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Quantification of Indoor Ocular Exposure to Solar Ultraviolet Light With Four Room Orientations: Using a Model Monitor Embedded in a Manikin Head

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ABSTRACT Solar ultraviolet (UV) radiation is an unavoidable physical environmental factor that contributes to a variety of eye diseases. Exposure to indoor solar UV radiation is an essential component of individual ocular UV exposure. However, few previous studies have attempted to quantify the exposure in term of indoor solar UV irradiance reaching the surface of the human eye under different exposure conditions. Hence, in the current study, we measured the UV exposure in rooms with four main orientations in Sanya (18.4° N, 109.7° E, the lowest-latitude city in mainland China) and Lhasa (29.7° N, 91.14° E, the highest-elevation city in mainland China) to obtain the general and maximum ocular exposure to indoor solar UV in China. A monitoring model consisting of a dual-channel spectrometer that implanted into the manikin eye was used to quantify the UV exposure at a range of times. This study revealed basic diurnal variations under different indoor exposure conditions. In summary, on a sunny summer day, if a person gazes out of an open window at a distance of 0.5 m away from the window, some danger to the eyes may exist in the solar elevation angle (SEA) range of 12° to 37° in an eastward-facing room and in the SEA range of 34° to 9° in a westward-facing room under the maximum open window UV exposure conditions in Lhasa. Similarly, the accumulated UV exposure in a southward-facing room in Sanya was in the SEA range of 67° to 88°. This study attempted to determine the maximum individual accumulated ocular unweighted UVA dose and biologically effective UV dose (UVBE) to serve as a reference for exposure to Sanya and Lhasa. These results can strengthen the understanding of human ocular health and further clarify the possible risks posed by continuous UV exposure.

INDEX TERMS Ultraviolet sources, spectral analysis, eye protection, indoor environments.

I. INTRODUCTION

Architecture is a science developed by humans that can protect us from risks while also connects us to the natural environment. Humans spend more time engaging in indoor activities than outdoor activities [1]. Consequently, indoor environments play a key role in human health, and sunlight is a crucial component of such an environment [2]. Solar ultraviolet (UV) radiation has wavelengths of 280 to 400 nm and can be seen as a double-edged sword. UV irradiance at an appropriate dose has a bactericidal effect [3] and can promote the synthesis of vitamin D [4]; however, UV radiation has also been previously reported to contribute to a variety of eye and skin diseases [5]–[7]. In particular, age-related cataracts, the most common type of cataracts and the principal cause of blindness and visual impairment worldwide, have been found to be correlated with solar UV radiation [8]–[10]. Therefore, it is important to quantify the UV irradiance to which the human eye is exposed. Previously, several studies on solar UV light have mainly focused on outdoor exposure under strong sunlight conditions [11], [12]. However, the level of individual ocular UV exposure indoors in terms of irradiance remains unknown.

Overall, individual ocular UV exposure indoors depends on the outdoor UV irradiance and is influenced by architectural factors and human activities. The outdoor UV irradiance

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depends on meteorological, geographic and temporal factors [13]. Regions at higher elevations and lower latitudes have higher UV irradiance. Furthermore, a clear sky and a smaller thickness of the ozone layer increase UV irradiance [14], [15].

Architectural factors, including the building structure, windows and indoor environment, can also affect the indoor UV exposure. As rooms on lower floors are more easily sheltered by surrounding obstructions, the exposure time to UV irradiance is always shorter in lower-floor rooms than in higher-floor rooms. In addition, an architectural design that provides shelter from windows can reduce UV exposure time. Windows are the most important source of UV light [16]. The number, size, location, type, glass transmittance, and orientation of windows can all affect indoor UV levels [17], [18], and it is difficult to separate the mixed effects of these factors.

Indoor individual ocular UV exposure is closely related to person's activities and eye geometry [19]. The distance from windows has previously been reported to affect the intensity of UV radiation, but personal activities are complex and difficult to quantify [20]. Furthermore, the orientation of the face during a person's activities also influences individual exposure. In addition, the diurnal variation of UV irradiance at the eye is reportedly different from that of horizontal ambient UV light [21], [22]. Previously, we have found a bimodal distribution of diurnal variation in outdoor ocular exposure to solar UV light due to the shelter provided by the eye frame structure relative to horizontal ambient exposure. However, the diurnal variation in indoor ocular exposure to solar UV light under different exposure conditions reminds unknown.

Therefore, in this study, a manikin model was used to simulate human indoor ocular UV exposure due to sunlight. We investigated the impact of the window orientation of the room on the UV exposure of the model's eye and the influences of window orientation in combination with the location and facial orientation of the model. Finally, we considered eye health in combination with the maximum individual accumulated unweighted UVA dose (mainly considered in closed window condition) and biologically effective UVB (UVBE) dose (mainly considered in open window condition) to the manikin's eye in the case of a high outdoor horizontal ambient UV irradiance background.

II. MATERIALS AND METHODS

A. EXPERIMENTAL INSTRUMENTS

Manikin heads have been frequently used in research focusing on individual UV exposure because of the anatomical features of the eye [15], [19]. In this study, a model simulating a standing posture was used, which consisted of three parts, namely, from top to bottom, a turntable base, a stand and a manikin head (Fig. 1). We have previously conducted some monitoring work using this model [21]–[24]. The model is 1.7 m tall, and its eyes are 1.6 m from the ground.

FIGURE 1. Rotating manikin with spectrometer, from top to bottom: a manikin head, a stand, and a turntable base.

The interpupillary distance is 0.06 m, and the separation between the eye and the superciliary arch is 0.6 cm. The angle and position of the manikin's head and eyes in relation to the horizon are shown in Fig. 2c. Three instruments were used on each monitoring day. One instrument was used to measure the outdoor solar UV radiation, and the other two instruments were used to measure the indoor exposure.

The UV irradiance was measured by using a high-quantum-efficiency miniature dual-channel fiber-optic spectrometer (Avantes, Netherlands). This spectrometer includes a 2045-pixel charge-coupled device (CCD) detector array and is suitable for low-light applications with less than 0.1% stray light. The full width at half maximum (FWHM) resolution of the spectrometer is 2.0 nm, the signal-to-noise ratio is 500 dB, and every detector has a cosine corrector (CC-UV/VIS) with an active area of 3.9 mm. The spectrometer was calibrated by the National Physical Laboratory (NPL), before the experiment, and the measurement uncertainty was approximately 6% (k =2, 300-400 nm). The spectrometer included two detectors for each manikin: one detector was affixed to the top of the head to determine the horizontal ambient UV irradiance, and the other detector was placed tangential to

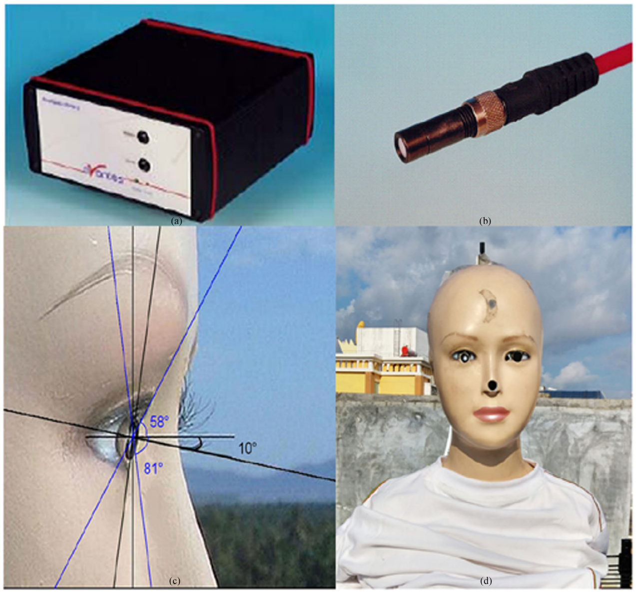

FIGURE 2. **Spectrometer (a), detectors (b), angle (c) and position (d) of the manikin head.**

the position of the manikin's right cornea to measure the UV irradiance reaching the manikin's eye (Fig. 2a, 2b and 2d).

B. GEOGRAPHICAL AND METEOROLOGICAL CONDITIONS

This study investigated indoor ocular exposure to UV irradiance in the case of a high outdoor UV background. For this purpose, we selected the summer season in Sanya (18.4° N, 109.7° E, 18 m above sea level) and Lhasa (29.7° N, 91.14° E, 3650 m above sea level) to determine the corresponding indoor UV levels under the maximum outdoor UV light conditions in China. Sanya is the lowest-latitude city in mainland China, with a maximum SEA of approximately 90° in May (when the experiments were conducted). Lhasa is the highest-elevation city in China. Both cities receive greater exposure to solar UV radiation than other cities and are associated with a high risk of cataracts [25], [26]. Both fine particulate matter (PM2.5) and air quality index (AQI) data show that the air quality in these two cities is fairly high, compared with other cities in mainland China (PM2.5 lower than 35 $\mu c \cdot m^{-3}$; AQI lower than 110). Detailed meteorological conditions on the monitoring days in Sanya and Lhasa are shown in the Table 1 of the Supplementary Materials [27].

The experiments were performed only on clear or slightly cloudy days. The final datasets were obtained on May 16 and 20, 2015, in Sanya and on May 19 and 24, 2016, in Lhasa. In Sanya, the indoor measurements were acquired in eastward- and westward-facing rooms on May 16, 2015, and in southward- and northward-facing rooms on May 20, 2015. In Lhasa, monitoring was performed on May 19, 2016, in eastward- and westward-facing rooms, and on May 24, 2016, in the southward and northward rooms. Measurements of UV irradiance exposure were obtained from 07:45 to 17:45 China Standard Time (CST) (SEA range of 21°-88°) in Sanya and from 08:00 to 20:00 CST (SEA range of 12°-81°) in Lhasa.

The SEA values corresponding to the indoor exposure of the manikin head to direct solar UV irradiation during this study are provided in subsection D of the Results section. However, the SEA corresponding to such exposure is not a definite value; instead, it is affected by a variety of factors, including the building environment, the region of the world, the season and the facial structure of the individual of interest.

C. INDOOR AND OUTDOOR CONDITIONS

The outdoor solar UV irradiance was measured on the roofs of five-story guesthouses, the surfaces of which were covered with concrete. The indoor irradiance levels were measured in rooms on the fifth floor; the floors were covered with white tiles in Sanya and brown carpet in Lhasa. We selected rooms with four main window orientations, namely, eastward-, westward-, northward- and southward-facing rooms, to assess the corresponding indoor UV exposure. Importantly, each room had only one window. However, the indoor layout of each room was not the same due to the room orientation requirements. The shapes and sizes of the windows were also not completely consistent. Some building shades were present outside the windows of the eastward- and southward- facing rooms in Sanya. Similarly, two handrails were present outside the window of the northward-facing room in Lhasa. Therefore, unfortunately, the measurements in these rooms were likely lower than the actual irradiance. The total net and open areas of the windows are enumerated in Table 2 of the Supplementary Materials.

