IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 11, 2020, accepted February 2, 2020, date of publication February 5, 2020, date of current version February 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2971734

The Relationship Between $PM_{2.5}$ and the Action Spectrum of Ultraviolet Radiation for Vitamin D Production Based on a Manikin Model

NAN WANG[1], RENTONG CHEN[1], YAN LIU[2], JIAMING YU[3], TIANYAO YANG[1], HUI HUA[1], DAN YANG[1], FANGFANG MA[1], XIN LI[1], MENGLIN LI[1], LITING HUANG[1], ZHENZHEN ZOU[1], YAN DENG[1], AND YANG LIU[1]

[1]Department of Environmental Health, School of Public Health, China Medical University, Shenyang 110122, China
[2]Department of Biomedical Engineering, School of Fundamental Sciences, China Medical University, Shenyang 110122, China
[3]Department of Ophthalmology, The Fourth Affiliated Hospital of China Medical University, Shenyang 110033, China

Corresponding author: Yang Liu (yangliu@cmu.edu.cn)

This work was supported by the Natural Science Foundation of LiaoNing Province under Grant 20180550904.

ABSTRACT Objectives: Fine particulate matter ($PM_{2.5}$) is the principal air pollutant and poses a serious threat to public health. This study explored the effects of $PM_{2.5}$ on the action spectrum of ultraviolet radiation for vitamin D production (UV_{vitD}) received by manikin surfaces. Methods: Multi-inclination angle ultraviolet radiation monitoring was conducted with different concentrations of $PM_{2.5}$. Combining monitoring data with the $PM_{2.5}$ concentration, solar elevation angle (SEA), and inclination angle, a UV_{vitD} exposure model for human body multi-inclined surfaces was constructed through a multiple linear regression analysis. A 3D manikin model was used to examine the $PM_{2.5}$ effects on UV_{vitD} received by the manikin surface. Results: When $PM_{2.5}$ concentrations ranged from 35 μg/m^3 to 100 μg/m^3 (average concentration of $PM_{2.5}$ in this range: 62 μg/m^3), the UV_{vitD} received by the whole body was reduced by approximately 8.45% to 19.82% compared with the UV_{vitD} received when $PM_{2.5}$ concentrations ranged from 6 μg/m^3 to 35 μg/m^3 (average concentration of $PM_{2.5}$ in this range: 17 μg/m^3) with SEAs between 30° and 50°. Moreover, the UV_{vitD} dose was reduced by 11.82% in the above comparisons. When further comparing $PM_{2.5}$ concentrations from 100 μg/m^3 to 161 μg/m^3 (average concentration of $PM_{2.5}$ in this range: 132 μg/m^3) with those from 6 μg/m^3 to 35 μg/m^3 (average concentration of $PM_{2.5}$ in this range: 17 μg/m^3), the UV_{vitD} received by the whole body was reduced by approximately 21.6% to 50.64% at SEAs between 30° and 50°. The UV_{vitD} dose was reduced by 30.2%. Conclusions: The occurrence of $PM_{2.5}$ obviously reduced the UV_{vitD} received by the manikin surface.

INDEX TERMS $PM_{2.5}$, ultraviolet radiation, manikin model, inclination angle, Vitamin D.

I. INTRODUCTION

Vitamin D insufficiency or deficiency is observed in humans globally [1], [2], and it has been estimated that nearly 1 billion individuals have vitamin D insufficiency or deficiency [3], [4]. Children, pregnant women, and the elderly are vulnerable groups because they need more vitamin D than other healthy adults [5]–[10]. Vitamin D deficiency makes these high-risk individuals more prone to various diseases, such as rickets, pregnancy complications, and osteoporosis [11]–[13]. Moreover, vitamin D deficiency is also related to increased morbidity and mortality from cardiovascular diseases [14], diabetes [15], [16], and some cancers, such as breast cancer, colorectal cancer, and pancreatic cancer [17]–[20]. It is well documented that 90% of vitamin D required by the human body is synthesized by ultraviolet radiation [21], [22]. However, some studies have indicated that air pollution could reduce the ultraviolet radiation intensity [23], which results in a negative effect on vitamin D synthesis [24], [25].

Air pollution, as one of the most important environmental risk factors, seriously affects human health. In 2012, more than 3.7 million people died prematurely from air pollution [26]. Multiple studies indicate that both long- and

The associate editor coordinating the review of this manuscript and approving it for publication was Yue Zhang.

short-term exposure to particulate matter (PM) is associated with the increased morbidity and mortality of chronic diseases, such as respiratory and cardiovascular diseases [27]–[30]. Fine particulate matter ($PM_{2.5}$) is considered the most dangerous among all PM [31] and can penetrate deep into human lungs and even into the blood because of its small size [32], [33]. A 10 μg/m^3 increase in exposure to $PM_{2.5}$ is associated with an 11% increase in cardiovascular mortality [34]. Exposure to $PM_{2.5}$ is also associated with an increased risk of hypertension [35]. Therefore, air pollution not only directly harms human health but also reduces vitamin D synthesis by decreasing ultraviolet radiation intensity. This harmful double impact of air pollution deserves significant attention.

Latitude and season influence the production of vitamin D3 in human skin, and vitamin D3 is converted from 7-dehydrocholesterol in the skin after UV radiation and thermal processing, which further affects the vitamin D status in the human body [36]–[38]. 25(OH)D (the main storage form of vitamin D in the human body) levels decrease with increasing latitude [39]. The National Diet and Nutrition Survey even indicated that in areas higher than 40° N latitude, the synthesis of vitamin D in the skin from October to March was reduced due to insufficient UV radiation [40]. In addition to the effects of latitude and season on vitamin D, air pollution is found to indirectly inhibit vitamin D synthesis by directly reducing ultraviolet radiation. Therefore, air pollution has a significant impact on public health, especially for high-risk groups living in middle and high latitudes who are prone to vitamin D deficiency.

The associations between the action spectrum of ultraviolet radiation for vitamin D production (UV_{vitD}) and $PM_{2.5}$, the solar elevation angle (SEA), and the inclination angle were examined using a homemade multiangle UV monitoring model and multiple linear regression analysis. Moreover, a 3D manikin model was also used to assess the impact of $PM_{2.5}$ on the UV_{vitD} received by the manikin surface. This work presents the most comprehensive study of the relationship between $PM_{2.5}$ and UV_{vitD} to date, and it aims to draw more attention to the risks of $PM_{2.5}$, especially among groups vulnerable to vitamin D deficiency.

II. MATERIALS AND METHODS

A. EXPERIMENTAL INSTRUMENTS AND EQUIPMENT CALIBRATION

A homemade multiangle UV monitoring model was used for data collection in this study. A computer-controlled dual-channel miniature fiber optic spectrometer was used to measure the UV intensities. Each spectrometer had two detectors that were placed on a tripod at a height of approximately 1 m. The tripod head could rotate vertically. A shelf was fixed on the tripod head, and the detectors were placed in front of the shelf. We also used these experimental instruments in a previous study [41].

A fiber optic spectrometer (AvaSpec-2048x14-2-USB2, Netherlands) with high-UV sensitivity and high-quantum efficiency was used to measure UV irradiance. The spectrometer design includes a 2048 pixel back-thinned CCD detector array and is based on the AvaBench-75 symmetrical Czerny-Turner. The signal-to-noise ratio is 500 dB, and the stray light is less than 0.1%. A USB2 interface with ultrafast data sampling of 450 spectra per second and a data transfer speed of 2.24 ms was used. The detector accepts light from a 180° solid angle, and it has a cosine corrector (CC-UV/VIS) with an effective area of 3.9 mm. For absolute irradiance measurements, the spectrometer was radiometrically calibrated over a range from 200 nm to 400 nm. Calibration was performed by the National Physical Laboratory (NPL) before the experiment.

B. MONITORING LOCATIONS AND METEOROLOGICAL CONDITIONS

The monitoring locations were five similar roofs of four- to five-story buildings located in five cities in China. The background was pavement, and the reflectivity was 0.08 and 0.05 for the UVA and UVB bands, respectively. The monitoring days were from May 14, 2015, to July 1, 2018, during which the maximum SEA was 82.43°. The measurement time was from 7:00 to 18:00 China Standard Time (CST) each day. Seventeen days were chosen as the best monitoring dates and are shown in Table 1.

C. MONITORING METHOD

Detector measurements were obtained at inclination angles from 0° to 180° in intervals of 10° in the direction facing the sun (Fig. 1). We detected the UV irradiation intensity 19 times in 1.5 minutes. The measurement interval was 1 h. This study used an inclination angle of 0° to 90° facing the sun and 90° to 180° facing away from the sun. The UV_{vitD} at each inclination angle was calculated by the following equation:

$$UV_{vitD} = \sum\nolimits_{UV} S(\lambda)A(\lambda)d(\lambda)$$

where S (λ) is the measured spectral irradiance, A (λ) is the vitamin D effective action spectrum (300 nm to 330 nm), and d (λ) is the wavelength increment of the spectral data (1 nm in this study).

D. STATISTICAL ANALYSIS

The Air Quality Index (AQI) is a dimensionless index that quantitatively describes air quality in China. The larger the AQI value is, the more serious the air pollution and the greater the health hazard to the human body. The AQI also specifies the IAQI (individual air quality index) for individual pollutants. The main pollutants involved in air quality assessment include $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3. The AQI is the maximum value of all IAQIs. When the AQI is above 50, the pollutant with the largest IAQI value is the primary pollutant.

The air pollution data from the monitoring days were collected from the China Air Quality Online Monitoring and

TABLE 1. Main monitoring days and locations.

Location (Nearest Monitoring Point)	Province	Latitude (°N)	Longitude (°E)	Altitude (m)	Total Ozone Column (DU)	Main Monitoring Day
Sanya (Hexi Sub Station)	Hainan	18.4	109.8	7.0	288.1	14 May 2015
Shaoxing (Chengdong Development Committee)	Zhejiang	30.0	120.6	12.0	279.5	16 October 2015
Shaoxing (Chengdong Development Committee)	Zhejiang	30.0	120.6	12.0	255.7	26 October 2015
Lhasa (Barkhor Street)	Xizang	29.7	91.1	3660.0	272.6	16 May 2016
Lhasa (Barkhor Street)	Xizang	29.7	91.1	3660.0	274.6	17 May 2016
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	287.1	14 July 2016
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	287.1	25 October 2016
Fuxin (Dongyuan)	Liaoning	42.0	121.7	146.0	308.5	17 November 2016
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	294.0	31 October 2017
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	298.6	01 November 2017
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	350.6	03 November 2017
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	Missing Value	05 November 2017
Shenyang (Jingshen Street)	Liaoning	42.0	123.5	51.0	Missing Value	22 March 2018
Sanya (Hexi Sub Station)	Hainan	18.4	109.8	7.0	292.8	03 May 2018
Sanya (Hexi Sub Station)	Hainan	18.4	109.8	7.0	Missing Value	04 May 2018
Fuxin (Dongyuan)	Liaoning	42.0	121.7	146.0	351.4	29 June 2018
Fuxin (Dongyuan)	Liaoning	42.0	121.7	146.0	333.4	01 July 2018

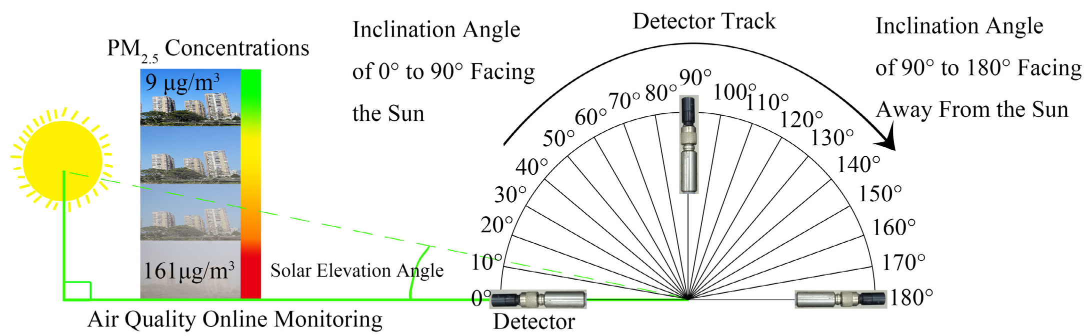

FIGURE 1. Multi-inclination angle ultraviolet radiation monitoring with different concentrations of $PM_{2.5}$. $PM_{2.5}$ is fine particulate matter.

