

# Detrimental correlation between air pollution with skin aging in Taiwan population

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## Abstract

Dissecting the complex relationships between skin aging and air pollution has been an ongoing effort. The increased exposure to air pollution over time imposed a negative effect on skin. This study explores the correlation between skin aging in the Asian population and levels of air pollutants to show different relationship between the two. This study was retrospective and included 389 patients, age between 30 and 74, who planned to receive a session of laser treatment for skin disorders in Kaohsiung Medical University Hospital (KMUH) from 2006 to 2019. Preoperative skin condition quantified by VISIA Complexion Analysis System (Canfield Imaging Systems, Fierfield, NJ, US). Eight air pollutants such as carbon monoxide (CO), non-methane hydrocarbon (NMHC), nitrogen oxides (NO, NO<sub>2</sub>, and NO<sub>x</sub>), particulate matters (PM<sub>2.5</sub> and PM<sub>10</sub>), ozone (O<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>) and 8 skin condition such as spots, wrinkles, textures, pores, ultraviolet spots (UV spots), brown spots, red area, and porphyrin were analyzed to explore correlation between air pollution and skin aging. Strong correlation was found between NMHC exposure and texture, pores and brown spots formation. A positive correlation between O<sub>3</sub> and better VISIA texture and pores scores was found. Brown spots was found to negatively associate with CO, NMHC, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, and SO<sub>2</sub>. The skin condition of population over age 45 affected by CO, NMHC, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, and SO<sub>2</sub>. Skin condition of the bottom 10% strongly correlates with exposure to PM<sub>10</sub> and SO<sub>2</sub>, whereas skin condition of the top 10% was affected by PM<sub>10</sub>. Air pollutants such as CO, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, and NMHC were found to correlate with negative skin quality strongly. In contrast, O<sub>3</sub> exposure is associated with less texture and pores. Future studies are warranted to further appreciate the relationships between air pollutants and skin condition.

**Abbreviations:** CO = carbon monoxide, KMUH = Kaohsiung Medical University Hospital, NMHC = non-methane hydrocarbon, NO, NO<sub>2</sub>, and NO<sub>x</sub> = nitrogen oxides, O<sub>3</sub> = ozone, PAHs = polycyclic aromatic hydrocarbons, PCBs = polychlorinated biphenyls, PM<sub>10</sub> = particulate Matter 10, PM<sub>2.5</sub> = particulate Matter 2.5, POPs = persistent organic pollutants, SO<sub>2</sub> = sulfur dioxide, UV spots = ultraviolet spots, WHO = World Health Organization.

**Keywords:** air pollution, NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, skin aging, VISIA

## 1. Introduction

Skin aging is associated with skin pigmentation, wrinkle formation, enlarged pores, loss of intradermal hydration, and skin laxity.<sup>[1-4]</sup> One major cause of skin aging is exposure to air pollutants, especially particulate matter of different sizes (PM<sub>2.5</sub> and PM<sub>10</sub>) and ozone (O<sub>3</sub>).<sup>[1,2,4]</sup> Air pollutants can penetrate the skin

via direct transcutaneous absorption through the hair follicles or via indirect systemic circulation. The accumulation of airborne pollutants in the skin triggers reactive oxidative stress, which causes cell stress and cytotoxicity, thereby resulting in hyperpigmentation, wrinkles, dry skin, and disruption of skin barrier.<sup>[4,5]</sup>

Although the relationships between skin aging and air pollutants have been well described, limited study was done

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Ethics Statement: The study protocol was approved by the Institutional Review Board of Kaohsiung Medical University Hospital (KMUHIRB-E(I)-20200363).

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in Taiwan to explore impacts of air pollutants on skin, and objective measurement of skin condition was also limited in previous studies.<sup>[6,7]</sup> Thus, this study aims to be the first study on Taiwan population to investigate the effects of air pollutants on skin aging. Moreover, the data of air pollutant was address-specific, collecting from the Taiwan Air Quality Monitoring Network of the Environmental Protection Administration in Taiwan. In addition, this study objectively explored the correlation between airborne pollutants and skin aging in a Taiwanese population by using the VISIA Complexion Analysis System.

## 2. Methods

### 2.1. Patient selection

This retrospective study used skin quality scores calculated by the VISIA system. We examined air pollution data against patients' addresses to identify the effect of both outdoor and indoor air pollution. This study included 389 patients, without dermatological disease, seeking laser therapy for cosmetic reasons. The study collected patients from 2006 to 2019 at Kaohsiung Medical University Chung-Ho Memorial Hospital, Taiwan (Table 1). A frontal view of their facial skin was taken before they underwent any cosmetic treatment. After the photographs had been taken, skin analysis was performed using the VISIA Complexion Analysis System (Canfield Imaging Systems, Fairfield, NJ). This study was approved by the Institutional Review Board of Kaohsiung Medical University Chung-Ho Memorial Hospital.