D. SOLAR UV EXPOSURE MEASUREMENTS

One manikin was placed outdoors with the eyes always pointed towards the sun. The horizontal ambient solar UV irradiance (via the detector on the top of the manikin head) and the corresponding irradiance at the eye (via the detector mounted in the intraorbital socket of the manikin eye) were measured simultaneously through synchronization of the dual-channel detectors.

Another manikin was positioned indoors in front of a window frame that was either open or closed window, respectively (Fig. 3). Three monitoring positions were defined in each room, 0.5, 1.0 and 1.5 m away from the window. Data were collected four times at each monitoring position, corresponding to four states of the manikin eye: with the manikin facing towards the open window, with the back of the manikin facing towards the open window, with the manikin facing towards the closed window, and with the back of the manikin facing towards the closed window. The horizontal ambient indoor solar UV irradiance and the corresponding irradiance at the eye were collected simultaneously, as described above, for each data collection step. Indoor and outdoor UV exposure measurements were acquired simultaneously using a timer. The interval between the collections of each set of monitoring data was approximately 900 s.

TABLE 1. Total and segmental maximum closed window unweighted UVA doses H_{UVA}) For four time ranges.

City	Time	Room orientation							
		East		West		South		North	
		$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose
Lhasa	08:00-11:00	1.64*	0.58	0.14	0.08	0.10	0.19	0.11	0.13
	11:00-14:00	0.62	0.22	0.19	0.12	0.17	0.31	0.21	0.25
	14:00-17:00	0.35	0.12	0.45	0.27	0.18*	0.32	0.37*	0.43
	17:00-20:00	0.23	0.08	0.87*	0.53	0.10	0.18	0.16	0.19
	08:00-20:00	2.83	1.00	1.65	1.00	0.55	1.00	0.86	1.00
Sanya	07:45-10:15	0.43*	0.49	0.09	0.14	0.26	0.22	0.13	0.20
	10:15-12:45	0.21	0.24	0.11	0.17	0.35*	0.30	0.19*	0.29
	12:45-15:15	0.15	0.17	0.12	0.19	0.34	0.29	0.19*	0.29
	15:15-17:45	0.09	0.10	0.32*	0.50	0.24	0.20	0.14	0.22
	07:45-17:45	0.88	1.00	0.64	1.00	1.19	1.00	0.66	1.00

* indicates the highest segmental accumulated dose over the entire day for the given room orientation.

TABLE 2. Total and segmental maximum open window unweighted UVA doses (H_{UVA}) for four time ranges.

City	Time	Room orientation							
		East		West		South		North	
		$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose	$H_{UVA}/10^4$ ($J \cdot m^{-2}$)	Proportion of daily dose
Lhasa	08:00-11:00	4.10*	0.58	0.35	0.08	0.25	0.19	0.28	0.13
	11:00-14:00	1.55*	0.22	0.48	0.12	0.43	0.31	0.53	0.25
	14:00-17:00	0.88	0.12	1.13*	0.27	0.45	0.32	0.93	0.43
	17:00-20:00	0.58	0.08	2.18*	0.53	0.25	0.18	0.40	0.19
	08:00-20:00	7.08	1.00	4.13	1.00	1.38	1.00	2.15	1.00
Sanya	07:45-10:15	1.08*	0.49	0.23	0.14	0.65	0.22	0.33	0.20
	10:15-12:45	0.53	0.24	0.28	0.17	0.88	0.30	0.48	0.29
	12:45-15:15	0.38	0.17	0.30	0.19	0.85	0.29	0.48	0.29
	15:15-17:45	0.23	0.10	0.80	0.50	0.60	0.20	0.35	0.22
	07:45-17:45	2.20	1.00	1.60	1.00	2.98	1.00	1.65	1.00

* indicates the segmental accumulated dose exceeding the limit value.

E. UV IRRADIANCE (E) AND UNWEIGHTED UVA DOSE (H_{UVA})

In this study, UV irradiance data were measured at all locations behind both open and closed windows. However, although window glass filters out most UVB light, some UVA light is still transmitted into rooms with closed windows [18]. Therefore, the unweighted UVA dose (corresponding to the spectral region of 315 nm to 400 nm) was used to evaluate the exposure conditions, especially in the closed-window case, which is predominantly associated with UVA radiation. Meanwhile, to further explore the UV exposure level under open-window conditions, the biologically effective UV (UVBE) dose (corresponding to the spectral region of 300 nm to 400 nm) was also calculated [28]–[31] in this study.

Solar spectral irradiance ($W \cdot m^{-2} \cdot nm^{-1}$) data were collected and converted into Excel format using AvaSoft 7.4 software (Avantes, Netherlands) (at 1-nm intervals). Due to the electrically noisy environment, measuring irradiance from 280 nm to 299 nm was difficult; therefore, the solar UV irradiance (E, unit: $W \cdot m^{-2}$) was calculated as an integral from 300 nm to 400 nm in this study.

FIGURE 3. The back (a) and profile (b) of the monitoring instrument used in the study (westward-facing monitoring room in Sanya).

The unweighted UVA dose (H_{UVA}) was calculated in accordance with the following equation:

$$H_{\mathrm{UVA}} = \sum\nolimits_{T} E_{\mathrm{UVA}}(T) \cdot T \tag{1}$$

where E_{UVA}(T) is the UV irradiance integrated from the measured spectral irradiance between 315 nm and 400 nm and is assumed to be constant throughout the exposure time. T is the exposure time, which was 900 s in this study. Due to the potential influence of variations in weather conditions, we did not consider measurements acquired under heavy cloud cover or rain. However, the data collected at a tiny minority of the time points could not be used directly for reasons related to the weather. At these time points, we used theoretically similar values instead of the measurements recorded in this study. If a time point with unusable measurement values was the first time point of the measurement period, we used the results collected at the same SEA at a different time instead of those collected at the starting time point (the variations of the SEA are symmetric, from 0° to 90° and back to 0°, throughout the day). In contrast, if a time point with unusable measurements was not the starting time point, we averaged the measured values from the two adjacent time points.

F. UVBE IRRADIANCE (E_{eff}), UVBE DOSE (H_{eff}) AND DATA ANALYSIS

The UVBE irradiance (E_{eff}) was integrated from 300 nm to 400 nm in accordance with the following equation:

$$E_{eff} = \sum E(\lambda) \cdot S(\lambda) \cdot \Delta\lambda \tag{2}$$

where E(λ) is the spectral irradiance, S(λ) is the relative spectral effectiveness related to eye damage (the spectral weighting function of S(λ) from 280 nm to 400 nm is shown in Fig. 4), and Δλ is the wavelength increment of the spectral data, which was 1 nm in this study.

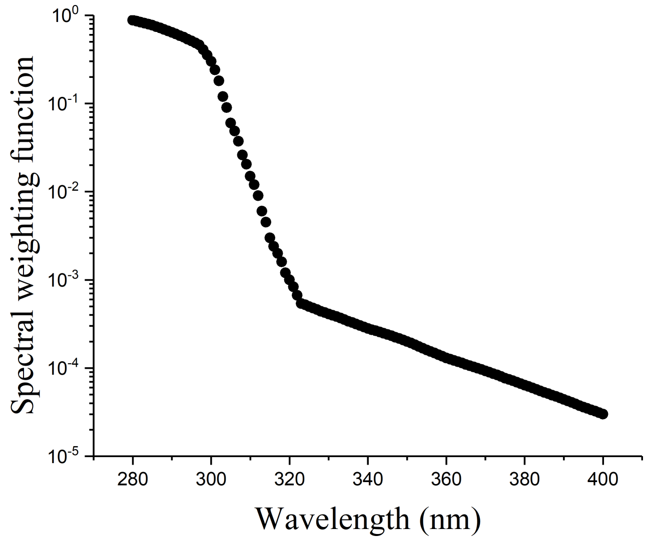

FIGURE 4. UVBE Spectral weighting function announced by ICNIRP.

The UVBE dose (H_{eff}) was calculated in accordance with the following equation:

$$H_{eff} = \sum_{T} E_{eff}(T) \cdot T \tag{3}$$

where E_{eff}(T) is the calculated UVBE irradiance and T is the exposure time, which was 900 s in this study. Because window glass filters out most UVB radiation, in the study, the weighted UVBE irradiance and UVBE dose were used to evaluate the UV exposure level only under open-window conditions.

The SPSS 22.0 (International Business Machines Corporation, USA) and OriginPro 2017 (OriginLab, USA) statistical programs were used for data analysis. Paired-sample t tests were used for within-group comparisons, and $p < 0.05$ was considered statistically significant.

III. RESULTS

A. DIURNAL VARIATION OF OPEN-WINDOW SOLAR UV IRRADIANCE IN THE SOUTHWARD-FACING ROOM IN Lhasa

The diurnal variation of the open-window solar UV irradiance in the southward-facing room in Lhasa exhibited a bell-shaped curve, as shown in Fig. 5a. When the manikin was placed 0.5 m away from the window and was pointed towards the window, the maximum relative averaged indoor UV irradiance was 38.95-fold higher than the UV irradiance measured when the manikin's face was placed back to the window at 1.5 m (Fig. 5b).