Analysis Platform (https://www.aqistudy.cn/). Six pollutants were included and averaged within 1 h in this study: PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3. According to the Chinese air quality classification standard, this study defines $PM_{2.5} \leq 35\ \mu g/m^3$ as clean and $PM_{2.5} > 35\ \mu g/m^3$ as pollution. Lhasa is located at high altitude where the air quality is always good; therefore, the data from Lhasa were considered as a separate group. The UV measurement data were divided into six groups by $PM_{2.5}$: a) SEA $\leq 30°$ and monitoring location in Lhasa; b) SEA $\leq 30°$ and $PM_{2.5} \leq 35\ \mu g/m^3$; c) SEA $\leq 30°$ and $PM_{2.5} > 35\ \mu g/m^3$; d) $30° <$ SEA $\leq 50°$ and monitoring location in Lhasa; e) $30° <$ SEA $\leq 50°$ and $PM_{2.5} \leq 35\ \mu g/m^3$; and f) $30° <$ SEA $\leq 50°$ and $PM_{2.5} > 35\ \mu g/m^3$. Groups a) and d) were the high-latitude control groups, groups b) and e) were the clean atmosphere control groups, and groups c) and f) were the polluted atmosphere exposure groups. The monitoring data of each group were described using means and SDs. Bivariate correlation

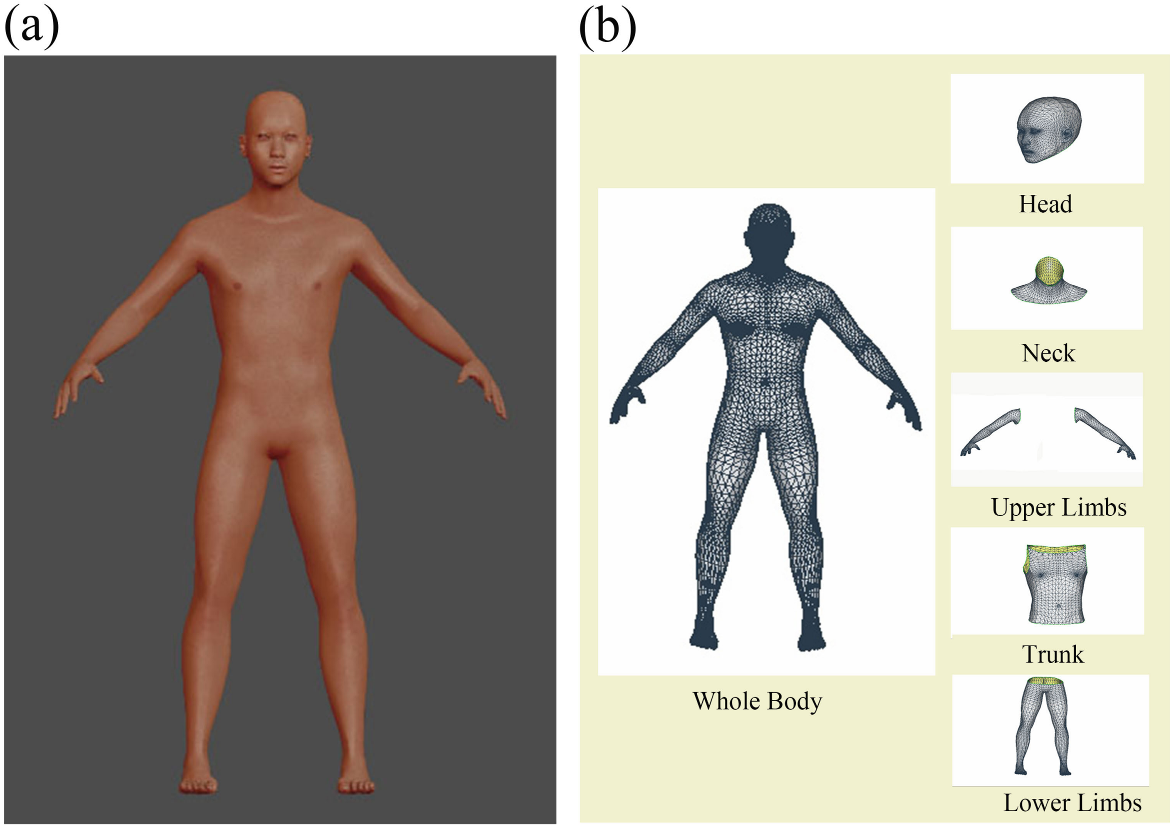

FIGURE 2. **3D manikin model. (a) MakeHuman Software; (b) MeshLab software.**

analysis was conducted to explore the relationships between AQI and the other pollutants. All statistical analyses were performed using IBM SPSS statistical software [version 22]. P values < 0.05 were considered statistically significant for all analyses.

E. CONSTRUCTION OF UV_{vitD} EXPOSURE MODEL OF MULTI-INCLINED SURFACES OF THE HUMAN BODY

The UV monitoring data ($n = 2880$) from 2015 to 2018 and the corresponding ambient air pollutant data were included in the analysis, among which 1360 data points were obtained facing the sun and 1520 were obtained facing away from the sun. The SEAs on the chosen monitoring days varied from 20.41° to 82.43°, and the concentrations of $PM_{2.5}$ on the chosen monitoring days varied from 6 $\mu g/m^3$ to 161 $\mu g/m^3$. We used the same method to construct a UV_{vitD} exposure model of multi-inclined surfaces of the human body in all study locations except Lhasa, including conditions facing toward the sun (model I) and facing away from the sun (model II). We used UV_{vitD} and its corresponding SEA, $PM_{2.5}$, and the inclination angle as set data. Then, data in all the groups were sorted by $PM_{2.5}$ from small to large. These values were selected from the first set of data, and group data were selected at two set data intervals. Finally, the selected 1/3 of the data was used to verify the rationality of the model, and the remaining 2/3 of the data was used for modeling. To reflect the relationship between the incident radiation and the inclination surface, we used the cosine between the SEA and the inclination angle. We used UV_{vitD} as the dependent variable, and SEA, $PM_{2.5}$, and the cosine between the SEA and the inclination angle ($\cos\alpha$) as independent variables for performing the multiple linear regression analysis. Finally, we performed variance analysis on simulated and measured values and judged the rationality of the model according to the p values. All statistical analyses were performed using IBM SPSS statistical software [version 22]. P values < 0.05 were considered statistically significant for all analyses.

F. CALCULATION OF THE AREAS AND INCLINATION ANGLES OF ALL INCLINED SURFACES ON THE 3D MANIKIN MODEL

A 3D virtual manikin of Asian descent and medium build with a standing posture and neutral gender at 173.31 cm tall was selected with MakeHuman Software [version 1.0.2]. The eye, hair, teeth, eyebrows, eyelashes, and tongue structures were excluded because this study focused only on the manikin surface (Fig. 2a). The manikin was divided into five parts by MeshLab software [version 1.3.3] according to human anatomy, including the head, neck, upper limbs (including the arms, axillae, and shoulders), trunk (including the chest

TABLE 2. Surface area of various parts of the manikin model.

	Area (m^2)	Area Percent (%)
Head Front	0.06	3.78
Head Back	0.05	3.09
Neck Front	0.04	2.33
Neck Back	0.04	2.12
Trunk Front	0.18	10.73
Trunk Back	0.17	9.87
Upper Limbs Front	0.18	10.54
Upper Limbs Back	0.18	10.79
Lower Limbs Front	0.48	27.98
Lower Limbs Back	0.32	18.76
Whole Body	1.70	100.00

and abdomen), and lower limbs (including the buttocks, legs, and feet) (https://en.wikipedia.org/wiki/Human_body), with redundant structures inside the manikin deleted. Every part of the manikin was further divided into front and back sections. Then, the manikin was adjusted to appear composed of multiple triangular meshes with an inclined angle to the horizontal plane (Fig. 2b). Then, the three-dimensional coordinates of the vertices of each triangle mesh were used as output. Finally, the area and inclination angle of each triangle mesh was calculated according to the three-dimensional coordinates of the vertex of the manikin (Table 2).

G. CALCULATION OF UV_{vitD} INTENSITY AND UV_{vitD} DOSE RECEIVED BY THE MANIKIN SURFACE

In this study, the maximum SEA in the monitoring locations during periods of pollution was 50.1°. The $PM_{2.5}$ concentrations during the monitoring period were categorized into three groups: 6 $\mu g/m^3$ to 35 $\mu g/m^3$, 35 $\mu g/m^3$ to 100 $\mu g/m^3$, and 100 $\mu g/m^3$ to 161 $\mu g/m^3$. The mean values of the above concentration ranges were 17 $\mu g/m^3$, 62 $\mu g/m^3$, and 132 $\mu g/m^3$, respectively. This study simulated the UV_{vitD} intensity received by the manikin surface under three different SEAs and $PM_{2.5}$ concentrations: the SEAs were 30°, 40°, and 50°, and the $PM_{2.5}$ values were 17 $\mu g/m^3$, 62 $\mu g/m^3$, and 132 $\mu g/m^3$. The areas and inclination angles in Method F were combined with the UV_{vitD} exposure model of multi-inclined surfaces of the human body in Method E to calculate the UV_{vitD} received by the whole manikin and each part of the manikin. The formula was as follows:

$$E = \sum_{i=1}^{n} Ei \times Si$$

where E is the UV_{vitD} received by the manikin (W), i is the number of triangle meshes included in the manikin, Ei is the UV_{vitD} intensity per unit area received by the i-th triangle mesh (W/m^2), and Si is the area of the i-th triangle mesh (m^2).

According to the National Oceanic and Atmospheric Administration (http://www.srrb.noaa.gov/highlights/sunrise/azel.html), the duration from 30° to 50° SEAs at 30° N, 40° N, and 50° N latitude in January to April and September to December was calculated. Then, the UV_{vitD} dose received by the manikin surface was calculated using the following equation:

$$D = E \times T$$

where D is the UV_{vitD} dose received by the manikin surface (J), E is the UV_{vitD} intensity received by the manikin surface (W), and T is the duration from 30° to 50° SEAs (s).

III. RESULTS

A. AIR POLLUTANT EXPOSURE

The values of $PM_{2.5}$ in the polluted atmosphere group were greater than those in the clean atmosphere group (Table 3). The average ambient $PM_{2.5}$ levels for the clean and polluted atmosphere were 16.18 ± 8.69 and 90.44 ± 38.13, respectively, when the SEAs were below 30°. The $PM_{2.5}$ value in the polluted atmosphere group was 5.59-fold that the clean atmosphere group. When the SEAs were between 30° and 50°, these values were 14.57 ± 8.29 and 73.94 ± 34.28, respectively. The $PM_{2.5}$ value in the polluted atmosphere group was 5.07-fold higher than that of the clean atmosphere group.

The correlations between the AQI and other pollutants are shown in Table 4. The correlation coefficient between the $PM_{2.5}$ level and AQI was the highest. The China Air Quality Online Monitoring and Analysis Platform also showed that $PM_{2.5}$ was the main pollutant. Therefore, this study focused on the effect of $PM_{2.5}$ on UV radiation intensity.

B. AMBIENT UV RADIATION INTENSITY OF CLEAN AND POLLUTED GROUPS

Cumulative UV_{vitD} values from 0° to 90° inclination angles were higher in Lhasa than in other groups due to the higher altitude. When grouping based on $PM_{2.5}$, the UV_{vitD} values of the clean atmosphere group were higher than those in the polluted atmosphere group and the values facing the sun were higher than those facing away from the sun (Fig. 3). When the SEAs were below 30°, the UV_{vitD} intensity in the polluted atmosphere group was reduced by 30.28% and 27.94% relative to the clean group in the direction of facing the sun and facing away from the sun, respectively. When the SEAs were between 30° and 50°, the UV_{vitD} intensity in the polluted atmosphere group was reduced by 31.75% and 32.3% relative to the clean group in the direction of facing the sun and facing away from the sun, respectively.

C. UV_{vitD} INTENSITY LEVELS OF CLEAN AND POLLUTED GROUPS RECEIVED UNDER DIFFERENT INCLINATION ANGLES

The changes in UV_{vitD} intensity with inclination angle at different SEAs are shown in Fig. 4. At all inclination angles,

TABLE 3. Means and standard deviations of the air pollutant variables used to analyze air pollution exposure by $PM_{2.5}$ (Mean ± SD).

