airey[36], and Wong *et al*.[41]. These discrepancies may be due to the differences in the geographical positions and measurement timings. The measurement locations at the forehead and the cheek of the manikin in the aforementioned studies are not standardized, which would also explain the differe nces in UV exposure values. Additionally, part of the reason for the discrepancies may well be the spectral responsivities of the detectors used in the other studies which are always different from those of this study (i.e., they principally respond to UVB). The daily UV exposure ratios for the other anatomical sites are not compared to previously published data for several reasons, including dissimilarities in UV exposure measurement techniques.

While the incidence of skin cancer is relatively low in China, most UV-related conditions impact the eyes. Cataract also causes the greatest UVR-associ ated disease burden in China[4]. With a population of 1.3 billion people, it is important for the Chinese to protect their eyes from excessive UV exposure. The results concerning diurnal distributions of UV exposure at the eyes and at other anatomical sites may be relevant to UV protection guidelines for the Chinese nationals.

ACKNOWLEDGEMENTS

We are grateful to Prof. Ge Wang (Virginia Tech, USA) and Prof. Masaji Ono (NIES, Japan) for their respective editorial assistance and instrumental support.

REFERENCES

1. Bergmanson J P, Sheldon T M (1997). Ultraviolet radiation revisited. *CLAO J* **23**(3), 196-204.
2. Godar D E (2005). UV doses worldwide. *Photochem Photobiol* **81**(4), 736-749.
3. Gallagher R P, Lee T K (2006). Adverse effects of ultraviolet radiation: a brief review. *Prog Biophys Mol Biol* **92**(1), 119-131.
4. WHO (2006). Solar Ultraviolet Radiation: Global burden of disease from solar ultraviolet radiation. Environmental Burden of Disease Series, no.13. World Health Organization, Geneva.
5. Boldeman C, Dal H, Wester U (2004). Swedish pre-school children's UVR exposure-a comparison between two outdoor environments. *Photodermatol Photoimmunol Photomed* **20**(1), 2-8.
6. Vishvakarman D, Wong J C, Boreham BW (2001). Annual occupational exposure to ultraviolet radiation in central Queensland. *Health Phys* **81**, 536-544.
7. Moehrle M, Korn M, Garbe C (2000). Bacillus subtilis spore film dosimeters in personal dosimetry for occupational solar ultraviolet exposure. *Int Arch Occup Environ Health* **73**(8), 575-580.
8. Moise A F, Gies H P, Harrison S L (1999). Estimation of the annual solar UVR exposure dose of infants and small children in tropical Queensland, Australia. *Photochem Photobiol* **69**(4), 457-463.
9. Gies P, Wright J (2003). Measured solar ultraviolet radiation exposures of outdoor workers in Queensland in the building and construction industry. *Photochem Photobiol* **78**(4), 342-348.
10. Parisi A V, Wong J C (2000). An estimation of biological hazards due to solar radiation. *J Photochem Photobiol B* **54**(2-3), 126-130.
11. Moehrle M, Heinrich L, Schmid A, *et al*. (2000). Extreme UV exposure of professional cyclists. *Dermatology* **201**, 44-45.
12. Antoine M, Pierre-Edouard S, Jean-Luc B, *et al*. (2007). Effective exposure to solar UV in building workers: influence of local and individual factors. *J Expo Sci Environ Epidemiol* **17**(1), 58-68.
13. Ono M, Munakata N, Watanabe S (2005). UV exposure of elementary school children in five Japanese cities. *Photochem Photobiol* **81**(2), 437-445.
14. Liu Y, Ono M, Yu D, *et al*. (2006). Individual solar-UV doses of pupils and undergraduates in China. *J Expo Sci Environ Epidemiol* **16**(6), 531-537.
15. Thieden E, Collins S M, Philipsen P A, *et al*. (2005). Ultraviolet exposure patterns of Irish and Danish gardeners during work and leisure. *Br J Dermatol* **153**(4), 795-801.
16. Thieden E, Philipsen P A, Heydenreich J, *et al*. (2004). UV radiation exposure related to age, sex, occupation, and sun behavior based on time-stamped personal dosimeter readings. *Arch Dermatol* **140**(2), 197-203.
17. Rigel E G, Lebwohl M, Rigel A C, *et al*. (2003). Daily UVB exposure levels in high-school students measured with digital dosimeters. *J Am Acad Dermatol* **49**(6), 1112-1114.
18. Moehrle M, Dennenmoser B, Garbe C (2003). Continuous long-term monitoring of UV radiation in professional mountain guides reveals extremely high exposure. *Int J Cancer* **103**(6), 775-778.
19. Duncan D D, Munoz B, Bandeen-Roche K, *et al*. (1997). Visible and ultraviolet-B ocular-ambient exposure ratios for a general population. Salisbury Eye Evaluation Project Team. *Invest Ophthalmol Vis Sci* **38**(5), 1003-1011.
20. Cockell C S, Scherer K, Horneck G, *et al*. (2001). Exposure of arctic field scientists to ultraviolet radiation evaluated using personal dosimeters. *Photochem Photobiol* **74**(4), 570-578.
21. Wright C Y, Reeder A I, Bodeker G E, *et al*. (2007). Solar UVR exposure, concurrent activities and sun-protective practices a mong primary schoolchildren. *Photochem Photobiol* **83**(3), 749-758.
22. Guy C, Diab R, Martincigh B (2003). Ultraviolet radiation exposure of children and adolescents in Durban, South Africa. *Photochem Photobiol* **77**(3), 265-270.
23. Webb A R, Weihs P, Blumthaler M (1999). Spectral UV irradiance on vertical surfaces: a case study. *Photochem Photobiol* **69**(4), 464-470.
24. Parisi A V, Kimlin M G (1999). Horizontal and sun-normal spectral biologically effective ultraviolet irradiances. *J Photochem Photobiol B* **53**(1-3), 70-74.
25. Weihs P (2002). Influence of ground reflectivity and topography on erythemal UV radiation on inclined planes. *Int J Biometeorol* **46**(2), 95-104.
26. Oppenrieder A, Hoeppe P, Koepke P (2004). Routine measurement of erythemally effective UV irradiance on inclined surfaces. *J Photochem Photobiol B* **74**(2-3), 85-94.
27. Hoeppe P, Oppenrieder A, Erianto C, *et al*. (2004). Visualization of UV exposure of the human body based on data from a scanning UV-measuring system. *Int J Biometeorol* **49**(1), 18-25.
28. Streicher J J, Culverhouse W C Jr, Dulberg M S, *et al*. (2004). Modeling the anatomical distribution of sunlight. *Photochem Photobiol* **79**(1), 40-47.
29. Philipona R, Schilling A, Schmucki D (2001). Albedo-enhanced maximum UV irradiance-measured on surfaces oriented normal to the sun. *Photochem Photobiol* **73**(4), 366-369.
30. Turner J, Parisi A V, Turnbull D J (2008). Reflected solar radiation from horizontal, vertical and inclined surfaces: Ultraviolet and visible spectral and broadband behaviour due to solar zenith angle, orientation and surface type. *J Photochem Photobiol B* **92**(1), 29-37.
31. Schauberger G (1990). Model for the global irradiance of the solar biologically-effective ultraviolet-radiation on inclined surfaces. *Photochem Photobiol* **52**(5), 1029-1032.
32. McCarty C A, Lee S E, Livingston P M, *et al*. (1997). Assessment of lifetime ocular exposure to UV-B: the Melbourne Visual Impairment Project. *Dev Ophthalmol* **27**, 9-13.
33. McKenzie R L, Paulin K J, Kotkamp M (1997). Erythemal UV irradiances at Lauder, New Zealand: relationship between horizontal and normal incidence. *Photochem Photobiol* **66**(5), 683-689.
34. Parisi A V, Kimlin M G (2004). Personal solar UV exposure measurements employing modified polysulphone with an extended dynamic range. *Photochem Photobiol* **79**(5), 411-415.
35. Ono M (2002). Studies on ultraviolet radiation and health effects: ocular exposure to ultraviolet radiation. *Dev Ophthalmol* **35**, 32-39.
36. Airey D K, Wong J C, Fleming R A (1995). A comparison of human- and headform-based measurements of solar ultraviolet B dose. *Photodermatol Photoimmunol Photomed* **11**(4), 155-158.
37. Kimlin M G, Parisi A V, Wong J C (1998). The facial distribution of erythemal ultraviolet exposure in south-east Queensland. *Phys Med Biol* **43**(2), 231-240.
38. Sakamoto Y, Kojima M, Emori Y, *et al*. (1997). Ultraviolet