Fig. 5c shows the effects of distance from the window under different conditions. The UV exposure levels in the 0.5 m and 1.0 m datasets were 8.75-fold and 3.20-fold higher than those in the 1.5 m dataset when the manikin was facing the window ($p < 0.01$). Regarding the horizontal ambient UV irradiance levels with the open window, the irradiance levels in the 0.5 m and 1.0 m datasets were 3.85-fold and 1.58-fold

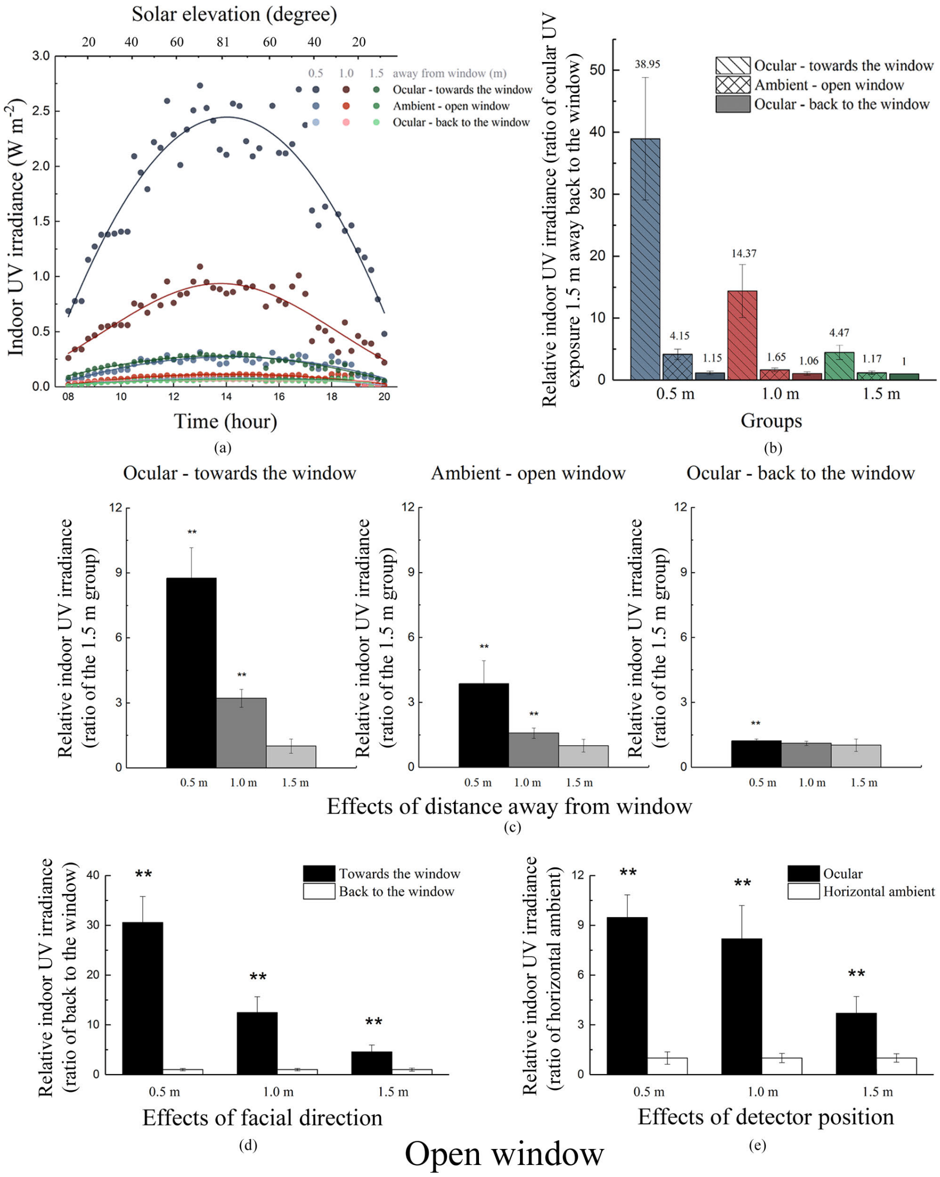

FIGURE 5. **Diurnal variation of open-window solar UV exposure in the southward-facing room in Lhasa. The results for three indoor solar UV exposure conditions with the window open (manikin face towards the window, open window horizontal ambient exposure and manikin face back to the window) at three monitoring positions (0.5 m, 1.0 m and 1.5 m away from the window) are shown in Fig. 5a. The relative average indoor UV irradiance levels under the aforementioned exposure conditions and at all monitoring positions are shown in Fig. 5b. The data are presented as the means ± SD. The effects of the distance from the window and the facial orientation of the manikin are shown in Fig. 5c and 5d. The relative UV exposure levels at the manikin's eye level compared with the horizontal ambient exposure are shown in Fig. 5e. The data are presented as the means ± SD.** $**p < 0.01$.

higher, respectively, than those in the 1.5 m dataset ($p < 0.01$). Compared with the UV exposure in the 1.5 m dataset, the UV exposure level in the 0.5 m dataset was significantly increased (1.22-fold higher than that in the 1.5 m dataset, $p < 0.01$) when the manikin's back was facing to the window. To illustrate the effects of the manikin's facial orientation, we show the relative indoor UV irradiance in Fig. 5d. Under open-window conditions, the UV irradiance levels with the manikin facing the window were 30.56-fold, 12.47-fold and 4.57-fold higher than those with the manikin's back facing the window in the 0.5 m, 1.0 m and 1.5 m datasets, respectively ($p < 0.01$). As shown in Fig. 5e, compared with the levels measured by the detector in the horizontal position, the UV irradiance levels measured by the detector implanted in the manikin's eye socket were markedly increased, being 9.47-fold, 8.18-fold and 4.22-fold higher than the horizontal ambient measurements in the 0.5 m, 1.0 m and 1.5 m datasets, respectively, under open-window condition ($p < 0.01$). In addition, we obtained similar results when comparing with the UV irradiance differences of manikin's eye and horizontal ambient in

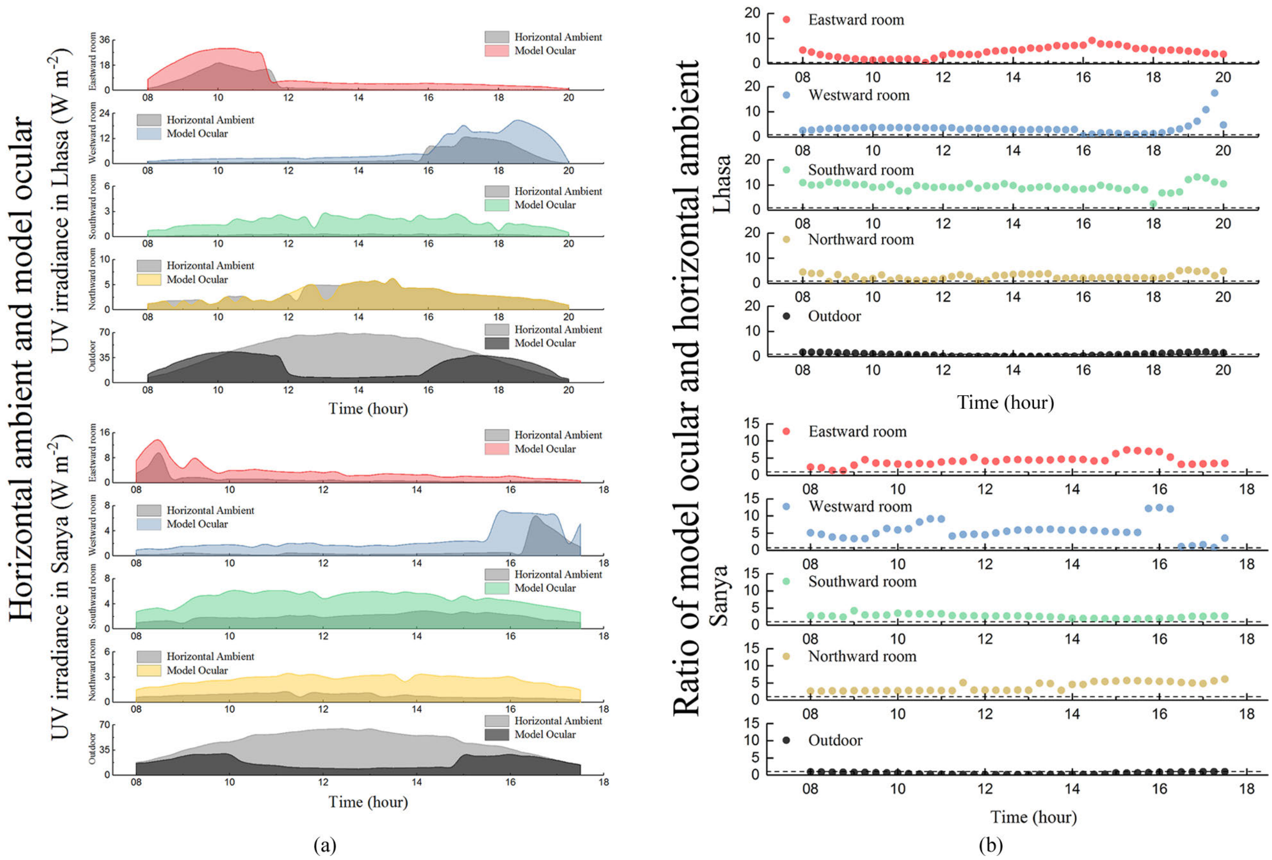

FIGURE 6. **Differences between horizontal ambient exposure and exposure at the manikin's eye level. At the monitoring position 0.5 m away from the window, with the detector in the eye socket of the indoor manikin oriented towards the open window and the outdoor detector oriented towards the sun, the horizontal ambient and eye-level UV irradiance conditions were measured using the same room orientation in Lhasa and Sanya, as shown in Fig. 6a. The exposure ratios between the manikin eye level and the horizontal ambient level are shown in Fig. 6b.**

other three orientation rooms in Lhasa and Sanya and shown in the Fig. 6.

B. DIURNAL VARIATION OF CLOSED-WINDOW SOLAR UV IRRADIANCE IN THE SOUTHWARD-FACING ROOM IN Lhasa

As shown in Fig. 7a, consistent with the open-window results shown in Fig. 5a, the diurnal variation of the solar UV irradiance in the southward-facing room in Lhasa with the window closed exhibited a bell-shaped curve. When the manikin was 0.5m away from the window, the maximum relative average indoor UV irradiance measured with the manikin facing the window was 14.98-fold higher than that was measured at the manikin was 1.5 m away from the window with the manikin's back facing the window (Fig. 7b).

When the indoor manikin was facing the window, the UV exposure levels in the 0.5 m and 1.0 m datasets were 3.80-fold and 2.52-fold higher, respectively, than those in the 1.5 m dataset ($p < 0.01$). Compared with the UV exposure in the 1.5 m dataset, the indoor horizontal ambient UV exposure levels were 3.04-fold and 1.56-fold higher in the 0.5 m and 1.0 m datasets, respectively. When the manikin face was placed 0.5 m and 1.0 m away from the window and was pointed back to the window, the UV irradiance were 1.28-fold ($p < 0.01$) and 1.11-fold ($p < 0.05$) higher, respectively, than those in the 1.5 m dataset (Fig. 7c). Under closed-window conditions, the UV irradiance levels with the manikin facing the window were 12.62-fold, 8.98-fold and 4.09-fold higher than those with the manikin's back towards the window in the 0.5 m, 1.0 m and 1.5 m datasets, respectively ($p < 0.01$) (Fig. 7d). Regarding the indoor UV exposure, the exposure levels detected at the manikin's eye level in the 0.5 m, 1.0 m and 1.5 m datasets, were 4.63-fold, 5.17-fold and 3.70-fold higher, respectively, than the horizontal ambient levels under closed-window conditions ($p < 0.01$) (Fig. 7e).