Pollutants	Lhasa	$PM_{2.5} \leq 35$ μg/m³*	$PM_{2.5} > 35$ μg/m³*
SEA ≤ 30°			
N	100	220	250
AQI	46.20 ± 4.77	36.41 ± 12.98	121.60 ± 48.28
$PM_{2.5}$ (μg/m³)	18.70 ± 2.25	16.18 ± 8.69	90.44 ± 38.13
PM_{10} (μg/m³)	35.80 ± 15.79	33.77 ± 18.64	136.16 ± 52.86
SO_2 (μg/m³)	7.60 ± 1.21	9.68 ± 11.10	77.52 ± 60.56
NO_2 (μg/m³)	13.70 ± 4.56	20.45 ± 15.82	51.44 ± 16.56
CO (mg/m³)	0.46 ± 0.07	0.55 ± 0.34	1.31 ± 0.51
O_3 (μg/m³)	144.90 ± 14.48	56.32 ± 34.40	48.56 ± 48.15
30°<SEA≤50°			
N	200	460	650
AQI	46.80 ± 5.71	33.98 ± 12.06	104.46 ± 42.65
$PM_{2.5}$ (μg/m³)	18.65 ± 5.30	14.57 ± 8.29	73.94 ± 34.28
PM_{10} (μg/m³)	36.75 ± 14.72	30.15 ± 15.15	116.52 ± 51.62
SO_2 (μg/m³)	7.40 ± 1.02	7.59 ± 13.30	48.15 ± 28.18
NO_2 (μg/m³)	13.95 ± 4.26	13.52 ± 8.87	52.26 ± 20.68
CO (mg/m³)	0.52 ± 0.17	0.45 ± 0.15	1.17 ± 0.44
O_3 (μg/m³)	141.40 ± 15.00	63.70 ± 36.94	63.91 ± 33.85

Notes: *All locations except Lhasa. The average SEAs for groups a-f were 26.28, 26.67, 25.68, 41.13, 38.82, and 37.7 by $PM_{2.5}$. SEA is the solar elevation angle. AQI is the air quality index.

TABLE 4. Correlations between different pollutants and the AQI.

	AQI	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	SO_2 (μg/m³)	NO_2 (μg/m³)	CO (mg/m³)	O_3 (μg/m³)
AQI	1	0.965**	0.958**	0.799**	0.878**	0.824**	-0.241**
$PM_{2.5}$ (μg/m³)	0.965**	1	0.932**	0.815**	0.884**	0.829**	-0.348**
PM_{10} (μg/m³)	0.958**	0.932**	1	0.794**	0.892**	0.826**	-0.295**
SO_2 (μg/m³)	0.799**	0.815**	0.794**	1	0.778**	0.652**	-0.292**
NO_2 (μg/m³)	0.878**	0.884**	0.892**	0.778**	1	0.854**	-0.347**
CO (mg/m³)	0.824**	0.829**	0.826**	0.652**	0.854**	1	-0.455**
O_3 (μg/m³)	-0.241**	-0.348**	-0.295**	-0.292**	-0.347**	-0.455**	1

Note: **$p < 0.01$, correlation is significant at the 0.01 level (2-tailed). AQI is the air quality index.

UV_{vitD} intensity was much higher in the clean atmosphere group than in the polluted atmosphere group. When SEAs were below 50° and facing the sun, the UV_{vitD} intensity was parabolic with the change in the inclination angle (Fig. 4a). The maximum reduction occurred when the inclination angle was 40° to 70°, and the maximum reduction was 66% due to the 74 μg/m^3 increase in the concentration of $PM_{2.5}$. When SEAs were below 50° and facing away from the sun, UV_{vitD} intensity increased with an increasing inclination angle (Fig. 4b). The maximum reduction occurred when the inclination angle was 60° to 90°, and the maximum reduction was 70% due to the 50.25 μg/m^3 increase in the concentration of $PM_{2.5}$.

D. UV_{vitD} EXPOSURE MODEL WITH MULTI-INCLINED SURFACES ON THE HUMAN BODY

In the multiple linear regression analysis results, the adjusted R^2 values of model I (facing the sun) and model II (facing away from the sun) were 0.828 and 0.776, respectively, and collinearity was not observed between variables. The p values of the variance analysis of the two models between the simulated and measured values were 0.727 and 0.858, respectively, and a significant difference was not observed. The UV_{vitD} intensity increased with increasing SEAs and cosα, and the UV_{vitD} intensity decreased with increasing $PM_{2.5}$ values. When facing the sun, SEA had the strongest effect on UV_{vitD} intensity, followed by cosα and $PM_{2.5}$. When facing

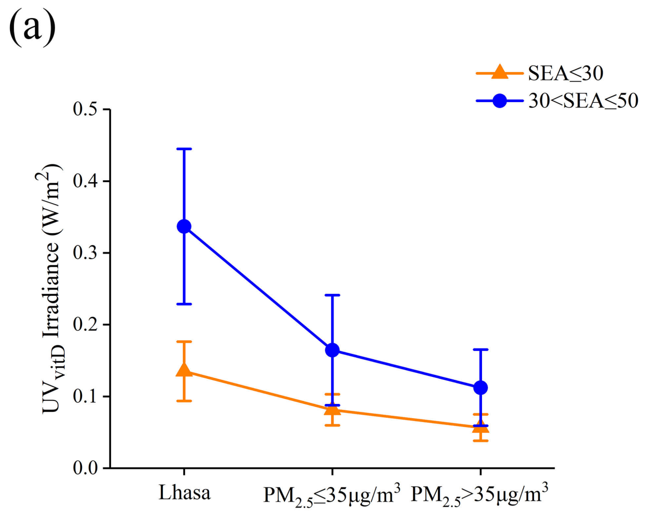

FIGURE 3. Changes in the intensity of UV_{vitD} in the different groups grouped by $PM_{2.5}$. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. The data for each group are shown as the mean and standard deviation. Lhasa is located at high altitude where the air quality is generally good; therefore, the data from the Lhasa area form a separate group. The UV_{vitD} data for $PM_{2.5} \leq 35$ $\mu g/m^3$, $PM_{2.5} > 35$ $\mu g/m^3$ excluded the data from Lhasa. (a) Ultraviolet radiation monitoring data in the direction facing the sun; (b) ultraviolet radiation monitoring data in the direction facing away from the sun.

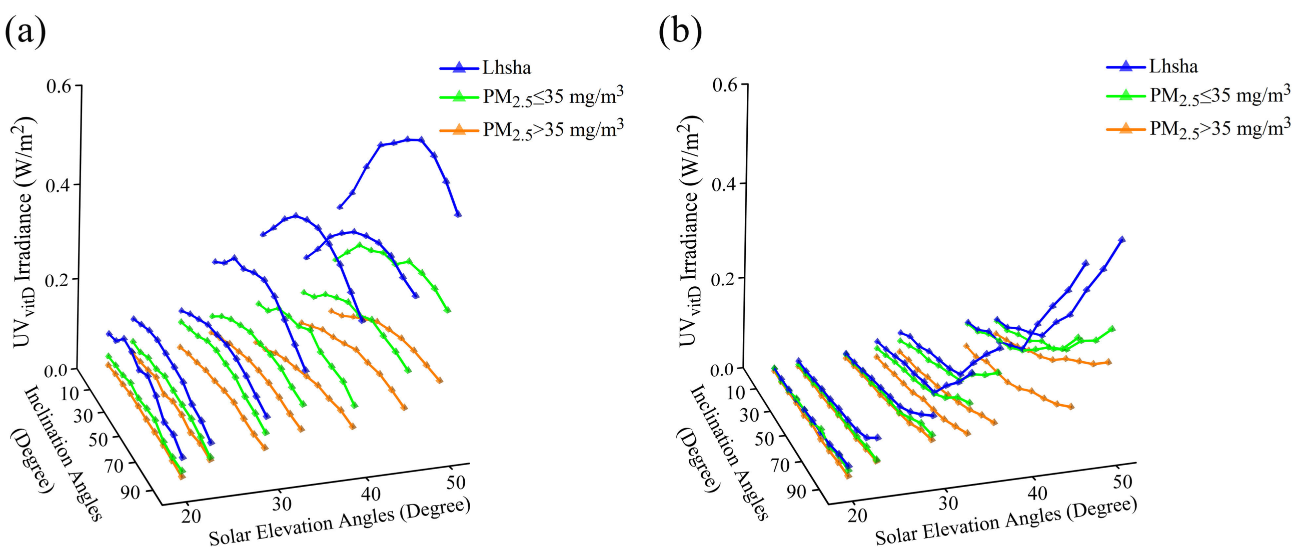

FIGURE 4. Changes in the UV_{vitD} intensity with inclination angle at different SEAs in Lhasa, $PM_{2.5} \leq 35$ $\mu g/m^3$, and $PM_{2.5} > 35$ $\mu g/m^3$ groups. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. Lhasa is located at high altitudes where the air quality is generally good; therefore, the data from the Lhasa area are a separate group. The UV_{vitD} data for $PM_{2.5} \leq 35$ $\mu g/m^3$, $PM_{2.5} > 35$ $\mu g/m^3$ excluded the data of Lhasa. (a) Ultraviolet radiation monitoring data in the direction facing the sun; (b) ultraviolet radiation monitoring data in the direction facing away from the sun.

away from the sun, cosα had the strongest effect on UV_{vitD} intensity, followed by SEA and $PM_{2.5}$. Compared with values obtained facing away from the sun, the SEA and $PM_{2.5}$ had a stronger effect on UV_{vitD} intensity when facing the sun while cosα was the opposite (Table 5).

E. UV_{vitD} INTENSITY RECEIVED BY THE MANIKIN SURFACE UNDER DIFFERENT CONCENTRATIONS OF $PM_{2.5}$

The UV_{vitD} intensity levels received by different parts of the manikin surface differed (Fig. 5) and were ordered from whole body > lower limbs > upper limbs > trunk > head > neck. The UV_{vitD} intensity increased with increasing SEAs and decreased with increasing $PM_{2.5}$ concentrations (Fig. 6). When $PM_{2.5}$ was 62 $\mu g/m^3$, the UV_{vitD} intensity received by the head, neck, trunk, upper limbs, lower limbs, and whole body were reduced by 0.0023 W, 0.0015 W, 0.0068 W, 0.0069 W, 0.0155 W, and 0.033 W, respectively, compared with $PM_{2.5}$, which was 17 $\mu g/m^3$ at SEAs between 30° and 50°. The UV_{vitD} intensity received by whole body was reduced by 8.45% to 19.82%. When $PM_{2.5}$ was 132 $\mu g/m^3$,

TABLE 5. Results of the multiple linear regression analysis.

	B	Beta	Sig.	VIF
Facing the sun				
Constant	-21.534		0	
SEA	0.635	0.841	0	1.161
cosα	16.882	0.232	0	1.003
$PM_{2.5}$	-0.052	-0.172	0	1.159
Model I	UV_{vitD} = -21.534 + 0.635 * SEA + 16.882 * cosα - 0.052 *$PM_{2.5}$			
Facing away from the sun				
Constant	-1.031		0	
SEA	0.345	0.484	0	1.358
cosα	11.272	0.511	0	1.252
$PM_{2.5}$	-0.033	-0.110	0	1.103
Model II	UV_{vitD} = -1.031 + 0.345 * SEA + 11.272 * cosα - 0.033 *$PM_{2.5}$			

Notes: B is a nonstandardized coefficient. Beta is the standard coefficient. Sig. is significance (p value); Sig. < 0.05 means that the variables are statistically significant. VIF is the variance inflation factor; VIF between 1 and 10 means there is no multicollinearity. SEA is the solar elevation angle. cosα is the angle formed between the SEA and the inclination angle. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production.

the UV_{vitD} intensity received by the head, neck, trunk, upper limbs, lower limbs, and whole body were reduced by 0.0058 W, 0.0037 W, 0.0173 W, 0.0177 W, 0.0397 W, and 0.0842 W, respectively, compared with $PM_{2.5}$, which was 17 $\mu g/m^3$ at SEAs between 30° and 50°. The UV_{vitD} intensity received by whole body was reduced by 21.6% to 50.64%.