### 2.2. Exposure to air pollution

The addresses of patients and the concentrations of airborne pollutants, namely CO, nonmethane hydrocarbons (NMHCs), NO, NO<sub>2</sub>, NO<sub>x</sub>, O<sub>3</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>, in their neighborhoods, were recorded. The level of airborne pollutants was continuously monitored and collected by the Taiwan Air Quality Monitoring Network under the Environmental Protection Administration (Fig. 1). Data were collected continuously from 2006 to the day of the clinic visit. To personalize exposure levels, we assigned air pollution concentrations to the patients' home addresses. First, the latitudes and longitudes of patients' addresses were obtained, on the basis of which the closest exposure concentration (measured at the closest monitoring station) was assigned. The levels of each air pollutant at each station between 2006 and 2019 were then respectively quantified and averaged. Data on the concentration of air pollutants and the patients' skin characteristics were matched and analyzed to examine correlation.

### 2.3. VISIA complexion analysis system

The VISIA Complexion Analysis System employs standard white light, UV light, and cross-polarized light to objectively evaluate a variety of skin characteristics, namely pigmented spots, texture, pores, UV spots, brown spots, porphyrin, wrinkles, and red areas.<sup>[8]</sup> VISIA performs a contact-free assessment of the skin by visualization and quantification of skin characteristics, all of which are matched and compared with a worldwide database within 5 minutes.<sup>[8]</sup> After the computerized analysis on VISIA, each patient received eight scores, each corresponding to a specific skin characteristic. A patient's skin score was rated by VISIA on a scale from 0 to 100 using a data bank containing average scores of skin characteristics according to different age groups. A higher score indicated that the individual had a better skin characteristic than those of their age group, and a lower score indicated a worse skin characteristic (Fig. 2).

**Table 1**

**Demographic characteristics of patients (n = 389).**

Characteristics	N(%) / mean ± SD
Age	44.90 ± 10.16
Gender	
Male	29 (7.5%)
Female	360 (92.5%)
Air pollutants	
CO (ppm)	0.60 ± 0.13
NMHC (ppb)	0.27 ± 0.08
NO (ppb)	6.22 ± 1.99
NO <sub>2</sub> (ppb)	20.98 ± 3.91
NO <sub>x</sub> (ppb)	27.19 ± 5.62
O <sub>3</sub> (µg/m <sup>3</sup> )	28.84 ± 2.59
PM <sub>10</sub> (µg/m <sup>3</sup> )	73.78 ± 7.21
PM <sub>2.5</sub> (µg/m <sup>3</sup> )	41.47 ± 4.13
SO <sub>2</sub> (ppb)	6.79 ± 1.65
Skin condition	
Spots (%)	66.62 ± 19.72
Wrinkles (%)	67.24 ± 20.78
textures (%)	66.06 ± 17.29
pores (%)	73.21 ± 16.51
UV spots (%)	46.92 ± 21.23
Brown spots (%)	54.55 ± 22.91
red area (%)	73.24 ± 16.38
porphyrin (%)	65.62 ± 31.30

CO = carbon monoxide; NMHC = nonmethane hydrocarbons; NO = nitrogen monoxide; NO<sub>2</sub> = nitrogen dioxide; NO<sub>x</sub> = nitrogen oxides; O<sub>3</sub> = ozone; PM<sub>10</sub> = particulate matter ≤10 µm; PM<sub>2.5</sub> = particulate matter ≤2.5 µm; SO<sub>2</sub> = sulfur dioxide.

### 2.4. Statistical analysis

Data are expressed as percentage or mean ± standard deviation for skin characteristic scores and pollutant levels. Age and sex were selected for multivariable analysis, in which linear regression analysis was used to explore the relationship between each pollutant and each skin characteristic. A cutoff age of 45 years was used to explore the effects of air pollutants on age cohort ≥45 years since the average age of the patients was 44.90. The skin characteristics of the top 10% of patients and those of the bottom 10% were also compared to ascertain their respective correlations with air pollutants. All statistical analyses were performed using SPSS 26.0 for Windows (SPSS Inc, Chicago, IL). A *P* value of <.05 indicated statistical significance.