C. EXPOSURE DIFFERENCES BETWEEN OPEN AND CLOSED-WINDOW CONDITIONS IN THE SOUTHWARD-FACING ROOM IN Lhasa

As shown in Fig. 8a and 8d, with the manikin facing the open window, the UV irradiance levels in the 0.5 m and 1.0 m datasets were significantly increased, by 2.56-fold and 1.41-fold, respectively, compared with those obtained under closed-window conditions ($p < 0.01$). In addition, the horizontal ambient UV irradiance levels with the window open

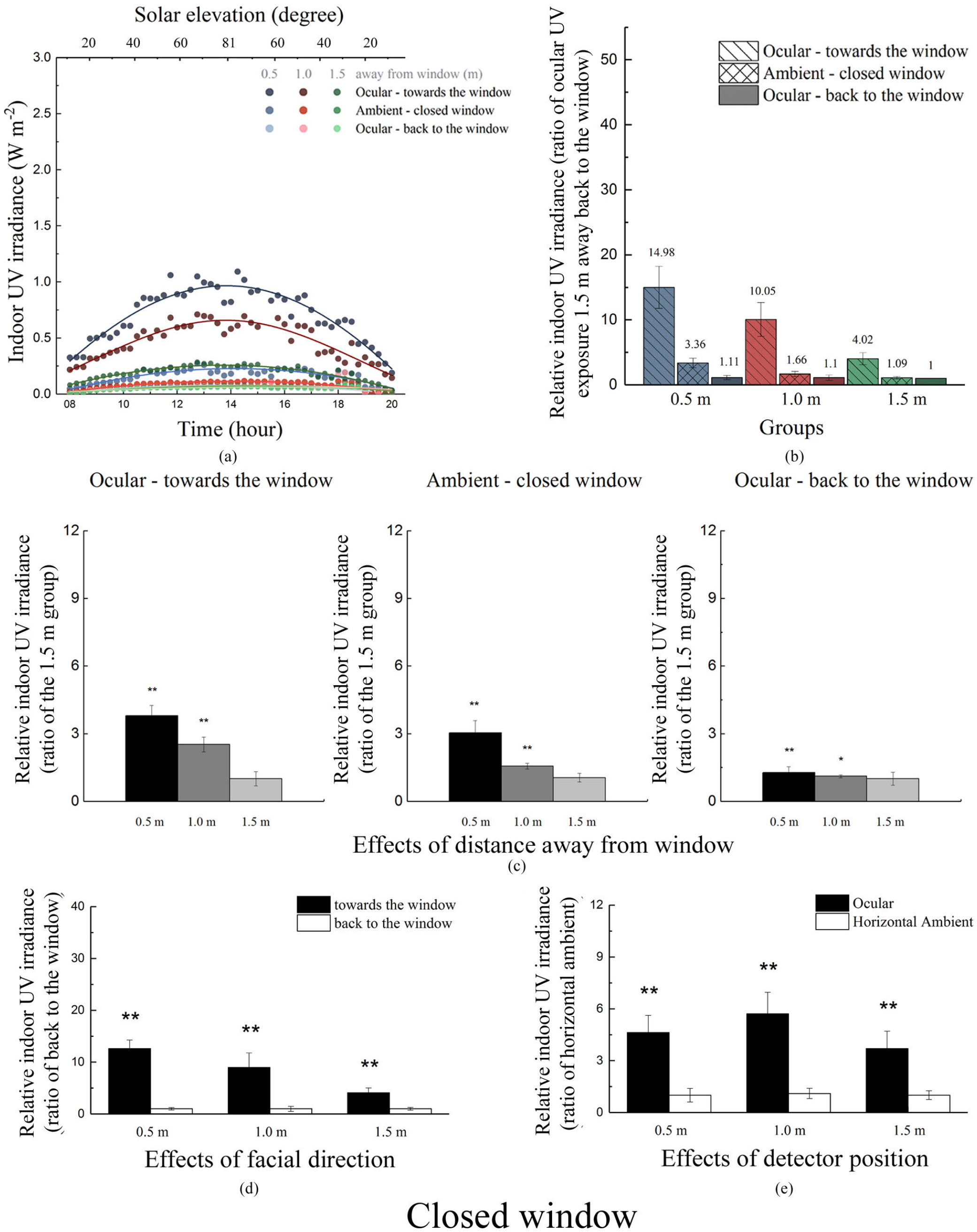

FIGURE 7. Diurnal variation of closed-window solar UV exposure in the southward-facing room in Lhasa. The results for three indoor solar UV exposure conditions with the window closed (manikin face towards the window, open window horizontal ambient exposure and manikin face back to the window) at three monitoring positions (0.5 m, 1.0 m and 1.5 m away from the window) are shown in Fig. 7a. The relative average indoor UV irradiance levels under the aforementioned exposure conditions and at all monitoring sites are shown in Fig. 7b. The data are presented as the means ± SD. The effects of the distance away from the window and the facial orientation of the manikin are shown in Fig. 7c and 7d. The relative UV exposure levels at the manikin's eye level compared with the horizontal ambient exposure are shown in Fig. 7e. The data are presented as the means ± SD. $*p < 0.05$, $**p < 0.01$.

were 1.24-fold higher than those with the window closed in the 0.5 m dataset, reflecting a significant difference ($p < 0.01$) (Fig. 8b and 8e). When the manikin's back was facing towards the window, no obvious differences between the open- and closed- window conditions were observed at any monitoring position (Fig. 8c and 8f).

D. OUTDOOR AND MAXIMUM OPEN-WINDOW INDOOR OCULAR UV EXPOSURE

The solar UV exposure under the maximum indoor exposure conditions in this study (at the monitoring position 0.5 m away from the window with the detector oriented towards the open window) is analyzed as follows. As shown in

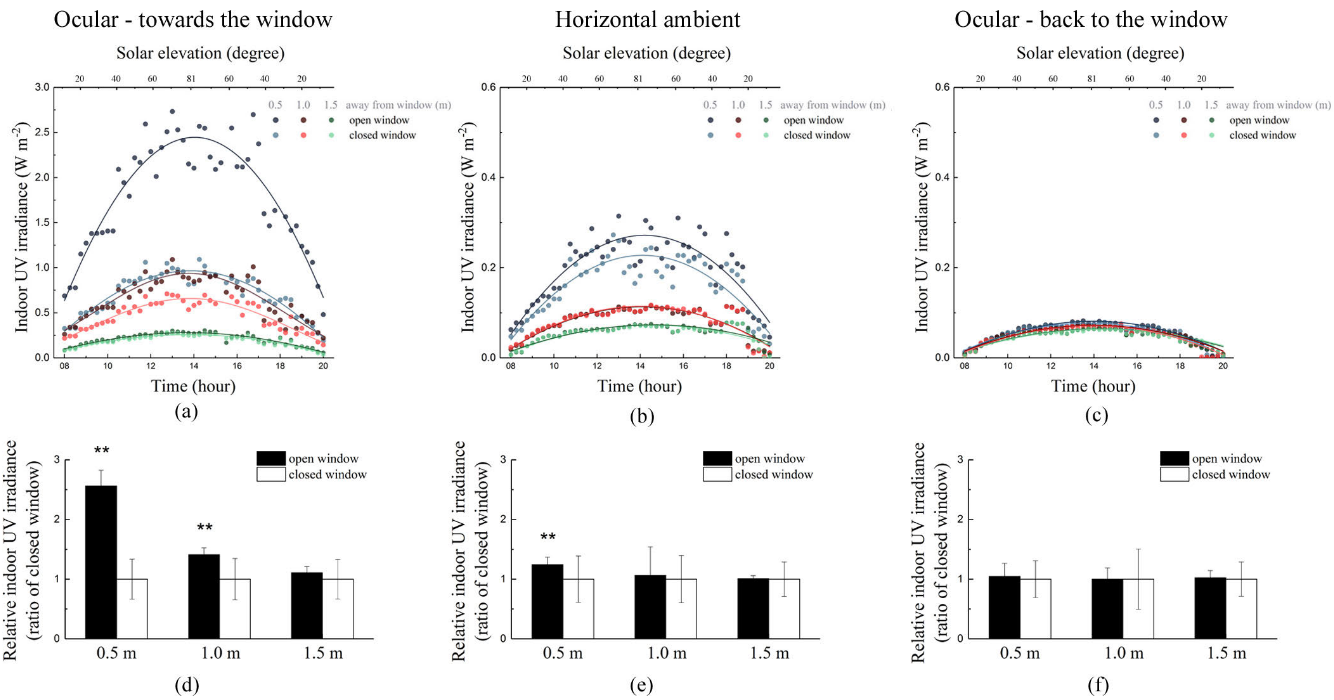

FIGURE 8. UV exposure differences between the open and closed-window conditions in the southward-facing room in Lhasa. The results for three indoor solar UV exposure conditions (manikin face towards the window, horizontal ambient exposure and manikin face back to the window) at three monitoring positions (0.5 m, 1.0 m and 1.5 m away from the window) are shown in Fig. 8a, 8b, and 8c. The relative UV exposure levels under the open- and closed-window conditions are shown in Fig. 8d, 8e, and 8F. The data are presented as the means ± SD. $**p<0.01$.

Fig. 9a and 9b, the diurnal variation in the outdoor horizontal ambient solar UV irradiance displayed a bell-shaped curve in both Lhasa and Sanya. In addition, the diurnal variation in the outdoor solar UV irradiance detected at the manikin's eye level corresponded to a double-peaked curve in both cities. The level of indoor solar UV exposure at the manikin's eye level in an eastward-facing room peaked in the morning. For this room orientation, direct solar UV exposure of the manikin's eye occurred in the SEA range of 12°-37° in Lhasa and in the SEA range of 25°-35° in Sanya. By contrast, the ocular exposure levels peaked in the afternoon in the westward-facing rooms and direct solar UV exposure of the manikin's eye occurred in the SEA range of 34°-9° in Lhasa and in the SEA range of 32°-14° in Sanya for this room orientation. The diurnal variation characteristics of the exposure in the southward- and northward-facing rooms were similar to those of the outdoor horizontal ambient exposure, although the irradiance was much lower indoors. The maximum outdoor horizontal ambient UV exposure was 70.0 W·m^{-2} in Lhasa and 64.4 W m^{-2} in Sanya, while the maximum UV exposure at the manikin's eye level was 43.1 W·m^{-2} in Lhasa and 29.6 W m^{-2} in Sanya. The maximum UV irradiance levels at the manikin's eye level were 30.0, 20.6, 2.7 and 6.2 W·m^{-2} in the eastward-, westward-, southward- and northward-facing rooms, respectively, in Lhasa. In Sanya, the corresponding levels were 13.5, 6.9, 6.1 and 3.4 W·m^{-2} for the four room orientations.