F. EFFECT OF $PM_{2.5}$ ON THE SEA OF EXPOSURE, UV_{vitD} DOSE RECEIVED BY THE MANIKIN SURFACE, AND EXPOSURE TIME

When the $PM_{2.5}$ values were 62 $\mu g/m^3$ and 132 $\mu g/m^3$ and the SEA was between 30° and 50°, the SEA needed to increase by 3.88° and 9.93°, respectively, to achieve a UV_{vitD} intensity at the manikin surface that was equal to the $PM_{2.5}$ value (17 $\mu g/m^3$) (Fig. 7).

At higher latitudes, the days that the SEA can reach 30° to 50° and the human body can receive UV_{vitD} doses in the range of 30° to 50° SEA are reduced. The total dose of UV_{vitD} that the manikin received throughout the year also decreased with increasing latitudes (Fig. 8). At 30° N latitude, the SEA could reach 30° every day of the year (Fig. 8a). At 40° N latitude, the maximum SEA was less than 30° in the two periods of January 1 to January 20 and November 22 to December 31 (Fig. 8b). At 50° N latitude, the maximum SEA was less than 30° in the two periods of January 1 to February 22 and October 20 to December 31 (Fig. 8c). When SEAs were from 30° to 50° and $PM_{2.5}$ increased from 17 $\mu g/m^3$ to 62 $\mu g/m^3$ and 132 $\mu g/m^3$, the monthly UV_{vitD} dose received by the manikin surface could be reduced by at least 11466.72 J and 29303.84 J and the minimum daily reduction was 382.22 J and 976.79 J at 30° N latitude, respectively; the minimum monthly reduction was 2212.67 J and 5654.6 J and the minimum daily reduction was 71.38 J and 182.41 J at 40° N latitude, respectively; and the minimum monthly reduction was 1180.48 J and 3016.79 J and the minimum daily reduction was 42.16 J and 107.74 J at 50° N latitude, respectively. When the $PM_{2.5}$ value increased from 17 $\mu g/m^3$ to 62 $\mu g/m^3$and 132 $\mu g/m^3$, the UV_{vitD} dose was reduced by 11.82% and 30.2%, respectively. The UV_{vitD} dose increased with increasing latitudes as shown in Fig. 8. This increase was due to our study evaluating only the duration during which the SEA was in the range of 30° to 50°. In fact, the lower the latitude, the longer the duration of high SEAs on the same day and the greater the dose of UV_{vitD} received.

To achieve an equivalent UV_{vitD} dose received by the manikin, greater $PM_{2.5}$ concentrations required more exposure time (Fig. 9).When the SEAs were 30° to 50°, for the manikin to receive the same UV_{vitD} dose at 30° N latitude, the $PM_{2.5}$ had to increase from 17 $\mu g/m^3$ to 62 $\mu g/m^3$ and 132 $\mu g/m^3$, and the exposure time had to increase by at least 19.95 h and 41.81 h per month and 0.43 h and 1.39 h per day, respectively (Fig. 9a); at 40° N latitude, the exposure time had to increase by at least 2.5 h and 8.07 h per month and 0.08 h and 0.26 h per day, respectively (Fig. 9b); and at 50° N latitude, the exposure time had to increase by at least 1.33 h and 4.3 h per month and 0.05 h and 0.15 h per day, respectively (Fig. 9c). To receive the same UV_{vitD} dose, when $PM_{2.5}$ value increased from 17 $\mu g/m^3$ to 62 $\mu g/m^3$ and 132 $\mu g/m^3$, the exposure time needed to increase by 11.82% and 30.2%, respectively.

IV. DISCUSSION

To the best of our knowledge, this is the first analysis of the associations between $PM_{2.5}$ and the UV_{vitD} intensity received by manikin surfaces based on a homemade multiangle UV monitoring model and 3D manikin model. These results showed that the UV_{vitD} intensity received by the manikin surface decreased with increasing $PM_{2.5}$ concentrations. When

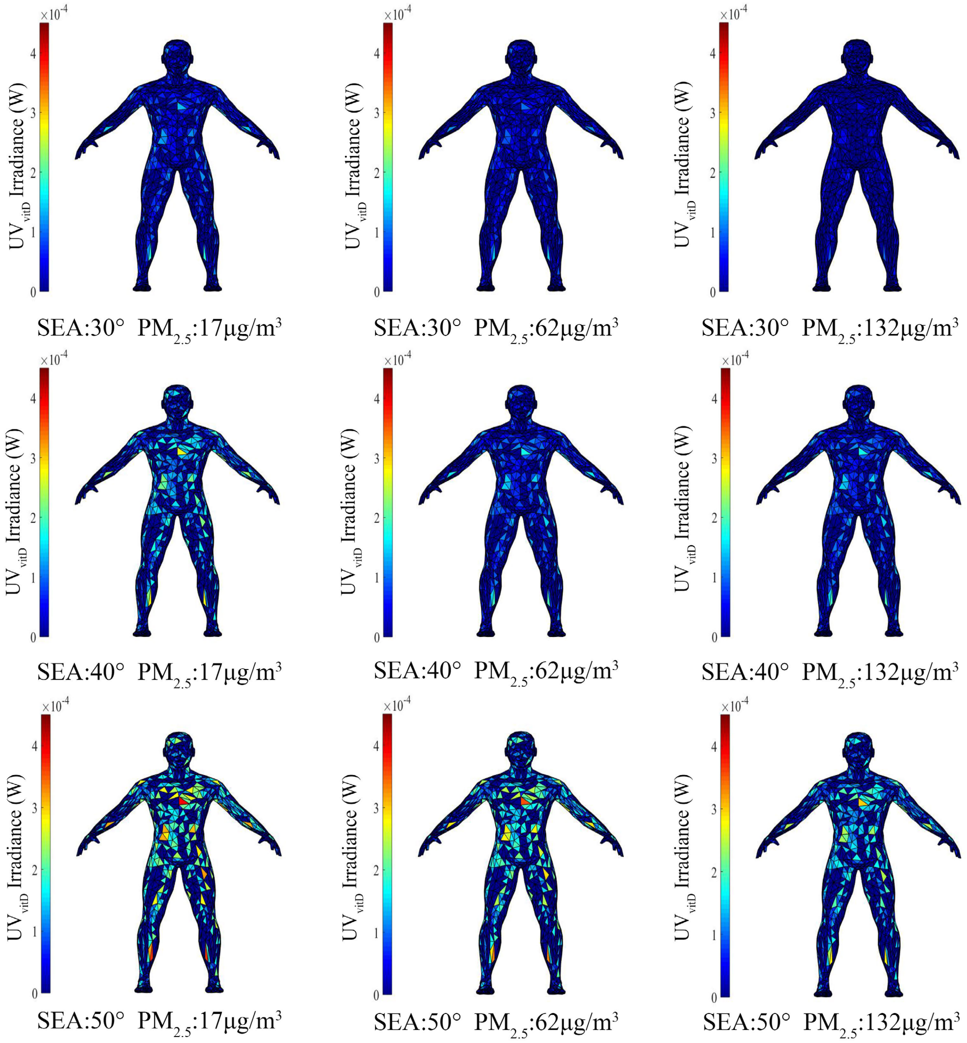

FIGURE 5. **UV_{vitD} intensity received by different triangle meshes of the manikin at different SEAs and $PM_{2.5}$ concentrations. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. SEA is the solar elevation angle.**

the $PM_{2.5}$ concentration was 62 μg/m^3, the UV_{vitD} intensity received by the whole body was reduced by between 8.45% and 19.82% compared with that when the $PM_{2.5}$ concentration was 17 μg/m^3 at SEAs between 30° and 50°. Moreover, UV_{vitD} dose showed a reduction of 11.82% in the above comparisons. When the $PM_{2.5}$ concentration was 132 μg/m^3, the UV_{vitD} intensity received by the whole body was reduced from 21.6% to 50.64% compared with a $PM_{2.5}$concentration of 17 μg/m^{3}at SEAs between 30° and 50°. Moreover, the UV_{vitD} dose showed a reduction of 30.2%.

Previous studies have explored whether air pollution could reduce the intensity of ambient UV radiation to some extent [42], [43]. Furthermore, the exposure to UV radiation at various inclination angles represents an important basis for the assessment of the UV radiation intensity received by human skin. Baczynska et al. and Oppenrieder et al.demonstrated that the intensity of UV radiation at different inclination angles is different [44], [45], which was consistent with our study.

Previous studies used multiple linear regression analysis to study the relationship between UV radiation and various influencing factors. H. Lee *et al.* used multiple linear regression analysis to study UV radiation with clouds, aerosols and ozone and described the surface solar irradiance in Seoul [46]. H.K. Cho *et al.* studied the effects of cloud, temperature and specific humidity on longwave irradiance by using multiple linear regression methods using measurements at the Antarctic Peninsula [47]. Our monitoring background in included monitoring the ultraviolet radiation intensity received by different inclines under sunny weather with different SEA and $PM_{2.5}$ conditions. The SEA was a major factor influencing the intensity of ambient UV_{vitD} radiation. The inclination angle was only effective when the SEA was present. To reflect the relationship between the incident radiation and the surface

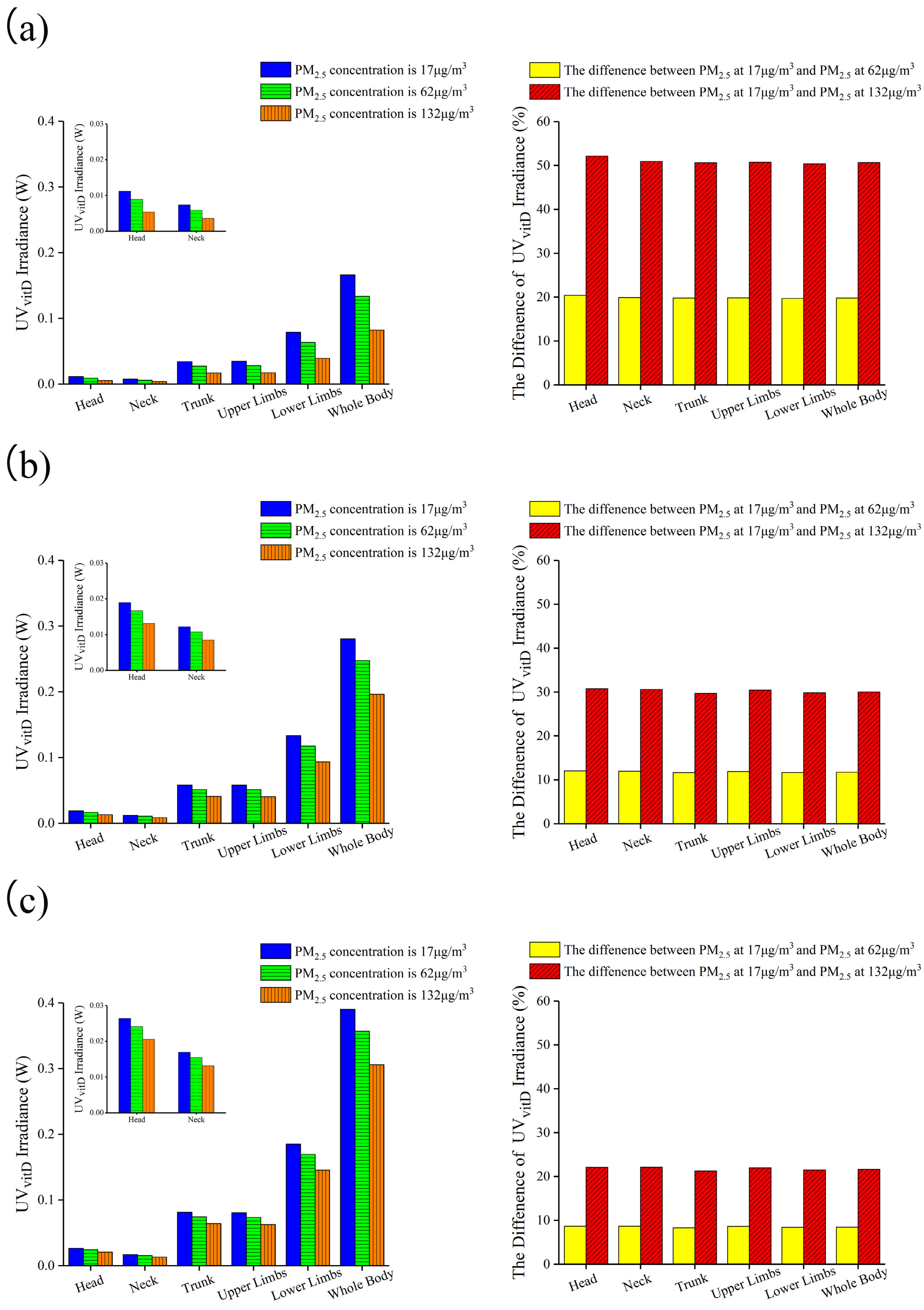

FIGURE 6. Change in UV_{vitD} intensity received by various parts of the manikin with different $PM_{2.5}$ concentrations at different SEAs and the difference in UV_{vitD} intensity under different $PM_{2.5}$ concentrations. (a) The SEA was 30°; (b) the SEA was 40°; (c) the SEA was 50°. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. SEA is the solar elevation angle. The difference in UV_{vitD} irradiance is expressed as a percent, which was calculated by dividing the difference value by the UV_{vitD} intensity when the $PM_{2.5}$ concentration was 17 $\mu g/m^3$.