## 3. Results

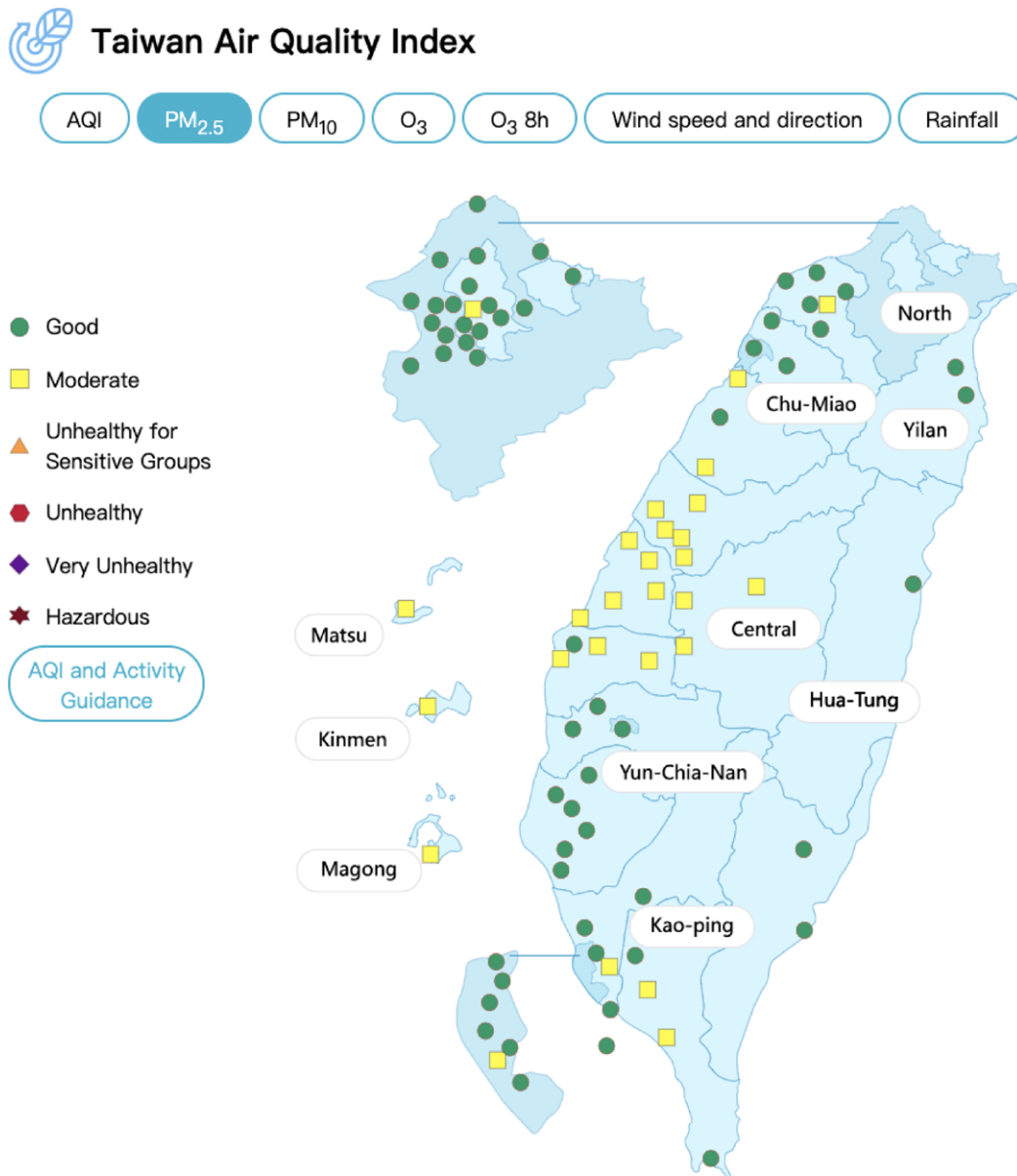
The average age of the 389 patients (29 men and 360 women) was 44.90 ± 10.16 years.

### 3.1. Demographic characteristics of patients (n = 389)

The demographic characteristics of the patients are presented in Table 1. A high score indicates good skin characteristics compared with individuals of the same age. Pores (73.21 ± 16.51) and red areas (73.24 ± 16.38) had the highest scores, followed by wrinkles (67.24 ± 20.78), spots (66.62 ± 19.72), porphyrin (65.62 ± 31.30), and brown spots (54.55 ± 22.91). UV spots (46.92 ± 21.23) had the lowest scores.

### 3.2. Correlation between skin characteristics and air pollutants

Table 2 presents the results of the multivariable linear regression analysis for the association between skin characteristics and air pollutants, which was adjusted for age and sex. We observed that high NMHC levels were significantly associated with low texture scores (coefficient β, -23.65; *P* = .03), low pore scores (coefficient β,



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**Figure 1.** Graph showing values of PM<sub>2.5</sub> at different monitoring stations. Values were collected from 2006 to 2019 and adjusted according to patients' addresses.<sup>[29]</sup>

-25.02;  $P = .02$ ), and high brown spot scores (coefficient  $\beta$ , 27.96;  $P = .05$ ). In addition, high O<sub>3</sub> levels were significantly associated with high texture scores (coefficient  $\beta$ , 0.86;  $P = .01$ ) and high pore scores (coefficient  $\beta$ , 0.9;  $P = .01$ ). Lastly, high PM<sub>10</sub> and PM<sub>2.5</sub> values were both associated with high brown spot scores (coefficient  $\beta$ , 0.48;  $P = .00$ , and coefficient  $\beta$ , 0.86;  $P = .00$ , respectively).