To compare the maximum open-window indoor and outdoor exposure levels, we calculated the ratio of the indoor to outdoor UV irradiance levels measured at the manikin's eye level at the same time point, and the diurnal variations of this ratio are shown in Fig. 9c and 9d. The maximum indoor-to-outdoor exposure ratios measured at the manikin's eye level were 0.84, 0.95, 0.37 and 0.79 in the eastward-, westward-, southward- and northward-facing rooms, respectively, in Lhasa. In Sanya, the corresponding ratios were 0.68, 0.36, 0.67 and 0.36. Furthermore, we calculated the ratio of the indoor UV irradiance at the manikin's eye level to the outdoor horizontal ambient irradiance at the same time point, as shown in Fig. 5e and 5f. In Lhasa, from 8:00 to 11:00 (SEA range of 12°-50°), the ratio of the indoor eye-level UV exposure to the outdoor horizontal ambient UV exposure was greater than 0.50 in the eastward-facing room, while this ratio was greater than 0.50 from 18:15 to 19:45 (SEA range of 31°-12°) in the westward-facing room. In the eastward-facing room in Sanya, the ratio of the indoor eye-level UV exposure to the outdoor horizontal ambient UV exposure was greater than 0.50 from 8:15 to 8:30 (SEA range of 28°-32°).

E. CLOSED-WINDOW MAXIMUM UNWEIGHTED UVA DOSES AND REFERENCES FOR INDIVIDUAL OCULAR EXPOSURE

To further assess the indoor ocular UV exposure level of the manikin, the day was divided into four segments. In Lhasa, the chosen time ranges were each approximately 3 h in

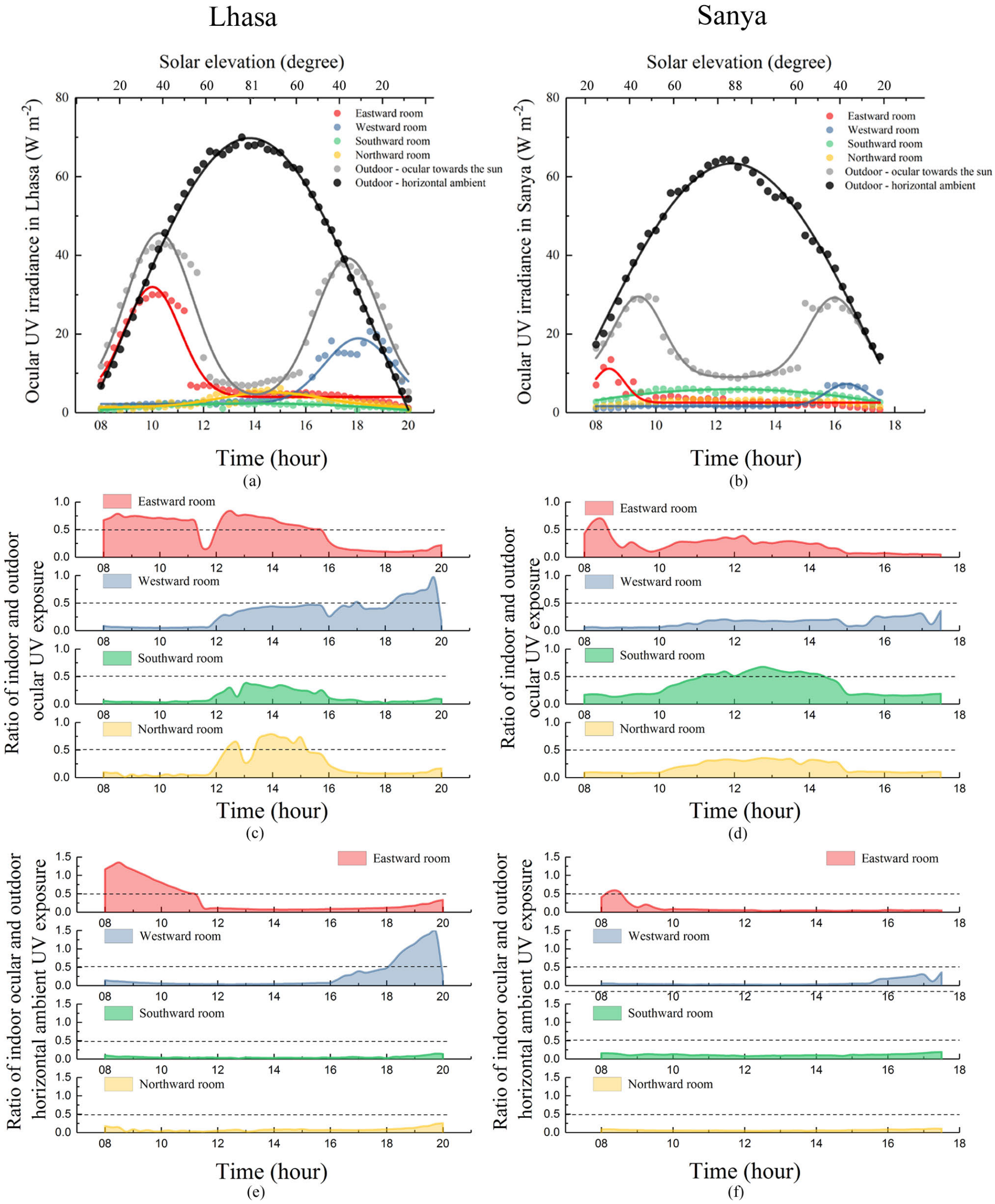

FIGURE 9. **Outdoor and maximum open-window indoor ocular UV exposure levels and indoor and outdoor UV exposure ratios (for the monitoring positions 0.5 m away from the window with the detector in the indoor manikin's eye oriented towards the open window and the detector in the outdoor manikin's eye oriented towards the sun). The outdoor and indoor UV exposure levels at the manikin's eye level for the four room orientations in Lhasa and Sanya are shown in Fig. 9a and 9b. The ratios of indoor to outdoor UV exposure levels measured at the manikin's eye level for the four room orientations are shown in Fig. 9c and 9d. The ratios of indoor to outdoor horizontal ambient UV exposure levels for the four room orientations are shown in Fig. 9e and 9f.**

length from 8:00 to 20:00, while in Sanya, the time ranges were 2.5 h in length from 7:45 to 17:45. The closed-window unweighted UVA dose values are shown as $H_{UVA}/10^4$ (unit: J·m^{-2}) in Table 1. The UV dose in the segmental from 8:00 to 11:00 (SEA ranges 12°-37°) in the eastward-facing room in Lhasa exceeded the 10^4 J·m^{-2} UVA limit recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [31] (marked with $*$ in Table 1). The segmental unweighted UVA doses in Sanya for all four room orientations were all within the safety limits. The open-window maximum unweighted UVA doses are shown in the Table 2.

Moreover, the hourly accumulated closed-window indoor unweighted UVA doses at the manikin's in Lhasa and Sanya are shown in Fig. 10a. The maximum hourly accumulated closed-window unweighted UVA dose at eye level was 6571 J·m^{-2}, which occurred in the eastward-facing room in Lhasa between 9:00 and 10:00 (SEA range of 24°-37°).

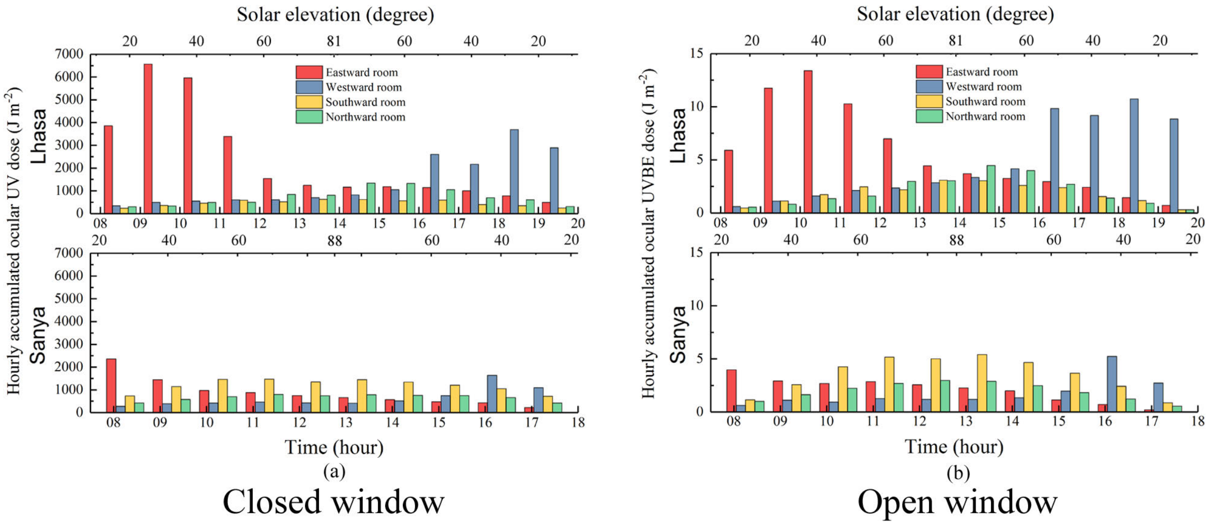

FIGURE 10. **Hourly accumulated indoor unweighted UVA doses and UVBE doses to the manikin's eye in Lhasa and Sanya (at the monitoring position 0.5 m away from the window, with the manikin's face oriented towards the window). The hourly accumulated ocular unweighted UVA doses in a room with the window closed are shown in Fig. 10a, and the hourly accumulated ocular UVBE doses in a room with the window open are shown in Fig. 10b.**

In Sanya, corresponding maximum value was 2360 J·m^{-2} and occurred in the eastward-facing room between 7:45 and 8:45 (SEA range of 21°-35°).

To further evaluate individual ocular UV irradiance exposure during the day, the predicted maximum individual ocular UV doses outdoors and indoors with the windows open and closed were calculated. Gaussian fitting was used to calculate the ocular UV doses in Lhasa and Sanya in 15-minute intervals, and the results are shown in Tables 3 and 4.

F. OPEN-WINDOW MAXIMUM UVBE DOSES AND REFERENCES FOR INDIVIDUAL OCULAR EXPOSURE

The UVBE doses were calculated from 300 to 400 nm in accordance with a report distributed by the ICNIRP, and the results are shown in Table 5. The UVBE dose in the segmental from 8:00 to 11:00 (SEA range of 12°-37°) in the eastward-facing room in Lhasa exceeded the 30 J·m^{-2} UVBE limit recommended by ICNIRP [31]. Similarly, all segmental UVBE doses measured for the outdoor horizontal ambient case exceeded the ICNIRP limit; the maximum segmental accumulated UVBE dose was measured during the second segment, from 11:00 to 14:00 (SEA range of 50°-81°) in Lhasa and from 10:15 to 12:45 (SEA range of 56°-88°) in Sanya. Furthermore, the maximum segmental outdoor UVBE dose at the manikin's eye level was measured detected in the first segment, from 8:00 to 11:00 (SEA range of 12°-37°) in Lhasa and from 7:45 to 10:15 (SEA range of 21°-56°) in Sanya (marked with ∗ in Table 5).