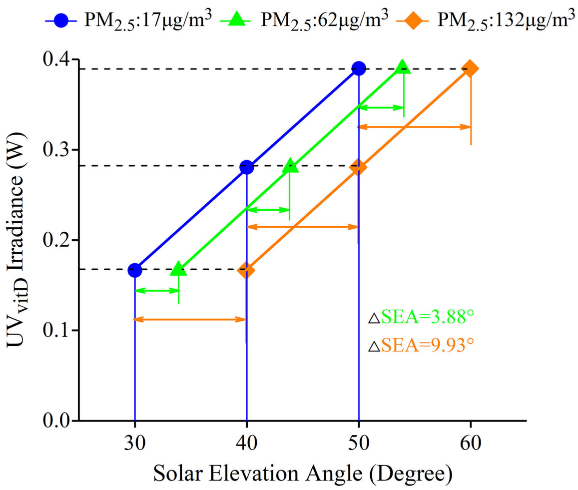

FIGURE 7. Changes in the UV_{vitD} intensity received by the manikin surface with various SEAs under different $PM_{2.5}$ concentrations. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. SEA is the solar elevation angle.

inclination, we used the cosine between the angle of incidence and the surface of the body. Therefore, this study included the SEA, the cosine of the angle formed between the SEA and the inclination angle ($\cos\alpha$), and $PM_{2.5}$ as independent variables. To evaluate the change of UV_{vitD} intensity under the combined effects of SEA, inclination and $PM_{2.5}$ factors, a multiple linear regression analysis was performed. Compared with facing away from the sun, direct light was received when facing the sun; therefore, the UV intensity received by the inclined surface was greatly affected by the SEA. While facing away from the sun, the inclined surface received diffuse scattered light, which might explain why the weight of $\cos\alpha$ was greater than that of the SEA. Although the coefficient of $PM_{2.5}$ in the regression model formula was smaller, its standard coefficient Beta value was not small, which indicated that $PM_{2.5}$ has a certain effect on the UV_{vitD} intensity.

Finally, Schrempf et al. used the 3D geometry of the human body to evaluate the association between melanoma prevalence and altitude [48]. C. Backes *et al.* used a well-defined 3-dimensional head morphology and 4 hat styles to explore the sun protection effect of hats under different exposure conditions by predicting UVR exposure doses on different facial anatomies [49]. D. Vernez *et al.* developed a model simulating human exposure to solar UV to assess outdoor occupational and recreational UV exposures [50]. In this study, we used a manikin with standing posture as the standard state. This posture is consistent with the anatomical position in medicine and represents a common posture when people are outdoors. The exposure state of the manikin model we set was facing the sun and undressed, and all parts could be exposed to the sun. Although external influencing factors were excluded, the human body will also be affected by its own shadow effect (e.g., shadow of the face on the neck). The purpose of this study was to explore the effect of $PM_{2.5}$ on UV_{vitD} received by the manikin model when all parts of the manikin model

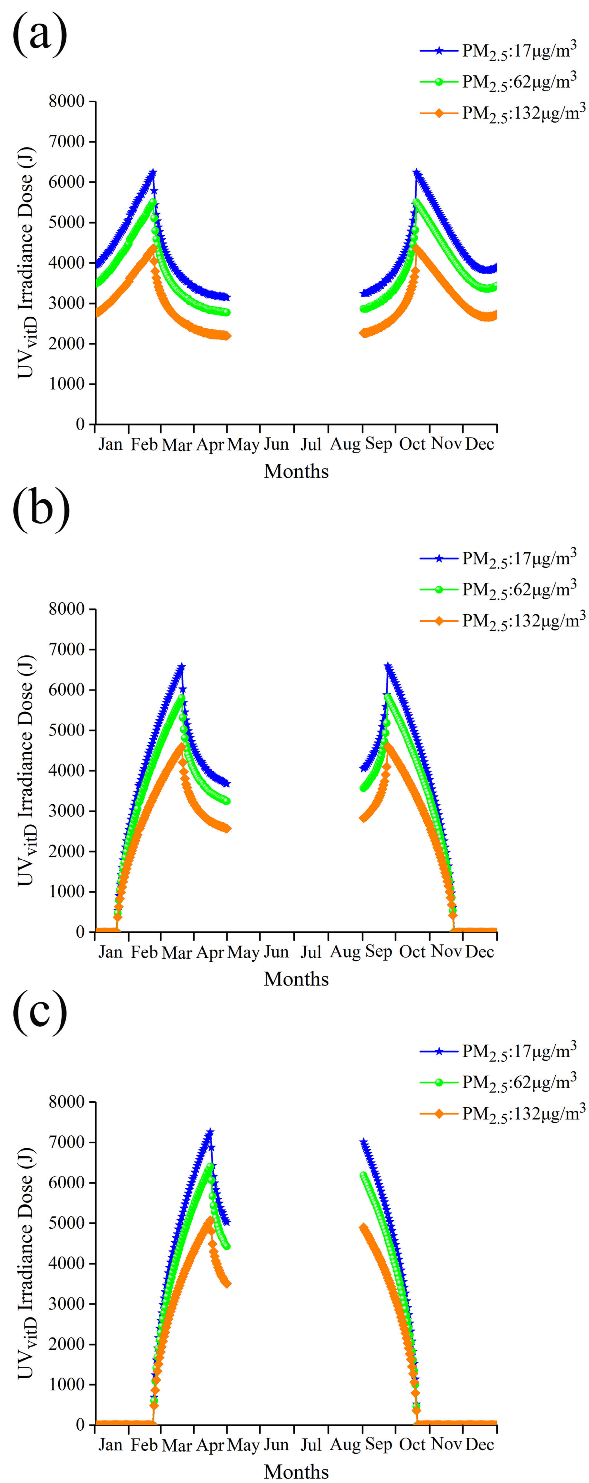

FIGURE 8. Changes in the UV_{vitD} dose received by the manikin surface by month at different latitudes under different $PM_{2.5}$ concentrations. (a) Latitude was 30° north; (b) latitude was 40° north; (c) latitude was 50° north. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. SEA is the solar elevation angle.

could receive sunlight. We first used a 3D human model to evaluate the relationship between $PM_{2.5}$ and UV_{vitD} received on the surface of the human model.

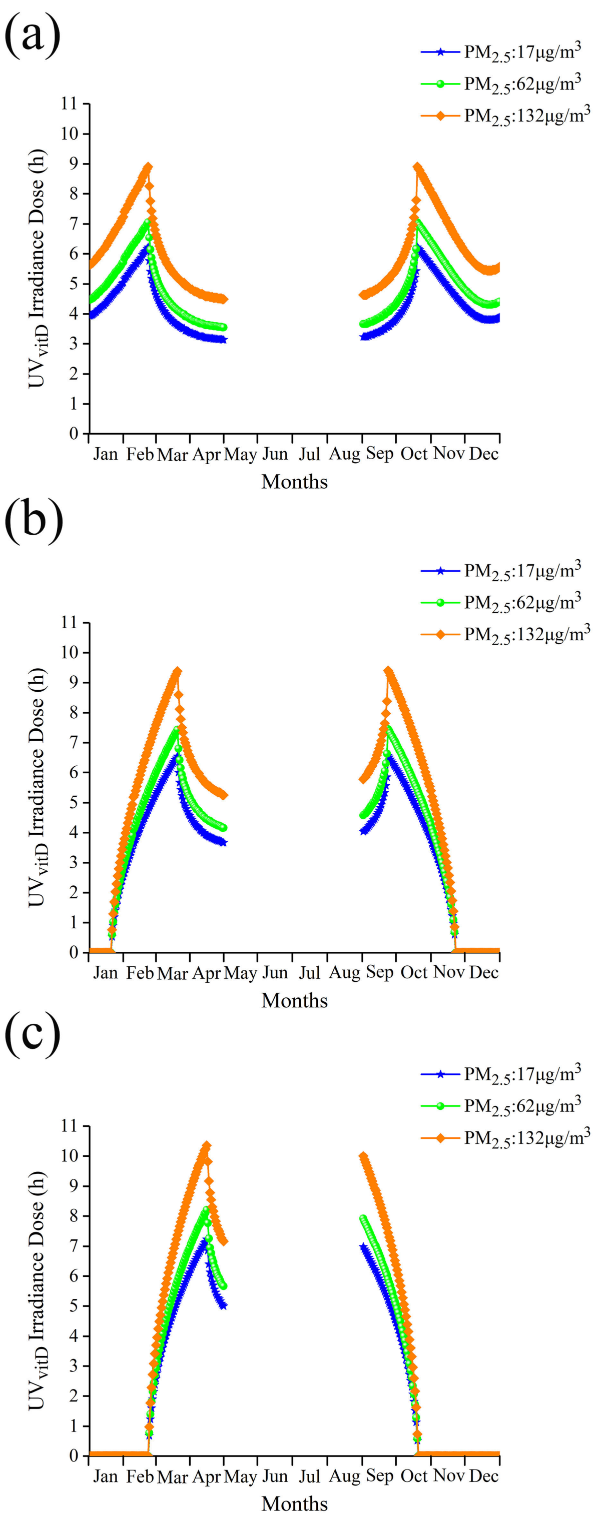

FIGURE 9. Changes in the exposure time required by the manikin surface by month at different latitudes under different $PM_{2.5}$ concentrations. (a) Latitude was 30° north; (b) latitude was 40° north; (c) latitude was 50° north. $PM_{2.5}$ is fine particulate matter. UV_{vitD} is the action spectrum of ultraviolet radiation for vitamin D production. SEA is the solar elevation angle. T = D/E; D was UV_{vitD} dose, E was UV_{vitD} intensity, D indicates that the concentration of $PM_{2.5}$ was 17 $\mu g/m^3$.

This study was conducted under the condition that other exposure conditions of the manikin model were the same and only $PM_{2.5}$ was varied. The purpose was only to explore the effect of $PM_{2.5}$ on the UV_{vitD} intensity received by the manikin. In fact, the intensity of UV radiation received by the human body can also be affected by many factors, such as weather, exposure time outdoor, and protective clothing [51]–[56]. These factors could also cause vitamin D deficiency in the body. However, our study suggested that $PM_{2.5}$ could not only cause respiratory system and cardiovascular system diseases of the human but might also lead to vitamin D deficiency by reducing the UV_{vitD} intensity received by the human body.

In this study, the effect of $PM_{2.5}$ on the UV_{vitD} intensity received by the manikin surface was explored on the basis of multi-inclination angle ultraviolet radiation monitoring under different $PM_{2.5}$ concentrations. As one of the primary pollutants causing air pollution, $PM_{2.5}$ is highly correlated with the AQI, and it also greatly affects the degree of vitamin D3 synthesis in human skin. Thus, this study mainly explored the associations between $PM_{2.5}$ and the UV_{vitD} intensity received by the manikin surface. Moreover, the UV radiation intensity received by the human body was reflected by the UV radiation intensity at different inclination angles. This homemade multiangle ultraviolet radiation monitoring model was also applied in our previous study [41]. After monitoring the ultraviolet radiation intensity received under different inclination angles under different concentrations of $PM_{2.5}$, multiple linear regression modeling was performed to better reflect the relationship between UV_{vitD} and the SEA, $PM_{2.5}$, and inclination angle. Finally, the UV_{vitD} received by the manikin surface was calculated through the above multiple linear regression formula combined with the surface area and inclination angles of each inclined surface of the manikin.