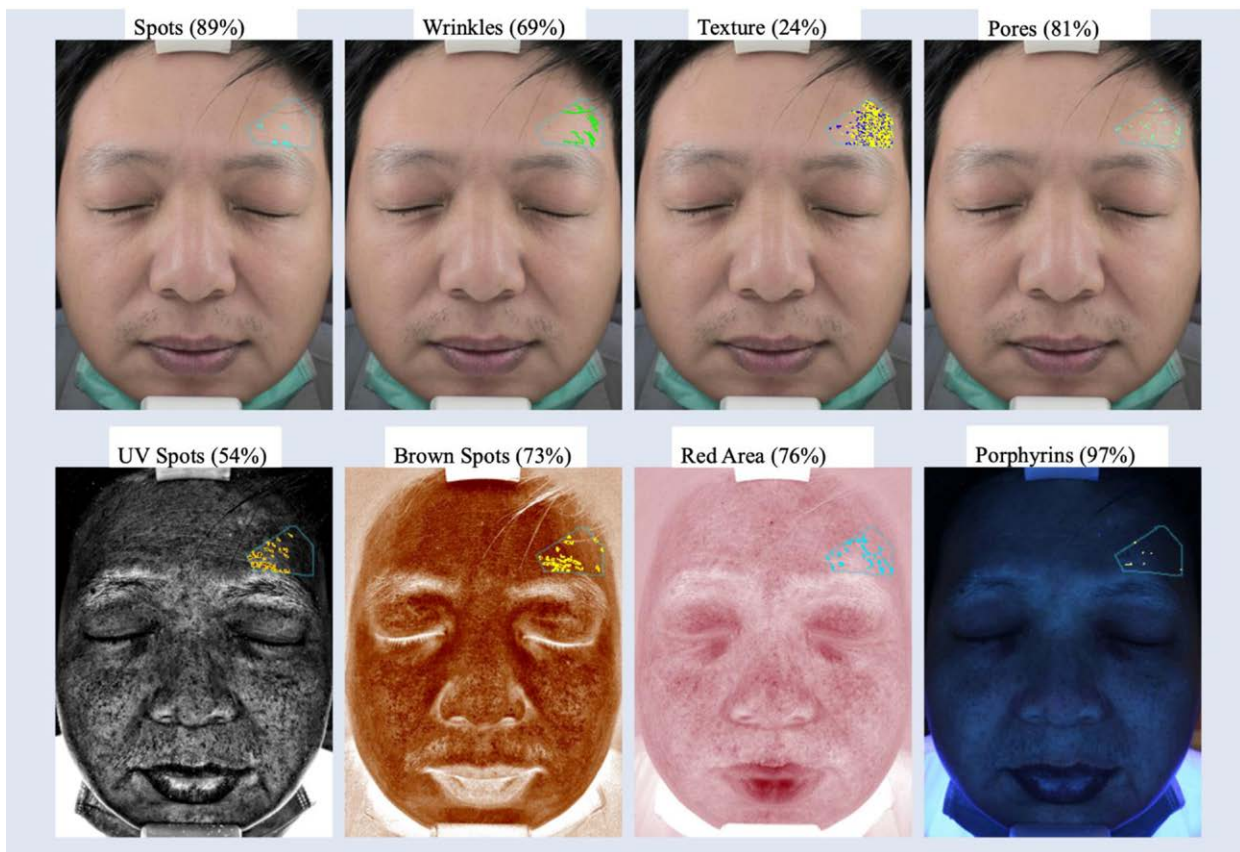
**3.3. Correlation between skin characteristics and air pollutants at a cutoff age of 45 years**

Multivariable linear regression analysis for the determinants of skin condition in the age cohort of  $\geq 45$  is summarized in Table 3. High texture score was significantly associated with high O<sub>3</sub> level (coefficient  $\beta$ , 0.96;  $P = .03$ ). High pore size score was also significantly associated with high O<sub>3</sub> level (coefficient  $\beta$ , 0.85;  $P = .03$ ). High UV spot score was significantly positively

associated with the following indices: CO (coefficient  $\beta$ , 24.35;  $P = .03$ ), NMHC (coefficient  $\beta$ , 37.81;  $P = .04$ ), and PM<sub>10</sub> (coefficient  $\beta$ , 0.63;  $P = .01$ ). In addition, high brown spot score was significantly positively associated with the following indices: CO (coefficient  $\beta$ , 26.81;  $P = .03$ ), NMHC (coefficient  $\beta$ , 51.25;  $P = .01$ ), NO<sub>2</sub> (coefficient  $\beta$ , 0.99;  $P = .02$ ), NO<sub>x</sub> (coefficient  $\beta$ , 0.57;  $P = .04$ ), PM<sub>10</sub> (coefficient  $\beta$ , 0.84;  $P < .00$ ), PM<sub>2.5</sub> (coefficient  $\beta$ , 0.95;  $P = .02$ ), and SO<sub>2</sub> (coefficient  $\beta$ , 2.18;  $P = .04$ ).