To further investigate the exposure ratios based on the UVBE dose, we calculated the indoor-to-outdoor ratio for the UVBE doses of manikin's eye. In Lhasa, the maximum whole-day and segmental accumulated indoor-to-outdoor eye level UVBE dose ratios were observed in the eastward-facing room. In Sanya, these ratios were maximal in the southward-facing room. The maximum indoor-to-outdoor whole-day accumulated weighted dose ratios measured at the manikin's eye level were 0.46 in Lhasa and 0.34 in Sanya (marked with †in Table 5). Then, we calculated the ratio of the indoor eye level UVBE dose to the outdoor horizontal ambient UVBE dose. The maximum whole-day accumulated weighted dose ratios between the indoor eye-level dose and the outdoor horizontal ambient dose were 0.17 in Lhasa and 0.11 in Sanya (marked with # in Table 5). Notably, unlike the maximum segmental UVBE dose ratio for the indoor eye-level dose to the outdoor eye-level dose, which was observed in the southward-facing room, the maximum segmental UVBE dose ratio for the indoor eye-level dose to the outdoor horizontal ambient dose was observed in the eastward-facing room in Sanya.

As shown in Fig. 6b, the maximum hourly accumulated indoor UVBE dose to the manikin's eye was 13 J·m^{-2}, which occurred in the eastward-facing room in Lhasa between 10:00 and 11:00 (SEA range of 37°-50°). In Sanya, the maximum hourly accumulated indoor UVBE dose to the manikin's eye was 5 J·m^{-2}, which occurred in the southward-facing room from 12:45 to 13:45 (SEA range of 88°-74°). In addition, the predicted maximum individual ocular UVBE dose exposure levels outdoors and indoors with the window open are provided in Tables 6 and 7 for reference to improve the understanding of continuous ocular UV exposure and to provide guidance for avoiding possible risk.

IV. DISCUSSION

Solar radiation is an unavoidable environmental physical factor that is a central component of architectural designs due to the potential bactericidal effects [32], better inhabitant experience [33], and health-promoting physiological [4], [34] and psychological [35] effects of sunlight. Unfortunately, excessive UV irradiance has also been shown to cause cataracts among other harmful effects [36]. Previous studies have reported that humans spend most of their time

TABLE 3. Maximum individual ocular unweighted UVA dose references values in Lhasa (unit: 10^4J·M^{-2}).

Time	East		West		South/North		Outdoors	Time	East		West		South/North		Outdoors
	open	closed	open	closed	open	closed			open	closed	open	closed	open	closed	
08:00-08:15	0.15	0.06	0.03	0.01	0.01	0.00	0.22	14:00-14:15	0.07	0.03	0.07	0.03	0.04	0.02	0.07
08:15-08:30	0.20	0.08	0.03	0.01	0.01	0.01	0.27	14:15-14:30	0.07	0.03	0.07	0.03	0.04	0.02	0.08
08:30-08:45	0.25	0.10	0.04	0.01	0.02	0.01	0.34	14:30-14:45	0.07	0.03	0.06	0.03	0.04	0.02	0.09
08:45-09:00	0.31	0.12	0.04	0.02	0.02	0.01	0.41	14:45-15:00	0.08	0.03	0.07	0.03	0.04	0.02	0.10
09:00-09:15	0.37	0.15	0.04	0.02	0.02	0.01	0.48	15:00-15:15	0.08	0.03	0.07	0.03	0.04	0.01	0.13
09:15-09:30	0.41	0.17	0.04	0.02	0.02	0.01	0.54	15:15-15:30	0.08	0.03	0.08	0.03	0.04	0.01	0.16
09:30-09:45	0.45	0.18	0.05	0.02	0.02	0.01	0.60	15:30-15:45	0.08	0.03	0.10	0.04	0.04	0.01	0.21
09:45-10:00	0.47	0.19	0.05	0.02	0.02	0.01	0.65	15:45-16:00	0.08	0.03	0.12	0.05	0.04	0.01	0.26
10:00-10:15	0.47	0.19	0.05	0.02	0.03	0.01	0.67	16:00-16:15	0.08	0.03	0.16	0.06	0.03	0.01	0.31
10:15-10:30	0.45	0.18	0.06	0.02	0.03	0.01	0.67	16:15-16:30	0.07	0.03	0.20	0.08	0.03	0.01	0.38
10:30-10:45	0.41	0.16	0.06	0.02	0.03	0.01	0.65	16:30-16:45	0.07	0.03	0.25	0.10	0.03	0.01	0.44
10:45-11:00	0.36	0.14	0.07	0.03	0.03	0.01	0.61	16:45-17:00	0.07	0.03	0.31	0.12	0.03	0.01	0.49
11:00-11:15	0.31	0.12	0.07	0.03	0.03	0.01	0.56	17:00-17:15	0.07	0.03	0.36	0.14	0.03	0.01	0.54
11:15-11:30	0.25	0.10	0.07	0.03	0.03	0.01	0.49	17:15-17:30	0.06	0.02	0.41	0.16	0.03	0.01	0.57
11:30-11:45	0.20	0.08	0.07	0.03	0.03	0.01	0.42	17:30-17:45	0.06	0.02	0.45	0.18	0.03	0.01	0.58
11:45-12:00	0.16	0.06	0.08	0.03	0.03	0.01	0.35	17:45-18:00	0.05	0.02	0.47	0.19	0.03	0.01	0.57
12:00-12:15	0.12	0.05	0.08	0.03	0.04	0.01	0.28	18:00-18:15	0.05	0.02	0.47	0.19	0.02	0.01	0.54
12:15-12:30	0.10	0.04	0.08	0.03	0.04	0.01	0.22	18:15-18:30	0.05	0.02	0.45	0.18	0.02	0.01	0.50
12:30-12:45	0.08	0.03	0.08	0.03	0.04	0.01	0.18	18:30-18:45	0.04	0.02	0.41	0.17	0.02	0.01	0.44
12:45-13:00	0.07	0.03	0.08	0.03	0.04	0.01	0.14	18:45-19:00	0.04	0.02	0.37	0.15	0.02	0.01	0.38
13:00-13:15	0.07	0.03	0.08	0.03	0.04	0.02	0.11	19:00-19:15	0.04	0.02	0.31	0.12	0.02	0.01	0.32
13:15-13:30	0.06	0.03	0.07	0.03	0.04	0.02	0.09	19:15-19:30	0.04	0.01	0.25	0.10	0.02	0.01	0.26
13:30-13:45	0.07	0.03	0.07	0.03	0.04	0.02	0.08	19:30-19:45	0.03	0.01	0.20	0.08	0.01	0.01	0.21
13:45-14:00	0.07	0.03	0.07	0.03	0.04	0.02	0.07	19:45-20:00	0.03	0.01	0.15	0.06	0.01	0.00	0.17

In Tables III and IV, "*open*" denotes the open-window case, and "closed" denotes the closed-window case.
According to the reference limit value, the accumulated ocular unweighted UVA dose over 8 h should not exceed 10^4 J·m^{-2}.

indoors [37]; therefore, indoor solar UV radiation levels are an essential component of individual ocular UV irradiance.

Both UVB and UVA wavelengths contribute to oxidative damage [38], [39]. Regarding indoor UV irradiance, all types of window glasses are able to affect indoor exposure to natural light by blocking the majority of UVB wavelengths and some UVA wavelengths [18], [40], [41]. In particular, residential structures are predominantly fitted with highly light-transmitting glass to meet lighting requirements [17]. In the present study, we analyzed the UV irradiance in a southward-facing room in Lhasa to elucidate the differences between open- and closed-window conditions, and the results showed that the maximum relative UV irradiance at eye level with the window open was 2.56-fold higher than that with the window closed. For the horizontal ambient exposure and the ocular exposure when the manikin's back was facing to the window, there were no significant differences between the open- and closed-window conditions (Fig. 8). However, the wavelength compositions of the light under the open- and closed-window conditions were different due to the filtering effect of the window glass. In general, our findings suggested that the indoor ocular and horizontal ambient UV irradiance with the window either open or closed varies with different room orientations (Fig. 6 and Fig. 9), different distances from the window, different facial orientations with respect to the window (Fig. 5 and Fig. 7) and different cities (Fig. 9 and Fig. 10).

In this study, it is obvious that the orientation of the room (i.e., the direction in which the window faces) can affect the ocular UV irradiance exposure. First, the diurnal variations of ocular UV irradiance in rooms of different window orientations were found to be different (Fig. 9). A previous study has demonstrated that the outdoor UV irradiance measured at the eye level of a manikin shows a bimodal curve, in contrast

TABLE 4. Maximum individual ocular unweighted UVA dose references values in Sanya (unit: $10^4 J\cdot M^{-2}$).

Time	East		West		South/North		Outdoors	Time	East		West		South/North		Outdoors
	open	closed	open	closed	open	closed			open	closed	open	closed	open	closed	
07:45-08:00	0.04	0.02	0.02	0.01	0.04	0.02	0.20	12:45-13:00	0.03	0.01	0.03	0.01	0.09	0.04	0.13
08:00-08:15	0.06	0.02	0.02	0.01	0.05	0.02	0.25	13:00-13:10	0.03	0.01	0.03	0.01	0.09	0.04	0.13
08:15-08:30	0.07	0.03	0.02	0.01	0.05	0.02	0.30	13:10-13:30	0.03	0.01	0.03	0.01	0.09	0.04	0.14
08:30-08:45	0.09	0.04	0.02	0.01	0.06	0.02	0.35	13:30-13:45	0.03	0.01	0.03	0.01	0.09	0.04	0.14
08:45-09:00	0.10	0.04	0.02	0.01	0.06	0.03	0.41	13:45-14:00	0.03	0.01	0.03	0.01	0.09	0.04	0.15
09:00-09:10	0.11	0.04	0.02	0.01	0.07	0.03	0.44	14:00-14:15	0.03	0.01	0.03	0.01	0.09	0.04	0.17
09:10-09:30	0.10	0.04	0.02	0.01	0.07	0.03	0.45	14:15-14:30	0.03	0.01	0.03	0.01	0.09	0.03	0.19
09:30-09:45	0.09	0.04	0.02	0.01	0.07	0.03	0.44	14:30-14:45	0.03	0.01	0.03	0.01	0.08	0.03	0.23
09:45-10:00	0.07	0.03	0.02	0.01	0.08	0.03	0.40	14:45-15:00	0.03	0.01	0.04	0.01	0.08	0.03	0.28
10:00-10:15	0.05	0.02	0.02	0.01	0.08	0.03	0.35	15:00-15:15	0.02	0.01	0.04	0.02	0.08	0.03	0.33
10:15-10:30	0.04	0.02	0.02	0.01	0.08	0.03	0.29	15:15-15:30	0.02	0.01	0.05	0.02	0.08	0.03	0.38
10:30-10:45	0.04	0.01	0.03	0.01	0.09	0.03	0.24	15:30-15:45	0.02	0.01	0.07	0.03	0.07	0.03	0.42
10:45-11:00	0.03	0.01	0.03	0.01	0.09	0.03	0.20	15:45-16:00	0.02	0.01	0.09	0.04	0.07	0.03	0.44
11:00-11:15	0.03	0.01	0.03	0.01	0.09	0.04	0.17	16:00-16:15	0.02	0.01	0.10	0.04	0.06	0.03	0.43
11:15-11:30	0.03	0.01	0.03	0.01	0.09	0.04	0.15	16:15-16:30	0.02	0.01	0.11	0.04	0.06	0.02	0.40
11:30-11:45	0.03	0.01	0.03	0.01	0.09	0.04	0.14	16:30-16:45	0.02	0.01	0.10	0.04	0.06	0.02	0.35
11:45-12:00	0.03	0.01	0.03	0.01	0.09	0.04	0.14	16:45-17:00	0.02	0.01	0.09	0.04	0.05	0.02	0.30
12:00-12:15	0.03	0.01	0.03	0.01	0.09	0.04	0.13	17:00-17:15	0.02	0.01	0.07	0.03	0.05	0.02	0.25
12:15-12:30	0.03	0.01	0.03	0.01	0.09	0.04	0.13	17:15-17:30	0.02	0.01	0.06	0.02	0.04	0.02	0.20
12:30-12:45	0.03	0.01	0.03	0.01	0.09	0.04	0.13	17:30-17:45	0.02	0.01	0.04	0.02	0.04	0.01	0.17