The phenomenon of $PM_{2.5}$ reducing the UV_{vitD} intensity received by the manikin surface can be attributed to the following reasons. Some studies have shown that $PM_{2.5}$ can absorb ultraviolet light in the atmosphere. Lan et al. analyzed the light absorption coefficient of the main chemical compositions of $PM_{2.5}$ and found that the effect of the black carbon mixing state could not be ignored, and this absorption of light accounts for 37.7% of the total PM [57]. J. Mok et al. found that brown carbon absorbs a significant amount of light in the ultraviolet band [58]. In addition, Zhang et al. indicated that the absorption of light by $PM_{2.5}$ water extract increased significantly from the visible range to the ultraviolet range [59]. Moreover, other studies have shown that $PM_{2.5}$ could scatter ultraviolet light. When the ultraviolet light reaches the surface of PM, the direction of propagation is changed and the light is scattered in all directions to further reduce the quality and quantity of ultraviolet radiation reaching the surface of the Earth [42], [60], [61]. Although the UV radiation reaching the surface of the Earth is mainly composed of UVA (≥95%) [62], UVB is more susceptible to interference by $PM_{2.5}$ due to its shorter wavelength. Moreover, UVB corresponds to the main wavelength that promotes the synthesis of vitamin D in human skin [63]. Therefore, $PM_{2.5}$ might indirectly reduce the UV_{vitD} by absorbing and scattering ultraviolet radiation.

It is well known that children, pregnant women, and elderly people are considered high-risk groups for vitamin D deficiency. These groups usually require more vitamin D than other healthy adults. For example, due to a crucial period of bone growth and development, the daily vitamin D need for children is 800 IU/d in winter [64], whereas the recommended vitamin D intake for adults is 600 IU/d. Furthermore, pregnancy requires more vitamin D to maintain maternal and fetal health [65], [66], although the precise dose of vitamin D required during pregnancy is unclear. For pregnant women, there are numerous differing recommended vitamin D doses, such as 1000 IU/d, 1500-2000 IU/d, 5000 IU/week, and a single dose of 200,000 IU or higher [67]–[70]. For the elderly, the Institute of Medicine (IOM) suggested in 2011 that the recommended vitamin D dose was 800 IU/d (> 70 years), because bone loss is accelerated and the ability to synthesize vitamin D is also reduced with age [1], [71].

A.R. Webb et al. indicated that the vitamin D requirements in the human body are mostly met through skin exposure to sunlight [21]. However, an obvious seasonal cycle of serum 25(OH)D concentrations was observed in populations at mid-high latitudes [72]–[74]. A.R. Webb et al. also reported that the average concentration was lowest in February and highest in September [75]. The UVB irradiance reaching the surface of the Earth is also related to latitude. The greater the latitude, the greater the distance from the equator, the more UVB radiation that is absorbed by the ozone layer, and the less UVB that reaches the Earth's surface [76]. Moreover, the actual sunlight absorbed by human skin is decreased because people generally wear more clothing in winter. Thus, the effective amount of vitamin D3 produced by human skin was very small in winter for people living in middle and high latitudes; and it is therefore necessary to increase the supplementation and storage of vitamin D in the spring and autumn for these people [77]–[79], particularly for children, pregnant women, and the elderly, who have greater vitamin D requirements than other healthy adults.

$PM_{2.5}$ pollution mostly occurs in winter because of straw burning. In this study, we found that $PM_{2.5}$ obviously reduced the UV_{vitD} dose received by the manikin surface. If air pollution occurs in certain seasons and areas, such as in China [80], people are more likely to have vitamin D deficiency. Additionally, previous studies also reported that $PM_{2.5}$ could directly cause many chronic diseases, such as respiratory and cardiovascular diseases, to which children, pregnant women, and elderly individuals are more susceptible [81]–[83]. The doubly harmful effects of $PM_{2.5}$ deserve our attention.

This study has several limitations. One limitation is that due to the limitations of the monitoring conditions, the highest SEA and $PM_{2.5}$ concentration in the monitoring locations during the polluted periods were 50.1° and 161 $\mu g/m^3$, respectively. We failed to obtain UV radiation data in polluted atmospheres at higher SEAs and with higher concentrations of $PM_{2.5}$. Thus, the UV_{vitD} exposure models of multi-inclination angles of the human body cannot be applied to environments with higher $PM_{2.5}$ concentrations. However, if the $PM_{2.5}$ concentration is higher, the harmful effects will be increased. The second limitation was that our UV radiation monitoring was performed in cloudless weather; therefore, the UV_{vitD} exposure models of multi-inclination angles of the human body might not be applicable to cloudy conditions. The third limitation is that our study was conducted under the premise that the manikin was facing the sun and all parts were fully exposed to the sun; thus, we did not consider shading effects (e.g., shadow of the face on the neck). In addition, this study used the manikin to analyze the effect of $PM_{2.5}$ on the UV_{vitD} intensity. However, it was also affected by other factors, such as the exposure time outdoors or protective clothing. These factors will be studied in the future.

V. CONCLUSION

In conclusion, the presence of $PM_{2.5}$ can significantly reduce the UV_{vitD} received by the manikin surface.

REFERENCES

[1] A. C. Ross, J. E. Manson, S. A. Abrams, J. F. Aloia, P. M. Brannon, S. K. Clinton, R. A. Durazo-Arvizu, J. C. Gallagher, R. L. Gallo, G. Jones, C. S. Kovacs, S. T. Mayne, C. J. Rosen, and S. A. Shapses, "The 2011 report on dietary reference intakes for calcium and vitamin D from the institute of medicine: What clinicians need to know," *Obstetrical Gynecolog. Surv.*, vol. 66, no. 6, pp. 356–357, Jun. 2011.

[2] C. J. Rosen, J. S. Adams, D. D. Bikle, D. M. Black, M. B. Demay, J. E. Manson, M. H. Murad, and C. S. Kovacs, "The nonskeletal effects of vitamin D: An endocrine society scientific statement," *Endocrine Rev.*, vol. 33, no. 3, pp. 456–492, Jun. 2012, doi: 10.1210/er.2012-1000.

[3] N. Van Schoor and P. Lips, "Global overview of vitamin D status," *Endocrinol. Metabolism Clinics North Amer.*, vol. 46, no. 4, pp. 845–870, Dec. 2017, doi: 10.1016/j.ecl.2017.07.002.

[4] M. F. Holick, "The vitamin D deficiency pandemic: Approaches for diagnosis, treatment and prevention," *Rev. Endocrine Metabolic Disorders*, vol. 18, no. 2, pp. 153–165, Jun. 2017, doi: 10.1007/s11154-017-9424-1.

[5] T. Winzenberg and G. Jones, "Vitamin D and bone health in childhood and adolescence," *Calcified Tissue Int.*, vol. 92, no. 2, pp. 140–150, Feb. 2013.

[6] M. F. Holick, "A call to action: Pregnant women in-deed require vitamin D supplementation for better health outcomes," *J. Clin. Endocrinol. Metabolism*, vol. 104, no. 1, pp. 13–15, 2019, doi: 10.1210/jc.2018-01108.

[7] C. Palacios, "Regimens of vitamin D supplementation for women during pregnancy," *Cochrane Database Syst. Rev.*, vol. 10, Oct. 2019, Art. no. D13446, doi: 10.1002/14651858.CD013446.

[8] E. M. Brouwer-Brolsma, A. M. Vaes, N. L. Van Der Zwaluw, J. P. Van Wijngaarden, K. M. Swart, A. C. Ham, S. C. Van Dijk, A. W. Enneman, E. Sohl, N. M. Van Schoor, N. Van Der Velde, A. G. Uitterlinden, P. Lips, E. J. Feskens, R. A. Dhonukshe-Rutten, and L. C. De Groot, "Relative importance of summer sun exposure, vitamin D intake, and genes to vitamin D status in dutch older adults: The B-PROOF study," *J. Steroid Biochem. Mol. Biol.*, vol. 164, pp. 168–176, Nov. 2016, doi: 10.1016/j.jsbmb.2015.08.008.

[9] S. Erem, A. Atfi, and M. S. Razzaque, "Anabolic effects of vitamin D and magnesium in aging bone," *J. Steroid Biochem. Mol. Biol.*, vol. 193, Oct. 2019, Art. no. 105400, doi: 10.1016/j.jsbmb.2019.105400.

[10] P. Pludowski, "Vitamin D supplementation guidelines," *J. Steroid Biochem.*, vol. 175, pp. 125–135, Jan. 2018, doi: 10.1016/j.jsbmb.2017.01.021.

[11] R. J. Moon, N. C. Harvey, J. H. Davies, and C. Cooper, "Vitamin D and skeletal health in infancy and childhood," *Osteoporosis Int.*, vol. 25, no. 12, pp. 2673–2684, Dec. 2014, doi: 10.1007/s00198-014-2783-5.

[12] R. Bouillon and G. Carmeliet, ''Vitamin D insufficiency: Definition, diagnosis and management,'' *Best Pract. Res. Clin. Endocrinol. Metabolism*, vol. 32, no. 5, pp. 669–684, Oct. 2018, doi: 10.1016/j.beem.2018.09.014.

[13] B. W. Hollis and C. L. Wagner, ''Vitamin D supplementation during pregnancy: Improvements in birth outcomes and complications through direct genomic alteration,'' *Mol. Cellular Endocrinol.*, vol. 453, pp. 113–130, Sep. 2017, doi: 10.1016/j.mce.2017.01.039.

[14] M. Apostolakis, E. Armeni, P. Bakas, and I. Lambrinoudaki, ''Vitamin D and cardiovascular disease,'' *Maturitas*, vol. 115, pp. 1–22, Sep. 2018, doi: 10.1016/j.maturitas.2018.05.010.

[15] P. Lucato, M. Solmi, S. Maggi, A. Bertocco, G. Bano, C. Trevisan, E. Manzato, G. Sergi, P. Schofield, Y. Kouidrat, N. Veronese, and B. Stubbs, ''Low vitamin D levels increase the risk of type 2 diabetes in older adults: A systematic review and meta-analysis,'' *Maturitas*, vol. 100, pp. 8–15, Jun. 2017, doi: 10.1016/j.maturitas.2017.02.016.

[16] R. SivritepeS Basat and D. Ortaboz, ''Association of vitamin D status and the risk of cardiovascular disease as assessed by various cardiovascular risk scoring systems in patients with type 2 diabetes mellitus,'' *Aging Male*, vol. 22, no. 2, pp. 156–162, 2019, doi: 10.1080/13685538.2018.1499080.

[17] T. Hamada *et al.*, ''Vitamin D status after colorectal cancer diagnosis and patient survival according to immune response to tumour,'' *Eur. J. Cancer*, vol. 103, pp. 98–107, Nov. 2018, doi: 10.1016/j.ejca.2018.07.130.

[18] S. Hatse, D. Lambrechts, A. Verstuyf, A. Smeets, B. Brouwers, T. Vandorpe, O. Brouckaert, G. Peuteman, A. Laenen, L. Verlinden, C. Kriebitzsch, A.-S. Dieudonne, R. Paridaens, P. Neven, M.-R. Christiaens, R. Bouillon, and H. Wildiers, ''Vitamin D status at breast cancer diagnosis: Correlation with tumor characteristics, disease outcome, and genetic determinants of vitamin D insufficiency,'' *Carcinogenesis*, vol. 33, no. 7, pp. 1319–1326, Jul. 2012, doi: 10.1093/carcin/bgs187.

[19] F. J. Van Duijnhoven *et al.*, ''Circulating concentrations of vitamin D in relation to pancreatic cancer risk in European populations,'' *Int. J. Cancer*, vol. 142, no. 6, pp. 1189–1201, Mar. 2018, doi: 10.1002/ijc.31146.

[20] G. Buono, M. Giuliano, C. De Angelis, R. Lauria, V. Forestieri, M. Pensabene, D. Bruzzese, S. De Placido, and G. Arpino, ''Pretreatment serum concentration of vitamin D and breast cancer characteristics: A prospective observational mediterranean study,'' *Clin. Breast Cancer*, vol. 17, no. 7, pp. 559–563, Nov. 2017, doi: 10.1016/j.clbc.2017.05.007.