**3.4. Correlation of air pollutants with skin characteristics of the top 10% and bottom 10% of patients**

Table 4 reveals that brown spot score correlated positively with exposure to PM<sub>10</sub> ( $r = 0.44$ ) in the top 10% patient scores. In the bottom 10% scores, high texture score correlated positively with PM<sub>10</sub> ( $r = 0.32$ ) and SO<sub>2</sub> ( $r = 0.33$ ).



**Figure 2.** Illustration of skin analysis using VISIA Complexion Analysis System. Eight skin characteristics were analyzed, and their corresponding scores were listed.

**Table 2**

**Multivariable linear regression analysis of the association between skin characteristics and air pollutants (n = 389).**

Air pollutants	Skin condition							
	Spots	Wrinkles	Texture	Pores	UV spots	Brown spots	Red area	Porphyryn
CO ( <i>t</i> )	-0.01	-0.06	-0.08	-0.07	0.09	0.10	0.00	0.02
<i>P</i>	.82	.24	.10	.15	.08	.05	.99	.64
NMHC ( <i>t</i> )	-0.04	-0.06	-0.12*	-0.11*	0.09	0.11*	-0.03	0.00
<i>P</i>	.41	.25	.02	.02	.09	.03	.55	.94
NO ( <i>t</i> )	-0.02	-0.02	-0.07	-0.09	0.01	0.07	-0.04	-0.02
<i>P</i>	.68	.63	.15	.09	.91	.19	.41	.70
NO <sub>2</sub> ( <i>t</i> )	-0.02	-0.05	-0.08	-0.08	0.05	0.08	-0.04	0.02
<i>P</i>	.64	.32	.10	.14	.32	.12	.39	.74
NO <sub>x</sub> ( <i>t</i> )	-0.01	-0.03	-0.07	-0.07	0.04	0.09	-0.04	0.00
<i>P</i>	.82	.52	.14	.15	.41	.09	.49	1.00
O <sub>3</sub> ( <i>t</i> )	0.07	-0.03	0.12*	0.14**	-0.01	-0.03	0.07	0.07
<i>P</i>	.16	.61	.01	.00	.77	.59	.15	.15
PM10 ( <i>t</i> )	0.00	-0.08	-0.05	0.00	0.07	0.15**	-0.02	0.02
<i>P</i>	.98	.11	.36	.99	.17	.00	.67	.77
PM2.5 ( <i>t</i> )	0.08	-0.10*	0.03	0.09	0.01	0.16**	0.00	0.05
<i>P</i>	.12	.04	.57	.09	.85	.00	.97	.30
SO <sub>2</sub> ( <i>t</i> )	-0.05	-0.06	-0.07	-0.05	0.00	0.08	-0.08	-0.01
<i>P</i>	.33	.28	.19	.30	.95	.12	.11	.86

Values are expressed as the unstandardized coefficient  $\beta$  and 95% confidence intervals. Values were adjusted for age and sex. Abbreviations are the same as in Table 1.

\**P* < .05

\*\**P* < .01.

#### 4. Discussion

This study revealed significant correlations between NMHCs and skin texture, pore size, and brown spots. O<sub>3</sub> also was significantly correlated with texture and pore size; PM<sub>2.5</sub> and PM<sub>10</sub>

were correlated with brown spots. In addition, in age group  $\geq 45$  years, the formation of UV spots was correlated with CO, NMHC, NO<sub>2</sub>, and PM<sub>10</sub>. The formation of brown spots was also found to be significantly negatively associated with CO, NMHC, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, and SO<sub>2</sub>. Among all skin

characteristics, only brown spot score was correlated with PM<sub>10</sub> in the top 10% of patients.

### 5. Ozone (O<sub>3</sub>)

Although it protects the Earth from UV radiation in the stratosphere, O<sub>3</sub> in the troposphere exerts adverse effects on human skin, such as biomolecule oxidation and production of ROS, which lead to skin barrier damage, collagen loss, and cytotoxicity.<sup>[2,5,7,9,10]</sup> Although long-term O<sub>3</sub> exposure can have adverse effect on the skin, short-term exposures can be beneficial.<sup>[9,11,12]</sup> O<sub>3</sub> is used in skin therapy to increase oxygenation and accelerate wound healing.<sup>[11]</sup>

He et al conducted a study in 2006 on 19 Caucasian women aged between 18 and 55 years and reported a positive correlation between O<sub>3</sub> and ROS.<sup>[13]</sup> ROS causes cell stress, which leads to the disruption of the skin barrier, thus resulting in skin aging.<sup>[1,4,5]</sup> Fuks et al in 2019 also reported a positive correlative relationship between O<sub>3</sub> exposure level and coarse wrinkles on the forehead.<sup>[10]</sup> Xu et al<sup>[14]</sup> conducted a study on an Asian population in 2011, collecting data of patients visiting emergency room for skin problems. The authors observed a positive correlation between O<sub>3</sub> level and red areas on patients' skin, such as in urticaria, eczema, rash, and contact dermatitis.<sup>[14]</sup>

In our study, O<sub>3</sub> level had a negative correlation with skin texture and pore size; in other words, the higher the ozone exposure, the better the skin condition. Previous studies that have described a detrimental effect ozone exposure on the skin involved an ozone concentration at least three times higher than that documented in our study. Our study result showed a possible mechanism that low exposure to ozone (28.84 µg/m<sup>3</sup>) could activate immunoregulatory and antioxidant mechanism, which in turn improved skin condition. Future molecular study is warranted to prove this hypothesis.

