*Iranian J Publ Health, Vol. 39, No.3, 2010, pp.70-81* **Original Article**

# Diurnal Variations in Solar Ultraviolet Radiation on Horizontal and Vertical Plane

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**(Received 22 Nov 2009; accepted 9 Jun 2010)**

## Abstract

**Background:** In general, measurements of solar ultraviolet (UV) radiation are related to horizontal surfaces. While the humans walking and standing outdoors expose to the natural solar UV radiation, their eyes, cheeks, extremities, trunks, or many other anatomical sites are close to vertical plane and random orient to different directions. In this study, we characterized the diurnal variations in solar UV on horizontal and vertical plane which may be helpful to obtain more relevant information on UV exposure of humans.

**Methods:** The UV exposure on vertical and horizontal plane were measured using Solar-UV Sensors in Shenyang (41°51′N, 123°27′E) and Sanya (18°19'N, 109°42'E), PR China.

**Results:** As the well known, the diurnal variations in solar UV on horizontal plane in a sunny day exhibited unimodal distributions, reached a single UV peak exposure at around solar noon. However, the diurnal variations on vertical plane presented bimodal distributions, with two peaks in summer in Shenyang and Sanya, and a unimodal distribution in winter in Shenyang. In spring and autumn in Shenyang, the UV exposure around noon were slightly flat with no significant peaks but relative high. When the Solar Elevation Angle (SEA) is about 40°, the vertical plane may potentially receiving maximal unweighted total solar UV radiation exposures.

**Conclusion:** The results potentially showed that the protection of some vertical and near-vertical anatomical sites of human body from high UV exposure should not only focused on the periods of before and after noon especially in high SEA places.

**Keywords:** *UV radiation, Solar radiation, UV exposure, Horizontal plane, Vertical plane*

## Introduction

Solar ultraviolet (UV) radiation is an important environmental factor that affects human health. Moderate UV radiation triggers vitamin D synthesis in the skin (1), contributes to protection against breast cancer, prostrate cancer and non Hodgkin's lymphoma etc (2). However, 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 (3-5). The depletion of ozone, the increasing life expectancy, and the changing modern life style will further increase this UV-related disease burden.

Based on data from 2006, the World Health Organization reported that globally around 1.5 million Disability Adjusted Life Years (0.1% of the total global burden of diseases) are lost every year due to excessive UV exposure (5). Skin cancer and cataracts are among the primary public health problems and are consequently of special concern (5), while the latter is the most severe public health problem in China. China is a large country in terms of both population and area. Meanwhile, China has the largest number of cataract patients and individuals with cataract-induced blindness. Sunlight enhances cataract formation in China (6). Therefore, it is important to quantify the UV exposure doses at eye sites and establish the relationship between the

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UV exposure and the age-related cataract. The prevention of the occurrence and the development of cataract is also significant.

The monitoring and evaluation of the UV in early time were mainly based on the horizontal solar UV-monitoring, which were always the downwelling and upwelling UV irradiances. This kind of monitoring are usually long-termed and broad-scaled which are from the government (Meteorological Department), scientific institutions, universities and other public corporations or private bodies (7-12). At present, the global UV monitoring network are gradually improved, and the theoretical calculation model of environmental UV radiation has been established (13, 14). These researches describes the distribution of the environment UV radiation doses in different parts of the world, and provides a wide range of basic data for the evaluation of the harmful effects of UV radiation on biological system. To detect the distribution and long-term trends of UV irradiance in China, an area-weighted average UV in the domain of 20°-50°N and 75°-130°E was analyzed from the TOMS (Total Ozone Mapping Spectrometer) products in a study (15). It found out that the erythemal UV irradiance was high in summer, maximized in July with a value of 250mWm$^{-2}$. The low erythemal UV irradiance occurred in winter, minimized in December with a value of 80mWm$^{-2}$. Yet the exposures at northern mid-latitudes were projected to peak around 2020, entailing an estimated 10% increase in effective ultraviolet radiation relative to 1980s levels (16). Therefore, the harmful effects of UV radiation on biological system potentially increased.

However, the biological effect of solar UV radiation on organism depends on the direction of the receiver relative to the sun as well as the surface orientation of the receiver (17-21). Humans, animals, and plants received UV on sun-exposed surfaces such as sun-normal, vertical, or other inclined ones. In theory, the distribution of UV exposure to inclined surfaces is different from that of horizontal plane. Therefore, the assessment of environmental solar UV radiation monitored on the horizon is not appropriate to that of the individual. Thus, apart from monitoring solar UV radiation on the horizon, some systemic UV radiation measurement on inclined surfaces should be carried out, which would providing more suitable data for the assessment of individual UV exposure. The understanding of diurnal variations of UV radiation on other inclined surfaces including the vertical may be helpful in developing ways to protect humans from the harmful effects of UV radiation and used to inform and educate the public about UV radiation.