[21] R. K. Marwaha and R. Goswami, ''Vitamin D deficiency and its health consequences in India,'' *Vitamin D* (Nutrition Health). Totowa, NJ, USA: Humana Press, 2010, pp. 529–542, doi: 10.1007/978-1-60327-303-9_27.

[22] V. Londhey, ''Vitamin D deficiency: Indian scenario,'' *J. Assoc. Phys. India*, vol. 59, pp. 695–696, Nov. 2011.

[23] S. Sudhanshu, P. Upadhyay, M. Sahu, V. Rawat, and V. Bhatia, ''Sun exposure, UV irradiance and serum 25-hydroxycholecalciferol in pregnant women in rural north India,'' *Public Health Nutrition*, vol. 20, no. 10, pp. 1755–1759, Jul. 2017, doi: 10.1017/s136898001600313x.

[24] E. Hoseinzadeh, P. Taha, C. Wei, H. Godini, G. M. Ashraf, M. Taghavi, and M. Miri, ''The impact of air pollutants, UV exposure and geographic location on vitamin D deficiency,'' *Food Chem. Toxicol.*, vol. 113, pp. 241–254, Mar. 2018, doi: 10.1016/j.fct.2018.01.052.

[25] E. Feizabad, A. Hossein-Nezhad, Z. Maghbooli, M. Ramezani, R. Hashemian, and S. Moattari, ''Impact of air pollution on vitamin D deficiency and bone health in adolescents,'' *Arch. Osteoporosis*, vol. 12, p. 34, Dec. 2017, doi: 10.1007/s11657-017-0323-6.

[26] *ES FS313 Ambient (Outdoor) Air Quality and Health*, Centro De Prensa, World Health Org., Geneva, Switzerland, 2014.

[27] A. De Marco, P. Amoatey, Y. O. Khaniabadi, P. Sicard, and P. K. Hopke, ''Mortality and morbidity for cardiopulmonary diseases attributed to $PM_{2.5}$ exposure in the metropolis of Rome, Italy,'' *Eur. J. Internal Med.*, vol. 57, pp. 49–57, Nov. 2018, doi: 10.1016/j.ejim.2018.07.027.

[28] A. Guilbert, K. De Cremer, B. Heene, C. Demoury, R. Aerts, P. Declerck, O. Brasseur, and A. Van Nieuwenhuyse, ''Personal exposure to traffic-related air pollutants and relationships with respiratory symptoms and oxidative stress: A pilot cross-sectional study among urban green space workers,'' *Sci. Total Environ.*, vol. 649, pp. 620–628, Feb. 2019, doi: 10.1016/j.scitotenv.2018.08.338.

[29] R. Khan, S. Konishi, C. F. S. Ng, M. Umezaki, A. F. Kabir, S. Tasmin, and C. Watanabe, ''Association between short-term exposure to fine particulate matter and daily emergency room visits at a cardiovascular hospital in Dhaka, Bangladesh,'' *Sci. Total Environ.*, vol. 646, pp. 1030–1036, Jan. 2019, doi: 10.1016/j.scitotenv.2018.07.288.

[30] I. Seeni, S. Ha, C. Nobles, D. Liu, S. Sherman, and P. Mendola, ''Air pollution exposure during pregnancy: Maternal asthma and neonatal respiratory outcomes,'' *Ann. Epidemiol.*, vol. 28, no. 9, pp. 612–618, 2018, doi: 10.1016/j.annepidem.2018.06.003.

[31] G. Sgrigna, C. Baldacchini, R. Esposito, R. Calandrelli, A. Tiwary, and C. Calfapietra, ''Characterization of leaf-level particulate matter for an industrial city using electron microscopy and X-ray microanalysis,'' *Sci. Total Environ.*, vols. 548–549, pp. 91–99, Apr. 2016, doi: 10.1016/j.scitotenv.2016.01.057.

[32] J. D. Parker, N. Kravets, and A. Vaidyanathan, ''Particulate matter air pollution exposure and heart disease mortality risks by race and ethnicity in the United States: 1997 to 2009 national health interview survey with mortality follow-up through 2011,'' *Circulation*, vol. 137, no. 16, pp. 1688–1697, 2018, doi: 10.1161/CIRCULATIONAHA.117.029376.

[33] R. Nabizadeh, F. Yousefian, V. K. Moghadam, and M. Hadei, ''Characteristics of cohort studies of long-term exposure to $PM_{2.5}$: A systematic review,'' *Environ. Sci. Pollut. Res.*, vol. 26, no. 30, pp. 30755–30771, Oct. 2019, doi: 10.1007/s11356-019-06382-6.

[34] T. Bourdrel, M. Bind, Y. Bejot, O. Morel, and J. Argacha, ''Cardiovascular effects of air pollution,'' *Arch. Cardiovascular Diseases*, vol. 110, no. 11, pp. 634–642, 2017, doi: 10.1016/j.acvd.2017.05.003.

[35] B.-Y. Yang, Z. Qian, S. W. Howard, M. G. Vaughn, S.-J. Fan, K.-K. Liu, and G.-H. Dong, ''Global association between ambient air pollution and blood pressure: A systematic review and meta-analysis,'' *Environ. Pollut.*, vol. 235, pp. 576–588, Apr. 2018, doi: 10.1016/j.envpol.2018.01.001.

[36] A. Spiro and J. L. Buttriss, ''Vitamin D: An overview of vitamin D status and intake in Europe,'' *Nutrition Bull.*, vol. 39, no. 4, pp. 322–350, 2014.

[37] M.-A. Serrano, ''Contribution of sun exposure to the vitamin D dose received by various groups of the Spanish population,'' *Sci. Total Environ.*, vols. 619–620, pp. 545–551, Apr. 2018, doi: 10.1016/j.scitotenv.2017.11.036.

[38] L. Tripkovic, H. Lambert, K. Hart, C. P. Smith, G. Bucca, S. Penson, G. Chope, E. Hyppönen, J. Berry, R. Vieth, and S. Lanham-New, ''Comparison of vitamin D_2 and vitamin D_3 supplementation in raising serum 25-hydroxyvitamin D status: a systematic review and meta-analysis,'' *Amer. J. Clin. Nutrition*, vol. 95, no. 6, pp. 1357–1364, Jun. 2012, doi: 10.3945/ajcn.111.031070.

[39] J. Valtuena, ''Factors associated with vitamin D deficiency in European adolescents: The HELENA study,'' *J. Nutritional Sci. Vitaminol.*, vol. 59, no. 3, pp. 161–171, 2013.

[40] *National Diet and Nutrition Survey: Headline Results from Years 1, 2 and 3 (Combined) of the Rolling Programme 2008/09–2010/11*, Dept. Health, Washington, DC, USA, 2011.

[41] Y. Liu, L. Hu, F. Wang, Y. Gao, Y. Zheng, Y. Wang, and Y. Liu, ''The angular distributions of ultraviolet spectral irradiance at different solar elevation angles under clear sky conditions,'' *Int. J. Biometeorol.*, vol. 60, no. 1, pp. 63–72, Jan. 2016, doi: 10.1007/s00484-015-1005-y.

[42] F. Hosseinpanah, S. H. Pour, M. Heibatollahi, N. Moghbel, S. Asefzade, and F. Azizi, ''The effects of air pollution on vitamin D status in healthy women: A cross sectional study,'' *BMC Public Health*, vol. 10, Aug. 2010, Art. no. 519, doi: 10.1186/1471-2458-10-519.

[43] S. E. Mousavi, H. Amini, P. Heydarpour, F. A. Chermahini, and L. Godderis, ''Air pollution, environmental chemicals, and smoking may trigger vitamin D deficiency: Evidence and potential mechanisms,'' *Environ. Int.*, vol. 122, pp. 67–90, Jan. 2019, doi: 10.1016/j.envint.2018.11.052.

[44] K. A. Baczynska, A. J. Pearson, J. B. O'Hagan, and J. Heydenreich, ''Effect of altitude on solar UVR and spectral and spatial variations of UV irradiances measured inWagrain, Austria in winter,'' *Radiat. Protection Dosimetry*, vol. 154, no. 4, pp. 497–504, May 2013, doi: 10.1093/rpd/ncs261.

[45] D. Serrano, M. J. Marin, M. P. Utrillas, F. Tena, and J. A. Martinez-Lozano, ''Modelling of the UV Index on vertical and 40 tilted planes for different orientations,'' *Photochem. Photobiol. Sci.*, vol. 11, no. 2, pp. 333–344, 2012, doi: 10.1039/c1pp05211j.

[46] H. Lee, W. Kim, Y. G. Lee, J. Kim, and H. K. Cho, ''Atmospheric transmission of ultraviolet and total solar radiation by clouds, aerosols, and ozone in Seoul, Korea: A comparison of semi-empirical model predictions with observations,'' *Asia–Pacific J. Atmos. Sci.*, vol. 55, no. 2, pp. 165–175, May 2019, doi: 10.1007/s13143-018-0082-3.

[47] H. K. Cho, J. Kim, Y. Jung, Y. G. Lee, and B. Y. Lee, ''Recent changes in downward longwave radiation at King Sejong Station, Antarctica,'' *J. Climate*, vol. 21, no. 22, pp. 5764–5776, Nov. 2008, doi: 10.1175/2008jcli1876.1.

[48] M. Schrempf, D. Haluza, S. Simic, S. Riechelmann, K. Graw, and G. Seckmeyer, "Is multidirectional UV exposure responsible for increasing melanoma prevalence with altitude? A hypothesis based on calculations with a 3D-human exposure model," *Int. J. Environ. Res. Public Health*, vol. 13, no. 10, p. 961, Sep. 2016, doi: 10.3390/ijerph13100961.

[49] C. Backes, A. Religi, L. Moccozet, L. Vuilleumier, D. Vernez, and J.-L. Bulliard, "Facial exposure to ultraviolet radiation: Predicted sun protection effectiveness of various hat styles," *Photodermatol., Photoimmunol. Photomedicine*, vol. 34, no. 5, pp. 330–337, Sep. 2018, doi: 10.1111/phpp.12388.

[50] D. Vernez, A. Milon, L. Francioli, J.-L. Bulliard, L. Vuilleumier, and L. Moccozet, "A numeric model to simulate solar individual ultraviolet exposure," *Photochem. Photobiol.*, vol. 87, no. 3, pp. 721–728, May 2011, doi: 10.1111/j.1751-1097.2011.00895.x.

[51] K. Lamy, "Clear-sky ultraviolet radiation modelling using output from the chemistry climate model initiative," *Atmos. Chem. Phys.*, vol. 19, no. 15, pp. 10087–10110, 2019, doi: 10.5194/acp-19-10087-2019.

[52] A. F. Bais, "Ozone–climate interactions and effects on solar ultraviolet radiation," *Photochem. Photobiol. Sci.*, vol. 18, no. 3, pp. 602–640, 2019, doi: 10.1039/c8pp90059k.

[53] B. Hu, H. Liu, and Z. Liu, "Spatiotemporal characteristics of ultraviolet solar radiation in China," *Atmos. Ocean. Sci. Lett.*, vol. 12, no. 4, pp. 302–304, Jul. 2019.

[54] M. G. Kimlin, "Personal ultraviolet Radiation exposure in a cohort of Chinese mother and child pairs: The Chinese families and children study," *BMC Public Health*, vol. 19, no. 1, p. 281, 2019, doi: 10.1186/s12889-019-6610-y.

[55] M. G. Kimlin, "Geographic location and vitamin D synthesis," *Mol. Aspects Med.*, vol. 29, no. 6, pp. 453–461, Dec. 2008, doi: 10.1016/j.mam.2008.08.005.

[56] A. Modenese, F. P. Ruggieri, F. Bisegna, M. Borra, C. Burattini, E. D. Vecchia, C. Grandi, A. Grasso, L. Gugliermetti, M. Manini, A. Militello, and F. Gobba, "Occupational exposure to solar UV radiation of a group of Fishermen working in the Italian North Adriatic Sea," *Int. J. Environ. Res. Public Health*, vol. 16, no. 16, p. 3001, Aug. 2019, doi: 10.3390/ijerph16163001.

[57] Z. Lan, "Source apportionment of $PM_{2.5}$ light extinction in an urban atmosphere in China," *J. Environ. Sci.*, vol. 63, pp. 277–284, Jan. 2018, doi: 10.1016/j.jes.2017.07.016.