### 6. PM<sub>2.5</sub> and PM<sub>10</sub>

Particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) has been noted to cause cancer as well as respiratory and cardiovascular problems.<sup>[2,15,16]</sup> The World Health Organization (WHO) air quality guidelines state that reducing particulate matter (PM<sub>2.5</sub>) from 35 µm to 10 µm could reduce air pollution-related deaths in developing countries by 15%.<sup>[17]</sup> More epidemiological studies are increasingly highlighting the adverse effects of particulate matter on skin aging.<sup>[2,18]</sup> Particulate matter (PM<sub>2.5</sub>) is sufficiently small to be absorbed by the lungs and enter systemic circulation, from where it can cause damage to the skin barrier.<sup>[1,4,16,18,19]</sup> Once particulate matter accumulates in the dermis, the biotransformation of polycyclic aromatic hydrocarbons (PAHs) within the particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) induces production of wrinkles and pigmented spots.<sup>[4,5,18]</sup>

Vierkotter et al conducted the first study (SALIA) to explore the clinical signs of skin aging among Caucasian women and reported that an increased exposure to PM<sub>2.5</sub> was positively correlated with the frequency of lentigines and wrinkles.<sup>[18]</sup> Furthermore, several studies examining the correlation between skin aging and particulate matter in Asian populations have demonstrated a direct association between skin aging and indoor PM<sub>2.5</sub> pollution from cooking.<sup>[6,15]</sup> Li et al in 2015 reported that indoor cooking smoke increased senile spots on the cheeks and back of the hands in two groups of 30- to 90-year-old women in China.<sup>[6]</sup> Another study by Peng et al in 2016 linked senile lentigines to air pollution in 400 Chinese women aged between 40 and 90 years old.<sup>[19]</sup> Ding et al in 2017 investigated the relationship between skin characteristics of 1877 families and 30 PM<sub>2.5</sub> values; their results revealed that PM<sub>2.5</sub> was positively related to spots on the forehead and wrinkles on the upper lip.<sup>[15]</sup> A

**Table 3** Multivariable linear regression analysis of the association between skin characteristics and air pollutants in the age cohort of ≥45 years (n = 182).

Air pollutants	Spots		Wrinkles		Textures		Pores		UV spots		Brown spots		Red area		Porphyrin	
	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P	β (95% CI) <sup>a</sup>	P
CO	3.02 (-18.81,24.84)	.79	-11.34 (-32.63,9.95)	.30	-9.02 (-27.78,9.75)	.34	-11.01 (-26.9,4.88)	.17	24.35 (2.54,46.16)	.03*	26.81 (3.27,50.36)	.03*	8.41 (-8.80,25.62)	.34	5.35 (-19.13,29.83)	.67
NMHC	-7.61 (-43.73,28.51)	.68	-20.82 (-56.03,14.4)	.25	-23.12 (-54.08,7.83)	.14	-22.63 (-48.86,3.6)	.09	37.81 (1.64,73.98)	.04*	51.25 (12.45,90.05)	.01*	7.47 (-21.07,36.01)	.61	7.07 (-33.46,47.60)	.73
NO	-0.25 (-1.61,1.11)	.72	-0.28 (-1.61,1.05)	.68	-0.58 (-1.75,0.59)	.33	-0.82 (-1.81,0.16)	.10	0.19 (-1.19,1.57)	.78	1.04 (-0.44,2.53)	.17	-0.28 (-1.36,0.79)	.61	-0.34 (-1.87,1.18)	.68
NO <sub>2</sub>	-0.10 (-0.87,0.66)	.79	-0.28 (-1.02,0.47)	.47	-0.48 (-1.13,0.18)	.15	-0.50 (-1.05,0.06)	.08	0.69 (-0.08,1.46)	.08	0.99 (0.17,1.82)	.02*	-0.04 (-0.64,0.57)	.90	0.07 (-0.79,0.92)	.88
NO <sub>x</sub>	-0.08 (-0.59,0.42)	.75	-0.16 (-0.65,0.34)	.53	-0.29 (-0.72,0.14)	.19	-0.33 (-0.7,0.04)	.08	0.32 (-0.19,0.83)	.21	0.57 (0.02,1.12)	.04*	-0.06 (-0.46,0.34)	.78	-0.02 (-0.58,0.55)	.95
O <sub>3</sub>	0.64 (-0.39,1.66)	.22	-0.04 (-1.06,0.98)	.94	0.96 (0.07,1.84)	.03*	0.85 (0.10,1.60)	.03*	-0.45 (-1.50,0.60)	.40	-0.95 (-2.08,0.17)	.10	0.25 (-0.58,1.07)	.56	0.60 (-0.56,1.76)	.31
PM10	-0.10 (-0.54,0.34)	.66	-0.37 (-0.79,0.06)	.10	-0.36 (-0.74,0.01)	.06	-0.13 (-0.45,0.19)	.42	0.63 (0.19,1.06)	.01**	0.84 (0.37,1.30)	.00	0.00 (-0.35,0.35)	.99	0.20 (-0.29,0.69)	.42
PM2.5	0.10 (-0.63,0.83)	.78	-0.50 (-1.21,0.21)	.17	-0.15 (-0.78,0.48)	.64	0.12 (-0.42,0.65)	.67	0.47 (-0.26,1.20)	.21	0.95 (0.17,1.73)	.02*	-0.13 (-0.71,0.44)	.65	0.60 (-0.22,1.41)	.15
SO <sub>2</sub>	-1.54 (-3.41,0.34)	.11	-1.01 (-2.86,0.83)	.28	-1.54 (-3.16,0.07)	.06	-0.97 (-2.35,0.40)	.16	0.57 (-1.34,2.49)	.56	2.18 (0.14,4.23)	.04*	-1.39 (-2.88,0.09)	.07	0.62 (-1.51,2.74)	.57