## Materials and Methods

### *Equipment*

The UV measurements in this study were carried out using Solar-UV Sensors (Model: SUB-T, Toray Industries, Tokyo, Japan). The chosen Solar-UV Sensor had previously been used to monitor UV exposure (22). The spectral sensitivity of this instrument covers solar UV radiation of wavelengths 280-390nm, as plotted in Fig.1. The sensor outputs cumulative UV exposure over any time period. When the SUB-T device was set under the visible light (longer than 400 nm), its intensity reading was zero. When the environmental temperature was less than 50° C, its relative sensitivity was nearly 100%, whereas for the environmental temperature of 70° C, 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.

### *Calibration*

In the factory, each UV sensor was calibrated to meet the requirements of the National Bureau of Standards. To monitor and reduce the system error, the two UV sensors were exposured on a horizontal surface at the same time, place 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 two sensors coincide well within 5%.

### *Geographic and meteorological conditions*

One of the two chosen monitoring locations was in Shenyang, Liaoning, PR China (41°51′N, 123°27′E, mean altitude of 50m). Seasonal changes are significant at this location. The other one was in Sanya, Hainan, PR China (18°19'N, 109°42'E, mean altitude of 3.55-4.5m) which is characterized with tropical oceanic monsoon climate. In this study, the periods of two weeks centered upon the equinoxes and solstices were separately chosen to measure the UV exposure in Shenyang. While, the UV exposure in Sanya, were monitored during one week around May 10, 2008. During these periods, the SEA were about 25°(winter solstice), 50°(spring equinox), 70°(summer solstice), 50°(autumn equinox) in Shenyang and 90°(May 10, 2008) in Sanya. All of the measurements were acquired on sunny days with clear skies or minimal cloud cover. The decision of whether to collect a measurement was based upon the 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*

UV measurements on vertical plane were performed hanging a sensor by a string of 100cm length attached to a holder of 255cm height. Therefore, the UV measurements were conducted approximately on a vertical plane at 155 cm levels from the ground. By the light air, the hanging sensor was generally rotated freely around the vertical axis of the string in the form of clockwise and anti-clockwise alternately.

The other sensor was horizontal placed near the vertical one. This sensor was activated over the same experimental period in order to measure the ambient solar UV dose in the locality of the vertical one. The two sensors were both unobstructed in an exposed, unobstructed area at the chosen measurement location. UV exposures in Shenyang were measured during 7:30-16:00 China Standard Time (CST) in autumn, 8:00-16:00CST in winter, 7:30-16:30 CST in spring, and 6:30-17:30CST in summer. UV exposure in Sanya was measured during 7:00-18:00CST. The cumulative data was recorded at 15 min intervals. The unit of measurement was kJ $m^{-2}$.

## Results

The measurement data in Shenyang was collected during one week around the equinoxes and solstices from December 2005 to June 2007. The UV exposure in Sanya was monitored during one week around May 10, 2008. Out of a maximum of 98 measurement days, the results were suitable on only 32 d due to weather and other inclement conditions as mentioned above in the method. On certain days, no measurements could be acquired due to rapidly changing weather patterns. In this study, 6 d, 5 d, 6 d and 8 d separately in 4 seasons were monitored in Shenyang. The UV exposures in Sanya were monitored for 7 d. The result of each season was shown in Fig. 2. Mean UV exposure and limit values (the difference between maximum and mean values, as well as mean and minimum values) were obtained for different time of each season.

As shown in Fig. 2, the diurnal variation in solar UV on vertical plane in winter of Shenyang was a curve with single UV peak as that on horizontal plane. However, in other seasons in Shenyang as well as in Sanya, the diurnal variations were no significant peaks. Moreover, the limit values shown that the monitoring data changed significantly with the weather conditions. Therefore, five representative measurement days (the days in the sunny weather, which changed weakly) were chosen, one day for each of the 4 seasons in Shenyang, and one day in Sanya. The days were Sept 29, 2006, Dec 14, 2006, Mar 18, 2007, Jun 14, 2007, and May 14, 2008. The solar positions at different times on these five days were listed in Table 1, and the UV exposure doses per 30 min were computed to show the representative seasonal diurnal variations in solar UV exposure on the two planes which were plotted in Fig 3. The UV exposure on the horizontal and vertical plane versus the Solar Elevation Angle (SEA) was shown in Fig. 4.