According to the reference limit value, the accumulated ocular unweighted UVA dose over 8 h should not exceed 10^4 J·m^{-2}.

to the bell curve measured for UV the horizontal ambient UV irradiance, because of the orbital structure shelters the ocular surface from solar UV radiation in the SEA range of 60° to 90° [21], [22]. In particular, in cities where the maximum SEA can be greater than 40° over the course of the day, the time ranges of maximal outdoor solar exposure of the manikin's eye were found to be between 8:00 and 10:00 and between 14:00 and 16:00 rather than at the time of the maximum SEA value, which was when the highest horizontal ambient UV levels were measured [15]. In this study, we chose to specifically investigate the maximum UV irradiance conditions (at a monitoring position 0.5 m away from the window, with the manikin's face oriented towards the open window), and the results showed that the diurnal variations of the indoor ocular UV irradiance exposure in eastward- and westward-facing rooms exhibited unimodal distributions with peaks in the morning and afternoon, respectively. The time ranges of maximal ocular solar UV exposure in the eastward- and westward-facing rooms corresponded to the time ranges of maximal outdoor ocular UV exposure. In addition, the irradiance corresponding to the maximum ocular UV exposure in the westward-facing room was lower than that in the eastward-facing room, possibly due to the lower level of outdoor horizontal ambient UV irradiance in the afternoon. The diurnal variations in the indoor ocular UV irradiance exposure in the southward- and northward-facing rooms exhibited bell-curve behavior over time (similar to the curve for the outdoor horizontal ambient UV exposure, as shown in Fig. 9). The maximal ocular UV irradiance was measured at the same time as the maximum SEA. Notably, in the summer season (corresponding to our monitoring conditions), when the sun is shining directly into a southward-facing room, the SEA range is relatively high. Meanwhile, the upwards angle of visibility is relatively low due to the shelter against the sunlight provided by the ocular frame structure for higher SEAs and the fixed field of view based on natural human ergonomics [42]. Therefore, in this study, although the sun itself was visible at some time points, the manikin's eye was mainly exposed to diffuse radiation in the southward-facing room under the monitoring conditions. Consequently, the results mainly reflect the influence of outdoor ambient diffuse radiation, without solar UV radiation directly impinging onto the manikin's eye through the open window.

It is insufficient to compare the differences between open- and closed-window conditions based only on the

TABLE 5. **Total and segmental UVBE doses (H_{EFF}) for four time ranges and dose ratios for four room orientations (at a monitoring positions 0.5 m away from the window, with the detector oriented towards the open window).**

City	Time	Room orientation								Outdoors				Room orientation							
		East		West		South		North		Eye		Ambient		East		West		South		North	
		H_{eff} (J•m^{-2})	All-day dose ratio	H_{eff} (J•m^{-2})	All-day dose ratio	H_{eff} (J•m^{-2})	All-day dose ratio	H_{eff} (J•m^{-2})	All-day dose ratio	H_{eff} (J•m^{-2})	All-day dose ratio	H_{eff} (J•m^{-2})	All-day dose ratio	Ratio of outdoor eye	Ratio of outdoor ambient	Ratio of outdoor eye	Ratio of outdoor ambient	Ratio of outdoor eye	Ratio of outdoor ambient	Ratio of outdoor eye	Ratio of outdoor ambient
Lhasa	08:00-11:00	31.06	0.46*	3.32	0.06	3.33	0.15	2.72	0.11	47.03	0.32*	46.92	0.12	0.66†	0.66#	0.07	0.07	0.07	0.07	0.06	0.06
	11:00-14:00	21.68	0.32	7.33	0.13	7.74	0.35	7.59	0.32	40.56	0.28	164.4	0.42*	0.53	0.13	0.18	0.04	0.19	0.05	0.19	0.05
	14:00-17:00	9.89	0.15	17.34	0.32	8.00	0.36*	11.17	0.46*	27.47	0.19	143.9	0.37	0.36	0.07	0.63	0.12	0.29	0.06	0.41	0.08
	17:00-20:00	4.58	0.07	26.93	0.49*	3.01	0.14	2.62	0.11	31.47	0.21	31.95	0.08	0.15	0.14	0.86	0.84	0.10	0.09	0.08	0.08
	08:00-20:00	67.21	1	54.91	1	22.08	1	24.09	1	146.5	1	387.1	1	0.46†	0.17#	0.37	0.14	0.15	0.06	0.16	0.06
Sanya	07:45-10:15	8.10	0.38*	2.28	0.13	5.74	0.16	3.66	0.19	33.05	0.32*	52.22	0.17	0.25	0.16#	0.07	0.04	0.17	0.11	0.11	0.07
	10:15-12:45	6.89	0.32	2.82	0.16	12.41	0.35*	6.86	0.35*	20.33	0.20	112.2	0.37*	0.34	0.06	0.14	0.03	0.61†	0.11	0.34	0.06
	12:45-15:15	4.89	0.23	3.25	0.18	11.98	0.34	6.37	0.33	22.25	0.22	105.7	0.34	0.22	0.05	0.15	0.03	0.54	0.11	0.29	0.06
	15:15-17:45	1.41	0.07	9.20	0.52*	5.03	0.14	2.58	0.13	26.74	0.26	36.62	0.12	0.05	0.04	0.34	0.25	0.19	0.14	0.10	0.07
	07:45-17:45	21.29	1	17.56	1	35.15	1	19.48	1	102.4	1	306.7	1	0.21	0.07	0.17	0.06	0.34†	0.11#	0.19	0.06

"*All-day dose ratio*" indicates the ocular exposure ratio between the **segmental accumulated UVBE** dose in the time range and the **total accumulated UVBE** dose over an entire day in the same room. * indicates the highest segmental accumulated dose over an entire day for each room orientation.

"*Ratio of outdoor eye*" indicates the exposure ratio of the accumulated dose at the **manikin eye indoors** to the accumulated dose at the **manikin eye outdoors** over the same SEA ranges. † indicates the highest "*Ratios of outdoor eye*" in Lhasa and Sanya, including the maximum total exposure dose ratios and the maximum segmental accumulated dose ratios for the four room orientations.

"*Ratio of outdoor ambient*" indicates the exposure ratio of the accumulated dose at the **manikin eye indoors** to the accumulated dose at the **horizontal ambient outdoors** over the same SEA ranges. # indicates the highest "*Ratios of outdoor ambient*" in Lhasa and Sanya, including the maximum total accumulated UVBE dose ratios and the maximum segmental accumulated dose ratios for the four room orientations.

UV irradiance. Therefore, this study also investigated indoor ocular UV doses calculated in two different ways. The UVBE dose (in the spectral region of 300 nm to 400 nm) was used to further assess the possible risk under open-window conditions, while the unweighted UVA dose was used to assess the exposure level under closed-window conditions in certain time ranges [31]. The guidelines published by ICNIRP indicate that the unweighted UVA dose to an unprotected eye over 8 h should not exceed 10^4 J·m^{-2}, whereas the corresponding UVBE dose should not exceed 30 J·m^{-2} [31]. As shown in Fig. 6a and Table 1, from 08:00 to 11:00 (SEA range of 12°-37°) in the eastward-facing room in Lhasa with the window closed, the accumulated ocular unweighted UVA dose exceeded the safe threshold for the case of a continuous exposure while gazing out the window. Note, however, that the unweighted UVA doses under real conditions will be lower than the values measured in this study. Furthermore, the maximum closed-window hourly accumulated ocular unweighted UVA dose was observed in the eastward-facing room in Lhasa between 9:00 and 10:00 (SEA range of 24°-37°). As shown in Fig. 6b and Table 4, from 08:00 to 11:00 (SEA range of 12°-37°) in the eastward-facing room in Lhasa with the window open, the accumulated UVBE dose to the manikin's eye also exceeded the safe threshold, as in the closed-window case. It is significant that the ocular UV exposed from 18:00 to 20:00 (SEA range of 34°-9°) in the westward-facing room. In Sanya, from 11:00 to 14:00 (SEA range of 67°-88°), a relatively high accumulated ocular UVBE dose was detected in the southward-facing room, with a high hourly UVBE dose over time, which is consistent with the conclusion of a previous study on indoor illumination [43].

Due to the relatively symmetrical whole-day exposure trend for the case of a southward-facing room, we analyzed the influence of various factors on the UV exposure in the southward-facing room in Lhasa. In this study, the detectors were positioned to capture the differences in UV irradiance between horizontal ambient conditions and the conditions at the manikin's eye. In a previous study, the horizontal ambient UV irradiance was greater than that measured at a manikin's eye outdoors [21]. In contrast, we found that the eye of the indoor manikin was exposed to a higher level solar

TABLE 6. Maximum individual ocular UVBE dose references values in Lhasa (unit: J·M^{-2}).