dosimetry utilizing a mannequin model. *Dev Ophthalmol* **27**, 50-55.
39. Parisi A V, Kimlin M G., Lester R, *et al*. (2003). Lower body anatomical distribution of solar ultraviolet radiation on the human form in standing and sitting postures. *J Photochem Photobiol B* **69**(1), 1-6.
40. Gies P, Javorniczky J, Roy C, *et al*. (2006). Measurements of the UVR protection provided by hats used at school. *Photochem Photobiol* **82**(3), 750-754.
41. Wong C F, Fleming R A, Carter S J, *et al*. (1992). Measurement of human exposure to ultraviolet-B solar radiation using a CR-39 dosimeter. *Health Phys* **63**(4), 457-461.
42. Diffey B L, Cheeseman J (1992). Sun protection with hats. *Br J Dermatol* **127**(1), 10-12.
43. Parisi A V, Kimlin M G, Wong J C, *et al*. (2000). Diffuse component of solar ultraviolet radiation in tree shade. *J Photochem Photobiol B* **54**(2-3), 116-120.
44. Sydenham M M, Collins M J, Hirst L W (1997). Measurement of ultraviolet radiation at the surface of the eye. *Invest Ophthalmol Vis Sci* **38**, 1485-1492.
45. Merriam J C (1996). The concentration of light in the human lens. *Trans Am Ophthalmol Soc* **94**, 803-918.
46. Birt B, Cowling I, Coyne S, *et al*. (2007). The effect of the eye's surface topography on the total irradiance of ultraviolet radiation on the inner canthus. *J Photochem Photobiol B* **87**(1), 27-36.
47. Holman C D, Gibson I M, Stephenson M, *et al*. (1983). Ultraviolet irradiation of human body sites in relation to occupation and outdoor activity: field studies using personal UVR dosimeters. *Clin Exp Dermatol* **8**(3), 269-277.
48. Parisi A V, Kimlin M G., Wong J C, *et al*. (2000). Personal exposure distribution of solar erythemal ultraviolet radiation in tree shade over summer. *Phys Med Biol* **45**(2), 349-356.
49. Sliney D H (1995). UV radiation ocular exposure dosimetry. *J Photochem Photobiol B* **31**(1-2), 69-77.
50. IRPA (1988). The anatomical distribution of solar UVR with emphasis on the eye. In: 7th International Congress of the International Radiation Protection Association. International Radiation Protection Association, pp. 341-344.
51. Diffey B L, Kerwin M, Davis A (1977). The anatomical distribution of sunlight. *Br J Dermatol* **97**, 407-410.

(*Received December* 28, 2009 *Accepted June* 9, 2010)