As shown in Table 1, the maximums of the SEA in 5 measurement days were approximately 46°, 25°, 47°, 71° and 88°. In all of these SEA ranges, the diurnal variations in solar UV on horizontal plane were the bell-shaped curves with single peaks as shown in Fig. 3(a). The UV exposure was increased with the rising of SEA as shown in Fig. 4 (a). The maximum UV exposure doses per 30 min occurred in 11:30-12:00CST in Shenyang and in 12:30-13:00CST in Sanya. The selected five days can be ordered by increasing peak 30 min UV exposure as follows: May in Sanya (99kJ $m^{-2}$), summer in Shenyang (93 kJ $m^{-2}$), spring in Shenyang (53 kJ $m^{-2}$), autumn in Shenyang (47 kJ $m^{-2}$), and winter in Shenyang (15 kJ $m^{-2}$). However, as shown in Fig. 3(b) and Fig. 4(b), the diurnal variations in solar UV on vertical plane were the same as the horizontal plane only in winter's day in Shenyang, but were quite different from that of the horizontal plane in the other four measurement days. The UV exposure doses per 30 min on vertical plane did not increased but even decreased during the noon, while the diurnal patterns exhibited more interesting variations in solar UV exposure. In summer in Shenyang as well as in Sanya, the diurnal variations in solar UV exposure on vertical plane showed bimodal curve featured two peaks, one in the morning (the peak half hour UV exposure doses was 11 kJ $m^{-2}$ in Shenyang and 12 kJ $m^{-2}$ in Sanya respectively) and the other in the afternoon (the peak half hour UV exposure doses was 12 kJ $m^{-2}$ in Shenyang and 15 kJ $m^{-2}$ in Sanya respectively). In spring and autumn in Shenyang, the UV exposure around noon were slightly flat with no significant peaks but relative high. In the other four measurement days, the UV exposure on vertical plane reaching its highest value when the SEA was about 40°, even when it reached the highest SEA of approximately 90°, the UV exposure on vertical plane did not increase as the horizontal UV but kept smooth or even dropped. Therefore, in winter when the maximum SEA was about 25° in Shenyang, the diurnal variation on vertical plane showed the same bell-shaped curve with single peak (which the peak half hour UV exposure doses was 7 kJ $m^{-2}$) as that of the horizontal plane, and the UV exposure were increased with the rising of SEA. Compared to the horizontal plane, the vertical UV exposure was lower and the diurnal discrepancy was smaller.

In this study, beside the cumulative exposure ratio (The ratio between the UV exposure on a particular plane and the horizontal plane) between 10:00 and 14:00, we also calculated the 30 min solar UV exposure ratios as shown in Table 2. In Shenyang, the cumulative exposure ratio in summer was the lowest, while the highest was in winter. In Sanya, though the SEA was much higher in summer than that of Shenyang, the cumulative exposure ratio was slightly higher than that of Shenyang. The 30 min solar UV exposure ratio decreased with the increasing SEA in four measured seasons except winter. In winter, it was increased in Shenyang. In a summer day both in Shenyang and Sanya, the 30 min solar UV exposure ratio between 10:00 and 14:00CST was stable, and the 30 min exposure ratio difference (the difference between the maximal and minimal 30 min UV exposure ratios) was 2.02% and 2.32%. However, from 8:00 to 16:00 CST on these two days, that dynamic range increased to 20.71% (in Shenyang) to 24.58% (in Sanya).

It is well known that solar UV exposure on the horizontal plane was strongest in the 4-h midday period during a sunny day. 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) on the horizontal and vertical plane were calculated, as shown in Table 3. During the 4 h midday period, the horizontal plane received 60.17% (in summer in Shenyang) to 73.53% (in winter in Shenyang) of the total 8 h UV exposure. In summer in Sanya and all the seasons in Shenyang except winter, the solar UV exposure on vertical plane during the aforementioned 4 h period were smaller (which the largest one was 54.48%) than those on the horizontal plane (which the lowest one was 60.17%). The vertical UV exposure did not reach to the peak around the noon but distributed relatively uniformly in every time. Especially in summer, the UV exposure dose in earlier and later time was even higher than in the time around the noon.