Abbreviations are the same as in Table 1.

**Table 4**  
**Association of air pollutants with skin characteristics of the top 10% and bottom 10% of patients.**

	Skin condition							
	Spots	Wrinkles	Texture	Pores	UV spots	Brown spots	Red area	Porphyria
lowest 10% (N)	41.00	40.00	41.00	41.00	44.00	40.00	45.00	39.00
Air pollutants								
CO (r)	-0.09	-0.07	0.19	0.21	0.02	0.25	-0.20	0.07
P	.59	.66	.23	.20	.89	.12	.20	.66
NMHC (r)	-0.05	-0.06	0.24	0.20	0.02	0.19	-0.18	0.05
P	.74	.73	.13	.21	.90	.24	.25	.76
NO (r)	-0.09	-0.16	0.23	0.20	-0.02	0.04	-0.11	0.10
P	.59	.32	.15	.22	.89	.79	.49	.53
NO <sub>2</sub> (r)	-0.10	-0.16	0.26	0.14	0.00	0.06	-0.16	0.08
P	.54	.32	.10	.38	.99	.73	.28	.64
NO <sub>x</sub> (r)	-0.10	-0.17	0.26	0.16	-0.01	0.05	-0.15	0.09
P	.55	.31	.11	.32	.96	.75	.34	.59
O <sub>3</sub> (r)	0.10	0.08	-0.06	-0.02	-0.10	-0.09	0.08	-0.25
P	.53	.61	.73	.91	.52	.60	.62	.12
PM10 (r)	-0.02	0.01	0.32*	0.05	0.01	0.30	-0.15	-0.06
P	.92	.94	.04	.73	.93	.06	.32	.73
PM2.5 (r)	-0.07	-0.08	0.24	-0.02	0.00	0.25	-0.21	-0.08
P	.67	.63	.13	.92	.98	.12	.17	.64
SO <sub>2</sub> (r)	-0.04	-0.15	0.33*	0.14	-0.05	-0.06	-0.03	0.00
P	.82	.37	.03	.39	.74	.73	.87	.99
Top 10% (N)	46.00	42.00	51.00	50.00	42.00	44.00	46.00	41.00
Air pollutants								
CO (r)	-0.18	0.23	-0.07	-0.07	-0.05	0.23	-0.06	-
P	.24	.14	.65	.64	.76	.14	.72	-
NMHC (r)	-0.02	0.26	-0.03	0.10	-0.04	0.28	0.00	-
P	.90	.10	.84	.47	.81	.07	.99	-
NO (r)	-0.02	0.21	-0.14	0.07	-0.09	0.14	-0.02	-
P	.90	.19	.32	.64	.56	.36	.90	-
NO <sub>2</sub> (r)	-0.19	0.07	-0.04	0.06	-0.07	0.11	0.05	-
P	.21	.65	.79	.69	.66	.49	.76	-
NO <sub>x</sub> (r)	-0.02	0.21	-0.12	0.11	-0.08	0.12	0.00	-
P	.89	.17	.42	.44	.62	.44	1.00	-
O <sub>3</sub> (r)	-0.15	-0.26	0.21	-0.14	-0.02	-0.10	-0.12	-
P	.32	.10	.14	.34	.91	.52	.42	-
PM10 (r)	0.19	0.24	0.02	0.09	-0.03	0.44**	0.06	-
P	0.20	0.13	0.90	0.54	0.87	0.00	0.67	-
PM2.5 (r)	0.18	-0.14	0.06	0.11	-0.12	0.10	-0.16	-
P	.24	.39	.69	.44	.43	.52	.29	-
SO <sub>2</sub> (r)	0.16	0.21	-0.06	0.25	-0.08	0.21	0.10	-
P	.28	.18	.66	.08	.61	.18	.52	-