Time	Orientation of rooms			Outdoors	Time	Orientation of rooms			Outdoors
	East	West	South and North	Eye level		East	West	South and North	Eye level
08:00-08:15	1.20	0.11	0.14	1.31	14:00-14:15	1.01	1.04	1.04	1.23
08:15-08:30	1.35	0.16	0.14	1.42	14:15-14:30	0.98	1.07	1.06	1.32
08:30-08:45	1.58	0.21	0.14	1.63	14:30-14:45	0.95	1.12	1.06	1.45
08:45-09:00	1.85	0.26	0.14	1.95	14:45-15:00	0.93	1.19	1.05	1.67
09:00-09:15	2.17	0.31	0.15	2.41	15:00-15:15	0.90	1.29	1.02	2.01
09:15-09:30	2.55	0.36	0.16	3.08	15:15-15:30	0.87	1.43	0.97	2.51
09:30-09:45	2.91	0.40	0.17	3.87	15:30-15:45	0.84	1.62	0.92	3.16
09:45-10:00	3.24	0.45	0.18	4.75	15:45-16:00	0.81	1.88	0.85	3.97
10:00-10:15	3.48	0.50	0.20	5.65	16:00-16:15	0.77	2.20	0.78	4.90
10:15-10:30	3.62	0.54	0.22	6.44	16:15-16:30	0.74	2.54	0.71	5.79
10:30-10:45	3.62	0.58	0.25	7.01	16:30-16:45	0.70	2.89	0.64	6.55
10:45-11:00	3.48	0.62	0.28	7.23	16:45-17:00	0.66	3.23	0.56	7.07
11:00-11:15	3.23	0.66	0.32	7.07	17:00-17:15	0.62	3.48	0.49	7.23
11:15-11:30	2.89	0.70	0.37	6.55	17:15-17:30	0.58	3.62	0.43	7.01
11:30-11:45	2.54	0.74	0.43	5.79	17:30-17:45	0.54	3.62	0.38	6.44
11:45-12:00	2.20	0.77	0.49	4.90	17:45-18:00	0.50	3.48	0.33	5.65
12:00-12:15	1.88	0.81	0.56	3.97	18:00-18:15	0.45	3.24	0.29	4.75
12:15-12:30	1.62	0.84	0.63	3.16	18:15-18:30	0.40	2.91	0.25	3.87
12:30-12:45	1.43	0.87	0.70	2.51	18:30-18:45	0.36	2.55	0.22	3.08
12:45-13:00	1.29	0.90	0.78	2.01	18:45-19:00	0.31	2.17	0.20	2.41
13:00-13:15	1.19	0.93	0.85	1.67	19:00-19:15	0.26	1.85	0.18	1.95
13:15-13:30	1.12	0.95	0.91	1.45	19:15-19:30	0.21	1.58	0.17	1.63
13:30-13:45	1.07	0.98	0.97	1.32	19:30-19:45	0.16	1.35	0.16	1.42
13:45-14:00	1.04	1.01	1.01	1.26	19:45-20:00	0.11	1.20	0.15	1.31

According to the reference limit value, the accumulated ocular UVBE dose over 8 h should not exceed 10^4 J·m^{-2}.

TABLE 7. Maximum individual ocular UVBE dose references values in Sanya (unit: J·M^{-2}).

Time	Orientation of rooms			Outdoors	Time	Orientation of rooms			Outdoors
	East	West	South and North	Eye level		East	West	South and North	Eye level
07:45-08:00	0.61	0.01	0.15	1.76	12:45-13:00	0.58	0.63	1.34	1.69
08:00-08:15	0.92	0.03	0.26	1.89	13:00-13:10	0.56	0.65	1.32	1.70
08:15-08:30	1.31	0.06	0.36	2.17	13:10-13:30	0.53	0.66	1.29	1.73
08:30-08:45	1.14	0.09	0.45	2.63	13:30-13:45	0.50	0.68	1.25	1.79
08:45-09:00	0.77	0.13	0.55	3.30	13:45-14:00	0.47	0.69	1.21	1.92
09:00-09:10	0.68	0.16	0.64	4.00	14:00-14:15	0.44	0.70	1.16	2.16
09:10-09:30	0.68	0.20	0.73	4.57	14:15-14:30	0.40	0.71	1.10	2.50
09:30-09:45	0.69	0.23	0.82	4.74	14:30-14:45	0.37	0.71	1.04	2.95
09:45-10:00	0.70	0.27	0.89	4.46	14:45-15:00	0.34	0.71	0.97	3.40
10:00-10:15	0.71	0.30	0.97	3.82	15:00-15:15	0.30	0.71	0.89	3.76
10:15-10:30	0.71	0.34	1.04	3.11	15:15-15:30	0.27	0.70	0.81	3.90
10:30-10:45	0.71	0.37	1.10	2.49	15:30-15:45	0.23	0.69	0.73	3.77
10:45-11:00	0.71	0.40	1.21	1.85	15:45-16:00	0.20	0.68	0.64	3.42
11:00-11:15	0.70	0.44	1.25	1.74	16:00-16:15	0.16	0.68	0.55	2.97
11:15-11:30	0.69	0.47	1.29	1.70	16:15-16:30	0.13	0.77	0.45	2.51
11:30-11:45	0.68	0.50	1.32	1.69	16:30-16:45	0.09	1.14	0.35	2.16
11:45-12:00	0.66	0.53	1.34	1.69	16:45-17:00	0.06	1.31	0.26	1.93
12:00-12:15	0.65	0.56	1.35	1.69	17:00-17:15	0.03	0.92	0.15	1.79
12:15-12:30	0.63	0.58	1.35	1.69	17:15-17:30	0.02	0.61	0.06	1.73
12:30-12:45	0.60	0.60	1.35	1.69	17:30-17:45	0.01	0.58	0.12	0.77

According to the reference limit value, the accumulated ocular UVBE dose over 8 h should not exceed 10^4 J·m^{-2}.

UV irradiance than the horizontal ambient level for different room orientations (Fig. 6) and under different exposure conditions (Fig. 5e and 7e). These observations can be attributed to differences in the sunlight direction: indoors, sunlight is incident only through the window (with the manikin's eye also oriented towards the window), while outdoors, sunlight is incident from all sides. Previous results reported by Lim H and Kim G showed that the distance from the window was the most significant factor affecting indoor environmental UV levels [20]. To further explore the role of the distance away from the window in determining the ocular UV exposure of the manikin, this study investigated the basic solar UV exposure ratios at distances of 0.5 m, 1.0 m and 1.5 m away from the window. We also assessed the relative average UV irradiance with the manikin facing towards the window and with its back to the window.

The SEA ranges and sunlight exposure durations vary in different cities. Sanya is the lowest-latitude city in mainland China, whereas Lhasa is the highest-elevation city in mainland China; consequently, both cities have higher levels of outdoor UV light compare with others. Moreover, Sanya and Lhasa are both known to be high-risk areas for cataracts based on epidemiological research [25], [26]. UV radiation reaches its highest values at times corresponding to the highest SEA throughout the day, and summer is characterized by higher levels of UV radiation compared with other seasons [15]. Simultaneously, during this season, the higher apparent temperatures in Sanya, which was caused by the combined effects of air temperature, relative humidity and wind speed, and the oxygen-poor atmosphere and the long days in Lhasa warrant the opening of windows. Therefore, for this study, the summer season in these two cities was chosen to investigate the highest possible levels of indoor ocular exposure to solar UV irradiance. Due to the different elevations and latitudes of the two cities, large differences in UV irradiance were observed in the data collected by the detector mounted in the eye socket of the indoor manikin. The monitoring results showed that compared with the conditions in Sanya, the higher elevation and thinner air in Lhasa resulted in stronger outdoor UV irradiance. In addition, the lower maximum SEA and longer sunlight hours in Lhasa contribute to higher ocular exposure to UV irradiance and, specifically, to higher accumulated ocular unweighted UVA doses and UVBE doses in eastward- and westward-facing rooms. In contrast, compared to Lhasa, the rate of variation in the SEA is higher in Sanya due to the lower latitude, resulting in more time spent in higher SEA ranges; as a result, the maximum indoor ocular solar UV irradiance exposure was observed in the eastward- and westward-facing rooms in Sanya, while higher accumulated ocular unweighted UVA doses and UVBE doses were observed in the southward-facing room.

Recent studies have found that even low-level solar UV radiation may exceed the threshold for damage to fair skin and suggest that advising 'no protection' can be appropriate in places only where the accumulated daily UV dose is less than the damage threshold [44]. Strikingly, unlike skin exposure to UV irradiance, there is no benefit of accumulated ocular exposure to UV irradiance. Moreover, eyelids and pupils typically open more widely indoors due to the weaker light, compared with outdoor conditions [45]. It is very important to recognize that exposure to solar UV irradiance is continuous and it does not completely stop after a person leaves the outdoor environment. Therefore, to demonstrate the contribution of indoor UV irradiance exposure to eye disease, we have compiled reference values for the maximum unweighted UVA dose and UVBE dose to the eye indoors based on the collected monitoring data by means of Gaussian fitting (shown in Tables 3, 4, 6 and 7). These data can be used to further assess an individual's level of continuous ocular exposure to UV irradiance in combination with outdoor exposure.

Nevertheless, this study still has some limitations. First, the SEA variations in different seasons may affect the diurnal variations of ocular UV exposure in rooms with different orientations. Second, to satisfy the room orientation requirements, the rooms chosen for data collection in this study could not have identical window environments. Unlike the rooms with other orientations in Lhasa, the southward-facing room had an out-swinging casement window, which may result in the lower UV irradiance observed in this room compared with the northward-facing room. Similarly, the presence of handrails and eaves outside the windows of the eastward-, westward- and northward-facing rooms in Sanya may have affected the results and resulted in measurements smaller than the actual values. Third, typical human activities involve highly complicated phenomena, including blinking, shaking or turning the head, and looking down at one's desk, all of which may cause the actual UV irradiance reaching an individual's eyes to be lower than the measured level. Finally, outdoor obstacles such as buildings on the horizon outside our monitoring sites may have affected the measured UV irradiance data, and the influence of other indoor environmental factors, such as the reflectivity of walls and floors was also not considered. However, the results show that how the solar UV irradiance and dose values vary with the SEA can serve as a valuable reference. In this study, a basic indoor model was built for estimating the UV irradiance reaching the eyes. This model can allow a person to roughly estimate his or her level of ocular UV exposure based on his or her position and facial orientation by referring to the corresponding maximum exposure dose reported in the present study. These results could be used for the assessment of continuous ocular UV exposure in combination with the UV level outdoors and thus can contribute to strengthening the understanding of human ocular health.

In summary, on a sunny summer day, if a person gazes out of an open window at a distance of 0.5 m from the window, some danger to the eyes may exist in the SEA range of 12° to 37° in an eastward-facing room and in the SEA range of 34° to 9° in a westward-facing room under the maximum open window UV exposure conditions in Lhasa. Similarly, the accumulated UV exposure in a southward-facing room in Sanya was in the SEA range of 67° to 88° warrants attention. Unweighted UVA dose and UVBE dose values reported to serve as a reference for both indoor and outdoor conditions could be used for the assessment of continuous ocular UV exposure in combination with the UV level outdoors. It is of important practical significance to provide both a theoretical and data-driven quantitative basis for measures for the prevention of cataracts associated with solar UV exposure.

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