**Table 1:** Solar positions associated with the five chosen measurement days in Shenyang and Sanya (°)

| Time | Sept 29, 2006 | | Dec 14, 2006 | | Mar 18, 2007 | | Jun 14, 2007 | | May 14, 2008 | |
|---|---|---|---|---|---|---|---|---|---|---|
| (CST) | SAA[a] | SEA[b] | SAA | SEA | SAA | SEA | SAA | SEA | SAA | SEA |
| 6:30 | | | | | | | 78.82 | 23.14 | | |
| 7:00 | | | | | | | 83.40 | 28.65 | 73.76 | 10.95 |
| 7:30 | 111.40 | 19.11 | | | 107.30 | 16.75 | 88.15 | 34.22 | 75.64 | 17.79 |
| 8:00 | 117.32 | 24.19 | 130.44 | 7.52 | 112.97 | 21.99 | 93.20 | 39.81 | 77.35 | 24.70 |
| 8:30 | 123.75 | 28.99 | 136.08 | 11.55 | 119.08 | 27.02 | 98.73 | 45.36 | 78.92 | 31.66 |
| 9:00 | 130.81 | 33.43 | 142.08 | 15.19 | 125.77 | 31.74 | 105.02 | 50.83 | 80.37 | 38.66 |
| 9:30 | 138.62 | 37.40 | 148.47 | 18.37 | 133.15 | 36.06 | 112.44 | 56.12 | 81.72 | 45.69 |
| 10:00 | 147.25 | 40.76 | 155.23 | 21.00 | 141.36 | 39.86 | 121.60 | 61.11 | 82.97 | 52.74 |
| 10:30 | 156.71 | 43.38 | 162.33 | 23.02 | 150.44 | 43.01 | 133.38 | 65.55 | 84.12 | 59.82 |
| 11:00 | 166.90 | 45.12 | 169.71 | 24.36 | 160.38 | 45.34 | 148.81 | 69.08 | 85.13 | 66.90 |
| 11:30 | 177.54 | 45.87 | 177.26 | 25.00 | 171.01 | 46.73 | 168.23 | 71.14 | 85.91 | 74.00 |
| 12:00 | 188.28 | 45.58 | 184.85 | 24.89 | 181.98 | 47.09 | 189.70 | 71.24 | 85.95 | 81.10 |
| 12:30 | 198.70 | 44.26 | 192.37 | 24.06 | 192.88 | 46.37 | 209.46 | 69.36 | 76.96 | 88.17 |
| 13:00 | 208.51 | 42.02 | 199.68 | 22.51 | 203.29 | 44.64 | 225.29 | 65.95 | 275.26 | 84.66 |
| 13:30 | 217.51 | 38.96 | 206.69 | 20.31 | 212.95 | 42.01 | 237.38 | 61.58 | 273.98 | 77.56 |
| 14:00 | 225.67 | 35.24 | 213.34 | 17.52 | 221.74 | 38.62 | 246.76 | 56.64 | 274.52 | 70.46 |
| 14:30 | 233.04 | 30.99 | 219.62 | 14.21 | 229.65 | 34.63 | 254.33 | 51.37 | 275.44 | 63.37 |
| 15:00 | 239.73 | 26.33 | 225.51 | 10.45 | 236.78 | 30.16 | 260.70 | 45.91 | 276.53 | 56.29 |
| 15:30 | 245.86 | 21.36 | 231.05 | 6.33 | 243.26 | 25.33 | 266.30 | 40.36 | 277.73 | 49.23 |
| 16:00 | 251.55 | 16.16 | 236.28 | 1.99 | 249.21 | 20.23 | 271.39 | 34.78 | 279.03 | 42.19 |
| 16:30 | | | | | 254.77 | 14.93 | 276.16 | 29.21 | 280.44 | 35.18 |
| 17:00 | | | | | | | 280.76 | 23.69 | 281.95 | 28.20 |
| 17:30 | | | | | | | 285.28 | 18.25 | 283.59 | 21.27 |
| 18:00 | | | | | | | | | 284.46 | 17.82 |

Note: SAA[a]: solar azimuth angle; SEA[b]: solar elevation angle.

**Table 2:** 30 min UV exposure ratios in five measurement days in Shenyang and Sanya

| Time(CST) | Exposure Ratio (%) | | | | |
|---|---|---|---|---|---|
| | Sept 29, 2006 | Dec 14, 2006 | Mar 18, 2007 | Jun 14, 2007 | May 14, 2008 |
| 8:00-8:30 | 44.44 | 0.00 | 35.71 | 22.22 | 34.78 |
| 8:30-9:00 | 43.48 | 40.00 | 36.84 | 13.79 | 32.43 |
| 9:00-9:30 | 38.71 | 37.50 | 34.48 | 10.45 | 25.53 |
| 9:30-10:00 | 30.30 | 44.44 | 30.56 | 9.33 | 15.25 |
| 10:00-10:30 | 27.50 | 50.00 | 25.58 | 7.50 | 14.52 |
| 10:30-11:00 | 23.26 | 54.55 | 21.74 | 7.95 | 12.50 |
| 11:00-11:30 | 21.74 | 53.85 | 21.28 | 8.70 | 10.59 |
| 11:30-12:00 | 20.45 | 46.67 | 20.83 | 7.69 | 11.11 |
| 12:00-12:30 | 23.40 | 50.00 | 16.98 | 8.60 | 11.70 |
| 12:30-13:00 | 23.26 | 50.00 | 19.23 | 8.79 | 10.20 |
| 13:00-13:30 | 24.32 | 50.00 | 25.00 | 9.52 | 11.11 |
| 13:00-14:00 | 26.47 | 33.33 | 26.67 | 10.13 | 11.70 |
| 14:00-14:30 | 32.00 | 28.57 | 30.00 | 11.43 | 13.79 |
| 14:30-15:00 | 36.36 | 25.00 | 34.38 | 15.25 | 13.92 |
| 15:00-15:30 | 37.50 | 0.00 | 50.00 | 24.49 | 18.06 |
| 15:30-16:00 | 44.44 | 0.00 | 61.54 | 28.21 | 25.86 |
| 10:00-14:00 | 23.65 | 49.00 | 21.93 | 8.60 | 11.53 |