[58] J. Mok, "Impacts of brown carbon from biomass burning on surface UV and ozone photochemistry in the Amazon Basin," *Sci. Rep.*, vol. 6, Nov. 2016, Art. no. 36940, doi: 10.1038/srep36940.

[59] Y. Zhang, J. Xu, J. Shi, C. Xie, X. Ge, J. Wang, S. Kang, and Q. Zhang, "Light absorption by water-soluble organic carbon in atmospheric fine particles in the central Tibetan Plateau," *Environ. Sci. Pollut. Res.*, vol. 24, no. 26, pp. 21386–21397, Sep. 2017, doi: 10.1007/s11356-017-9688-8.

[60] C. Liu, X. Zhang, Q. Wang, and K. Shi, "Role of $PM_{2.5}$ in the photodegradation of the atmospheric benzene," *Environ. Pollut.*, vol. 247, pp. 447–456, Apr. 2019, doi: 10.1016/j.envpol.2019.01.020.

[61] B. Zegarska, K. Pietkun, W. Zegarski, P. Bolibok, M. Wiśniewski, K. Roszek, J. Czarnecka, and M. Nowacki, "Air pollution, UV irradiation and skin carcinogenesis: What we know, where we stand and what is likely to happen in the future?" *Postępy Dermatologii i Alergologii*, vol. 1, pp. 6–14, 2017, doi: 10.5114/ada.2017.65616.

[62] T. Passeron, R. Bouillon, V. Callender, T. Cestari, T. Diepgen, A. Green, J. Pols, B. Bernard, F. Ly, F. Bernerd, L. Marrot, M. Nielsen, M. Verschoore, N. Jablonski, and A. Young, "Sunscreen photoprotection and vitamin D status," *Brit. J. Dermatol.*, vol. 181, no. 5, pp. 916–931, Nov. 2019, doi: 10.1111/bjd.17992.

[63] A. Anastasiou, S. N. Karras, A. Bais, W. B. Grant, K. Kotsa, and D. G. Goulis, "Ultraviolet radiation and effects on humans: The paradigm of maternal vitamin D production during pregnancy," *Eur. J. Clin. Nutrition*, vol. 71, no. 11, pp. 1268–1272, 2017, doi: 10.1038/ejcn.2016.188.

[64] T. J. Smith and K. H. Hart, "Vitamin D during childhood and adolescence: Evidence-based dietary requirements for adequacy and implications for bone health," *Nutrition Bull.*, vol. 42, no. 1, pp. 55–60, Mar. 2017.

[65] S. A. Hamilton, "Profound vitamin D deficiency in a diverse group of women during pregnancy living in a sun-rich environment at latitude 32 N," *Int. J. Endocrinol.*, vol. 2010, nos. 1687–8337, 2010, Art. no. 917428.

[66] D. Johnson, C. Wagner, T. Hulsey, R. Mcneil, M. Ebeling, and B. Hollis, "Vitamin D deficiency and insufficiency is common during pregnancy," *Amer. J. Perinato.l*, vol. 28, no. 01, pp. 007–012, Jan. 2011.

[67] B. W. Hollis, "Vitamin D requirement during pregnancy and lactation," *J. Bone Mineral Res.*, vol. 22, no. S2, pp. V39–V44, Feb. 2008.

[68] M. F. Holick, "Evaluation, treatment, and prevention of vitamin D deficiency: An endocrine society clinical practice guideline," *J. Clin. Endocrinol. Metabolism*, vol. 96, no. 12, pp. 1911–1930, 2011.

[69] D. E. Roth, "Vitamin D replacement in pregnant women in rural north India: A pilot study," *Eur. J. Clin. Nutrition*, vol. 64, no. 8, pp. 914–915, Aug. 2010, doi: 10.1038/ejcn.2010.1.

[70] C. K. H. Yu, L. Sykes, M. Sethi, T. G. Teoh, and S. Robinson, "Vitamin D deficiency and supplementation during pregnancy," *Clin. Endocrinol.*, vol. 70, no. 5, pp. 685–690, May 2009.

[71] J. F. Aloia, "The 2011 report on dietary reference intake for vitamin D: Where do we go from here?" *J. Clin. Endocrinol. Metabolism*, vol. 96, no. 10, p. 2987, 2011.

[72] A. Hanel and C. Carlberg, "Vitamin D and evolution: Pharmacologic implications," *Biochem. Pharmacol.*, to be published, doi: 10.1016/j.bcp.2019.07.024.

[73] R. M. Lucas, A.-L. Ponsonby, K. Dear, P. C. Valery, B. Taylor, I. Van Der Mei, A. J. Mcmichael, M. P. Pender, C. Chapman, A. Coulthard, T. J. Kilpatrick, J. Stankovich, D. Williams, and T. Dwyer, "Vitamin D status: Multifactorial contribution of environment, genes and other factors in healthy Australian adults across a latitude gradient," *J. Steroid Biochem. Mol. Biol.*, vol. 136, pp. 300–308, Jul. 2013, doi: 10.1016/j.jsbmb.2013.01.011.

[74] D. E. Godar, S. J. Pope, W. B. Grant, and M. F. Holick, "Solar UV doses of young Americans and vitamin D_3 production," *Environ. Health Perspect.*, vol. 120, no. 1, pp. 139–143, 2012, doi: 10.1289/ehp.1003195.

[75] A. Webb, R. Kift, M. Durkin, S. O'Brien, A. Vail, J. Berry, and L. Rhodes, "The role of sunlight exposure in determining the vitamin D status of the UK white adult population," *Brit. J. Dermatol.*, vol. 163, no. 5, pp. 1050–1055, Nov. 2010, doi: 10.1111/j.1365-2133.2010.09975.x.

[76] M. Wacker and M. F. Holick, "Sunlight and vitamin D: A global perspective for health," *Dermato-Endocrinol.*, vol. 5, no. 1, pp. 51–108, 2013, doi: 10.4161/derm.24494.

[77] E. K. Calton, K. N. Keane, R. Raizel, J. Rowlands, M. J. Soares, and P. Newsholme, "Winter to summer change in vitamin D status reduces systemic inflammation and bioenergetic activity of human peripheral blood mononuclear cells," *Redox Biol.*, vol. 12, pp. 814–820, Aug. 2017, doi: 10.1016/j.redox.2017.04.009.

[78] A. Raza, "Incidence of vitamin D deficiency in different seasons in the adult Karachi population presenting in the medical outpatient department with generalized body ache," *Cureus*, vol. 11, no. 7, p. e5167, 2019, doi: 10.7759/cureus.5167.

[79] C. G. Aydin, Y. M. Dincel, Y. Arikan, S. K. Tas, and S. Deniz, "The effects of indoor and outdoor sports participation and seasonal changes on vitamin D levels in athletes," *SAGE open Med.*, vol. 7, Mar. 2019, Art. no. 2106909480, doi: 10.1177/2050312119837480.

[80] Z. Cheng, "Status and characteristics of ambient $PM_{2.5}$ pollution in global megacities," *Environ. Int.*, vols. 89–90, pp. 212–221, Apr. 2016.

[81] X. Q. D. JiangX Mei and D. Feng, "Air pollution and chronic airway diseases: What should people know and do?" *J. Thoracic Disease*, vol. 8, no. 1, p. E31, 2016.

[82] K. K. Nishimura *et al.*, "Early-life air pollution and asthma risk in minority children. The GALA II and SAGE II studies," *Amer. J. Respiratory Crit. Care Med.*, vol. 188, no. 3, pp. 309–318, Aug. 2013, doi: 10.1164/rccm.201302-0264oc.

[83] M. H. Askariyeh, S. Vallamsundar, J. Zietsman, and T. Ramani, "Assessment of traffic-related air pollution: Case study of pregnant women in South Texas," *Int. J. Environ. Res. Public Health*, vol. 16, no. 13, p. 2433, Jul. 2019, doi: 10.3390/ijerph16132433.

NAN WANG received the B.M. degree from China Medical University, China, in 2016, where she is currently pursuing the Ph.D. degree in labor and environmental hygiene. Her main research aims at the study of ultraviolet exposure in China and exploring the associations between PM2.5 and ultraviolet radiation.

RENTONG CHEN was born in Yingkou, Liaoning, China, in 1991. She received the B.M. and Ph.D. degrees from China Medical University, in 2014 and 2019, respectively. Her main research aims at the study of ultraviolet exposure in China and exploring the associations between ocular UV exposure and human facial anatomy.

YAN LIU received the Ph.D. degree from China Medical University, in 2015. After graduation, she worked at the Department of Biomedical Engineering, School of Fundamental Sciences, China Medical University. Her research focuses the relationship between ultraviolet radiation and vitamin D.

JIAMING YU received the bachelor's degree from the Department of Public Health, Shenyang Medical College, in 1992, and the master's and Ph.D. degrees from China Medical University, in 2000 and 2004, respectively. She once was a JSPS Postdoctoral Fellow studied at Tokushima Bunri University, Japan, from 2005 to 2007. She is currently a Professor with the Lens Laboratory of the Fourth Affiliated Hospital, China Medical University, China. She has authored or coauthored over ten refereed publications in international journals. Her research interests include the study of ultraviolet exposure and ophthalmological epidemiology.

TIANYAO YANG received the Ph.D. degree from China Medical University, in 2017. After graduation, she worked at the Department of Environmental Health, School of Public Health, China Medical University. Her research focus mainly on the MeHy-induced neurotoxicity and the oxidative stress induced by ultraviolet.

HUI HUA received the B.M. degree from China Medical University, China, in 2014, where she is currently pursuing the Ph.D. degree in labor and environmental hygiene. She aims to explore the ultraviolet exposure intensity in China outdoors and indoors. Her research also focused on the mechanism of the process of cataractogenesis in vivo and vitro.

DAN YANG received the B.M. and M.M. degrees from China Medical University, China, in 2015 and 2018, respectively, where she is currently pursuing the Ph.D. degree with the School of Public Health. Her main research aims at the study of ultraviolet exposure in China and exploring the associations between environmental factors and malarial risk through processing big data.

FANGFANG MA received the B.M. degree in preventive medicine from Jining Medical University, Jining, Shandong, in 2016, and the M.M. degree from China Medical University, in 2019. Her research interest includes ultraviolet biological effect.

XIN LI received the B.M. degree from Xin Xiang Medical University, in 2016, and the M.M. degree from China Medical University, in 2019. Her main research aims to study the relationship between ultraviolet radiation and outdoor activity time in China, and to explore the relationship between ultraviolet radiation and meteorological factors.

MENGLIN LI was born in Anqing, Anhui, China, in 1994. She received the B.M. degree from Anhui Medical University, China, in 2017. She is currently with the School of Public Health, China Medical University. Her main research aims at the study of sunlight exposure in different ethnic groups and exploring the associations between visible light exposure and human orbital structure in different facial model.

LITING HUANG received the B.M. degree from China Medical University, China, in 2017, where she is currently pursuing the master's degree with the School of Public Health. Her main research aims at the study of ultraviolet exposure in China and exploring the associations between various age groups and ocular UV exposure.

ZHENZHEN ZOU received the B.M. degree from the Liaoning University of Traditional Chinese Medicine, in 2017, where she is currently pursuing the master's degree with the School of Public Health. Her main research aims at the study of ultraviolet exposure in China and the relationship between eyeball protrusion and eyelid structure.

YAN DENG received the B.M. and M.M. degrees from China Medical University, China, in 2010 and 2013, respectively, where she is currently pursuing the Ph.D. degree in labor and environmental hygiene. She is currently with the Editorial Department of the Chinese Journal of Health Statistics, China Medical University, as an Editor. Her main research aims at the study of ultraviolet exposure in China, text mining of medicial big data, and evaluation of science and technology productivity.

YANG LIU received the bachelor's degree from the Department of Public Health, China Medical University, in 1983, and the master's and Ph.D. degrees from China Medical University, China, in 1997 and 2002, respectively. He was with Jichi Medical University and Fukushima Medical University, Japan, as a Visiting Scholar, in 1996 and 2000, respectively. He is currently a Professor with the Department of Environmental Health and Environmental Physical Factors and Health, School of Public Health, China Medical University. He has authored or coauthored over 30 refereed publications in international journals. He has supervised dozens of Ph.D. and master's students in China Medical University. His research interests include the study of ultraviolet exposure and evaluation of science and technology productivity.