**Table 3:** UV exposure per hour as a percentage of the total daily (8:00-16:00 CST) UV exposure

| Time (CST) | Horizontal plane (%) | | | | | Vertical plane (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Sept29, 2006** | **Dec14, 2006** | **Mar18, 2007** | **Jun14, 2007** | **May14, 2008** | **Sep29, 2006** | **Dec14, 2006** | **Mar18, 2007** | **Jun14, 2007** | **May14, 2008** |
| 8:00-9:00 | 8.02 | 5.15 | 5.72 | 8.88 | 5.12 | 12.41 | 3.28 | 7.69 | 13.64 | 11.49 |
| 9:00-10:00 | 12.52 | 12.50 | 11.27 | 12.24 | 9.04 | 15.17 | 11.48 | 13.46 | 10.61 | 12.07 |
| 10:00-11:00 | 16.24 | 16.91 | 15.42 | 14.48 | 12.11 | 14.48 | 19.67 | 13.46 | 9.85 | 10.92 |
| 11:00-12:00 | 17.61 | 20.59 | 16.46 | 15.78 | 15.69 | 13.10 | 22.95 | 12.82 | 11.36 | 11.49 |
| 12:00-13:00 | 17.61 | 20.59 | 18.20 | 15.86 | 16.37 | 14.48 | 22.95 | 12.18 | 12.12 | 12.07 |
| 13:00-14:00 | 13.89 | 15.44 | 14.73 | 14.05 | 16.45 | 12.41 | 14.75 | 14.1 | 12.12 | 12.64 |
| 14:00-15:00 | 9.20 | 8.09 | 12.48 | 11.12 | 14.15 | 11.03 | 4.92 | 14.74 | 12.88 | 13.22 |
| 15:00-16:00 | 4.89 | 0.74 | 5.72 | 7.59 | 11.08 | 6.90 | 0.00 | 11.54 | 17.42 | 16.09 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 10:00-14:00 | 65.36 | 73.53 | 64.82 | 60.17 | 60.61 | 54.48 | 80.33 | 52.56 | 45.45 | 47.13 |

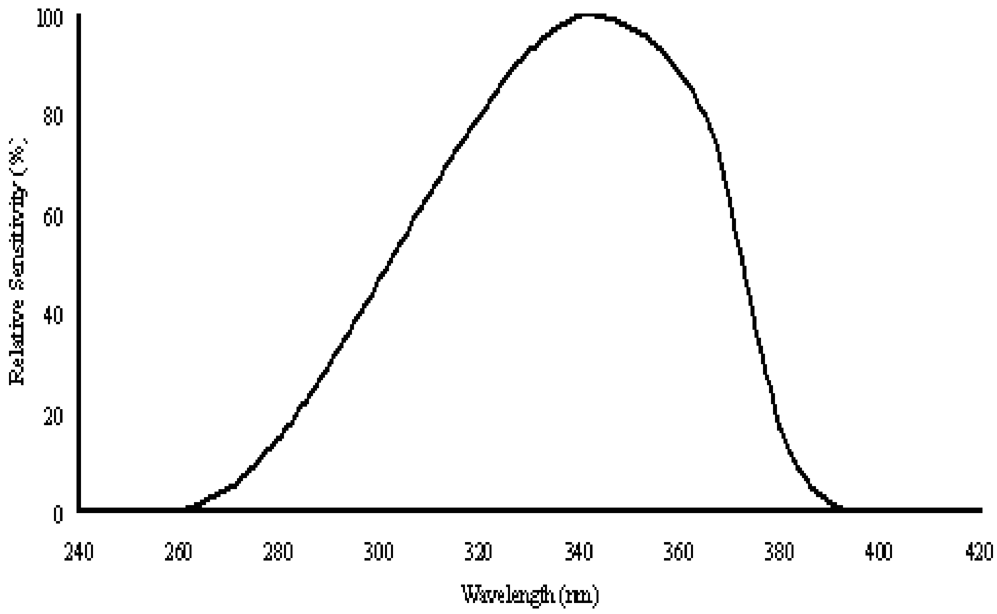
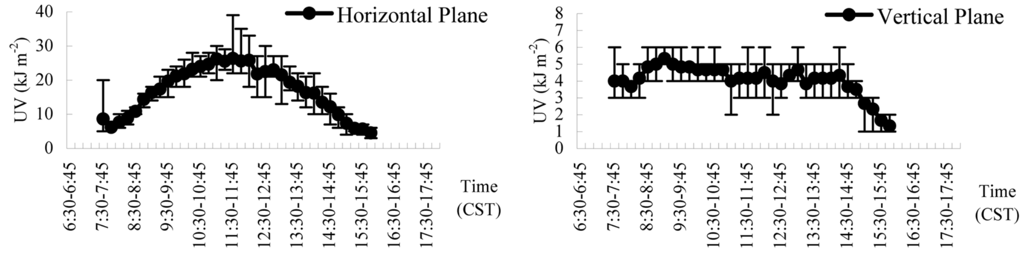
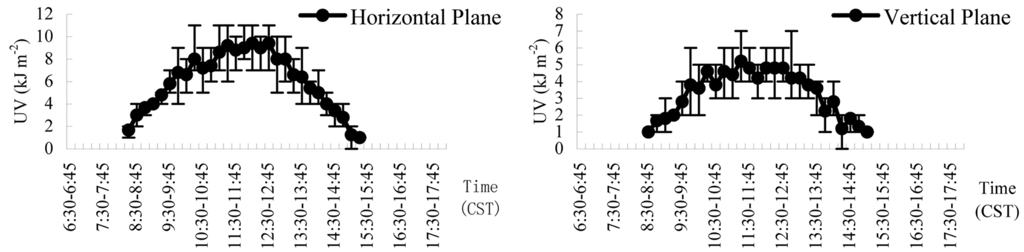


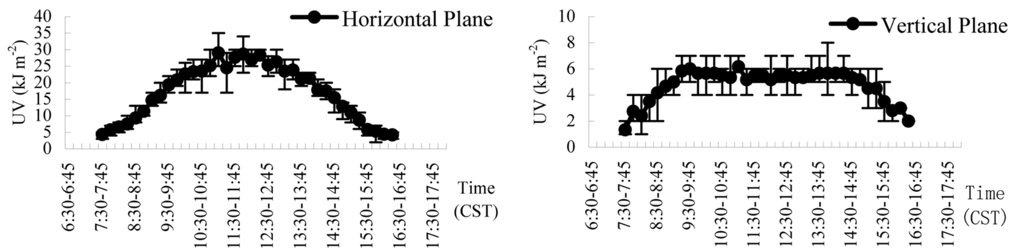

**Fig. 1:** Spectral sensitivity of the Solar-UV Sensor, SUB-T



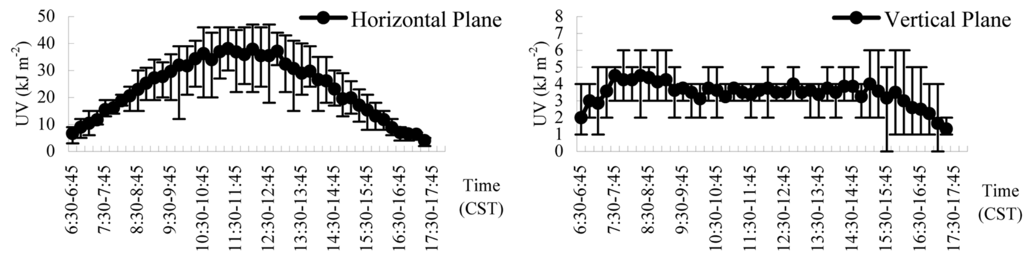

a 6 days around autumnal equinox, Shenyang




b 5 days around winter solstice, Shenyang




c 6 days around spring equinox, Shenyang




d 8 days around summer solstice, Shenyang

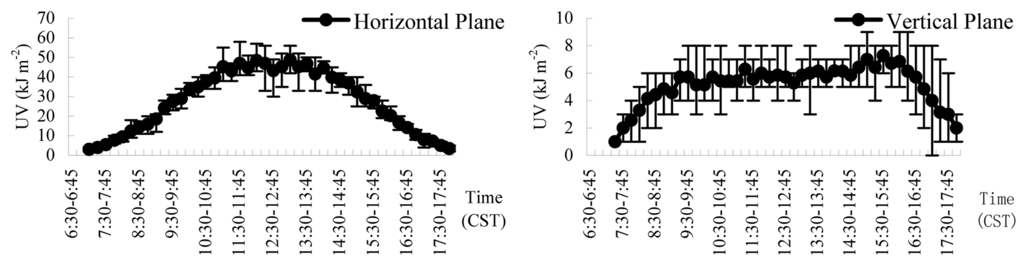



**Fig. 2:** The mean seasonal diurnal UV exposures and limit values (the difference between maximum and mean values, as well as mean and minimum values) on horizontal and vertical plane in Shenyang (a-d) and Sanya (e)

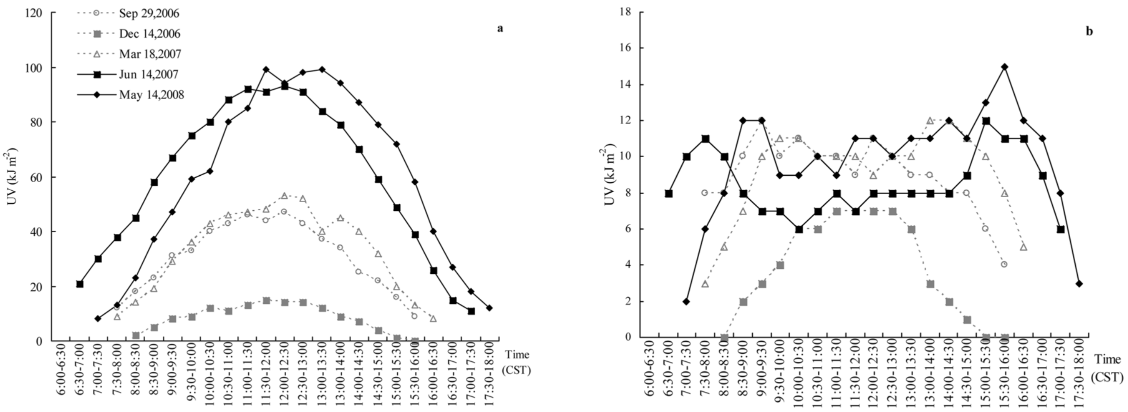



**Fig. 3:** Representative seasonal diurnal variations in solar UV exposure on horizontal (a) and vertical (b) plane in Shenyang and Sanya

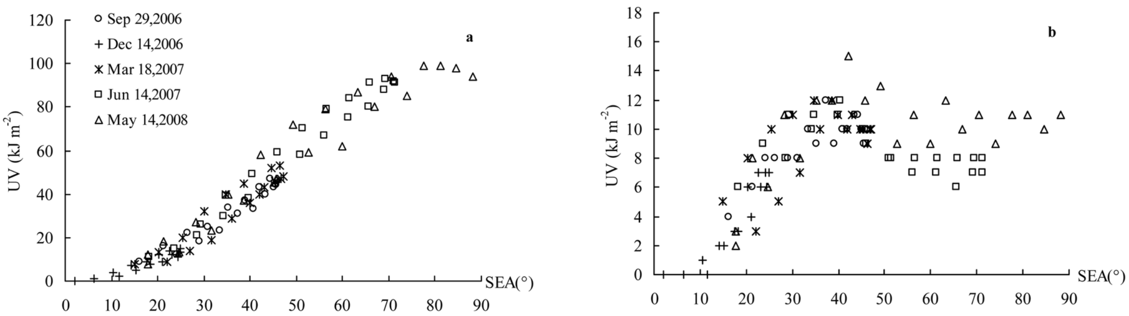



**Fig. 4:** UV exposure doses per 30 min on the horizontal (a) and vertical (b) plane versus the SEA. The vertical axis represents cumulative UV dose per 30 min, while the horizontal axis shows the SEA of the measurement time interval. The changes in SEA over 30 min are shown in Table 1

## Discussion

At present, solar ultraviolet radiation on horizontal plane is studied more extensive, and the global UV monitoring network has greatly improved. These long-term solar UV radiation monitoring data are basic data for the studies of global UV radiation climate evolution trends, as well as its relationship with the study of ozone depletion and UV radiation harmful effects on biological system. Global UV monitoring data are also important support date for the determination of human solar UV exposure and the UV protection strategy of Global solar UVR index (23). China is a large country in terms of area. Mainly due to its geographical position, with most of China at low and middle latitudes, China has high levels of ambient solar UVR in comparison with European countries such as Finland et al, while it has low levels of solar UVR in comparison with countries closer to the equator such as Australia et al. As the same reason, the solar UVR in Sanya (18°N, 109°E) are normally higher than that in Shenyang (41°N, 123°E).

In China, there has a significant problem with solar UVR to the eye, as evidenced by the fact that it has the highest cataract rates in the world (6). To investigated the dose-effect relationship between excessive solar UV exposure and detrimental health impacts such as cataract, not only is it important to know what the levels of ambient solar UVR are, but it is also important to know how much of this ambient UVR people are exposed to. Commonly, UV damage to the tissues happened only when the UV absorbed by the tissues. The humans walking and standing out doors exposed to the natural solar UV radiation, their eyes, cheeks, extremities, trunks, and many other anatomical parts are close to vertical of the ground (or slightly forward or backward), and random oriented to different directions. These characteristics of anatomical structures and behavioral trait determined that the human UV exposure were largely different from environmental solar UV. Nowadays, scientists has concerned about the UV exposure at different inclined planes.

Blumthaler (24) and Webb (25) et al. conducted a vertical plane of the UV spectral radiation measurements. Parisi and Kimlin (26) measured and analyed the UV exposure on horizontal plane and the sun normal plane. Oppenrieder et al. (27) and Schauberger (28, 29) provided the relative irradiances of the UV exposures on inclined surfaces over ground surfaces. These measurement data at different inclined planes is consistent with the theoretical speculation, and confirmed the distribution of UV radiation exposure on inclined planes were different from that of the horizontal plane. The vertical surface will receive more irradiance than a horizontal surface when solar zenith angles are large and the vertical surface is facing the direction of the sun. But the orientation is an important factor that affect UV exposure.

Therefore, the vertical plane in this study presents the free rotation approach to reduce the influence of orientation. While it also simulated the exposure status of human random faced different directions in the natural environment. The results showed that the UV exposure on vertical plane was significantly lower than horizontal plane. Though the UV exposure on horizontal plane had significant seasonal variations in Shenyang city, the seasonal variation of the exposure on vertical plane were relatively much smaller, even the exposure might higher in spring and autumn than that of summer.

It is well known that the diurnal variations on the horizontal plane in a sunny day exhibited unimodal distributions, reached a single UV peak exposure at around solar noon. The measurement in this study presented this law again. However, the diurnal variations at other inclined planes were less presented before. The understanding of diurnal variations of UV radiation at other inclined surfaces including vertical surface may be helpful in developing ways to protect humans from the harmful effects of UV radiation.

To characterize the diurnal variations of UV exposure on vertical surface, the UV exposure values are measured at 15 min intervals using Solar-UV Sensors in Shenyang and Sanya, China. The vertical plane presents some near-vertical anatomical sites of human body, and the free rotation approach simulated the exposure status of human random faced different directions in the natural environment. As shown in this study, the diurnal variations of UV exposure on vertical surface exhibited bimodal distributions, with two peaks in summer in Shenyang and Sanya, and a unimodal distribution in winter in Shenyang. In spring and autumn in Shenyang, the diurnal variations were slightly flat with no significant peaks. Correspondingly, the solar UV exposure on the horizontal plane was strongest in the 4-h midday period. During this period, the horizontal plane received 60.17% (in summer) to 73.53% (in winter) of the total 8-h UV exposure. In all of the seasons except winter, the solar UV exposure on vertical surface during the aforementioned 4-h period was smaller than those of the horizontal plane were. That was almost 10% lower. These data potentially showed that the protection of some vertical and near-vertical anatomical sites of human body from high UV exposure should not only focused on the periods of before and after noon especially in summer. Therefore, to protect the vertical and near-vertical anatomical sites, such as the cheeks, chest, arms, legs and especially the eyes against solar UVR, people have to take positive steps from early hours of the morning to the late hours of the afternoon. The measures include wearing appropriate clothing, sunglasses, and sunscreens when outdoors.

Both the relatively uniform distribution and the bimodal distribution of the UV exposure on vertical plane indicate that when the SEA was about 40°, the vertical plane might potentially receiving maximal exposures. This is to be true for the unweighted total solar UV radiation. However, taking into account of the effectiveness of the incident UV radiation early and late in the day, that is when the sun is low in the sky, the UVB content of the incoming solar UV is lower, whether the vertical plane may potentially as dangerous as that around solar noon needs to be proven by further experiments. Changes in diurnal solar spectrum incident on the UV sensors and the relative biological effectiveness of the spectrum UV radiation (the UVB content of the incoming solar UV) needs to be adequately measured.

Solar UV radiation is an important environmental factor that affects human health. Humans or parts of the human body always exposed in a vertical direction but not horizon. The understanding of diurnal variations of UV radiation to other planes besides horizon may be helpful in developing ways to protect humans from the harmful effects of UV radiation. Except for the surface direction, the different anatomical locations of an individual may have mutual influence to each other. For example, the eye in the orbit was blocked by the eye crack, the superciliary arch and the nose, and the chest was blocked by the head etc. Therefore, it is widely agreed that there is a need for more accurate quantification of UV radiation at representative anatomical regions of interest.

## Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC30700652; NSFC30800895), the Research Fund for the Doctoral Program of Higher Education of China (20070159022), and the Liaoning Province Science and Technology Fund (20062087). We are grateful to Prof. Masaji Ono (NIES, Japan) and Prof. Ge Wang (Virginia Tech, USA) for their instrumental support and editorial assistance, respectively. The authors declare that they have no conflict of interests.

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