Abbreviations are the same as in Table 1.

meta-analysis by Ngoc et al showed that PM<sub>10</sub> ≥ 47.09 µg/m<sup>3</sup> and PM<sub>2.5</sub> ≥ 26.04 µg/m<sup>3</sup> could have adverse effects on human skin.<sup>[20]</sup>

In this study, what similar to the previous studies was that PM<sub>10</sub> and PM<sub>2.5</sub> were also observed to be associated with the formation of brown spots. High PM<sub>2.5</sub> levels were associated with increased wrinkles. In contrast to previous studies, PM<sub>10</sub> and PM<sub>2.5</sub> were negatively correlated with the formation of brown spots. A possible explanation is that the formation of brown spots affected by intrinsic aging outweighed effects of air pollutants.

### 7. Nitrogen oxides (NO, NO<sub>2</sub>, and NO<sub>x</sub>)

The combustion of automobile and industrial fuel constitutes a major source of nitrogen oxide emission.<sup>[1]</sup> Nitrogen oxides can react with radicals and cause oxidative damage to cells, ultimately leading to apoptosis.<sup>[21]</sup> Nitrogen oxides regulate vascular homeostasis, proliferative processes, and immune reactions.<sup>[22]</sup> Hüls et al in 2016 reported a relationship between NO<sub>2</sub> and the frequency of cheek lentigines in two cohorts: Caucasian and Asian.<sup>[23]</sup> Similarly, a Taiwanese study on middle-school students revealed a positive relationship between flexural eczema

and traffic pollutants such as NO<sub>x</sub>.<sup>[1,24]</sup> Another study in 2018 on a German population compared atopic eczema between populations from two different areas.<sup>[25]</sup> The results revealed an association between NO<sub>x</sub> and distance of home from NO<sub>x</sub>-measured road,<sup>[25]</sup> which increased susceptibility to atopic eczema. In several studies, nitrogen oxides were also correlated with oxidative stress, which triggered pigmentation and inflammation in the skin.<sup>[23–25]</sup>

In our study, NO<sub>2</sub> and NO<sub>x</sub> were positively correlated with brown spots in patients 45 years or older, which is consistent with previous studies. This result can be explained by cellular senescence that causes the accumulation of lipofuscin due to oxidative stress from nitrogen oxides.

### 8. Sulfur dioxide (SO<sub>2</sub>)

A common source of SO<sub>2</sub> is industrial fuels such as crude oil and coal. SO<sub>2</sub> has been known to cause respiratory tract maladies such as bronchitis and bronchospasm<sup>[26]</sup>; however, only a few studies have investigated the relationship between SO<sub>2</sub> and skin alterations. Similar to nitrogen oxides, SO<sub>2</sub> is a reactive oxidant that can cause oxidative stress, possibly leading to the disruption of the skin barrier.

Our study showed high SO<sub>2</sub> levels were related to decreased texture score, more red areas, and fewer brown spots in age group >45 years. The occurrence of more red areas and decreased texture score is consistent with the detrimental effects of sulfur dioxide on the skin barrier. The association of sulfur dioxide with fewer brown spots, can be possibly explained that exposure to SO<sub>2</sub> under specific conditions promote lipofuscin degradation. Additional studies are required to further investigate the causality between the effects of SO<sub>2</sub> and skin characteristics.

## 9. Persistent organic pollutants

Persistent organic pollutants (POPs) such as nonmethane hydrocarbons (NMHCs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins, polychlorinated biphenyls (PCBs), and polychlorinated dibenzofurans are air pollutants that permeate the environment.<sup>[5]</sup> PAHs have been linked to DNA damage resulting from the activation of ROS.<sup>[27]</sup> In a 2008 study in which occurrences of black comedones in patients with Yusho disease (n = 1131) who ingested rice oil contaminated with PCBs were analyzed and compared with unaffected controls, the prevalence of black comedones was positively associated with blood POP levels.<sup>[15,7,28]</sup> In our study, NMHCs exhibited a negative correlation with texture score and pore score respectively. We hypothesized that NMHCs would be negatively correlated with skin quality on the basis of the results of the other air pollutants.

## 10. Limitations

Our study had several limitations. First, selection bias may have affected the results. Second, all patients enrolled in our study had dermatological problems, which may have also influenced the results. Third, land-use regression models or satellite data were not available to estimate exposure concentrations measured at the closest monitoring station. Because this study served as a pilot study, we plan to include confounding factors such as personal lifestyle and socioeconomic status in our next study. Future studies on air pollutants in industrial neighborhoods are required to further substantiate the relationships between air pollution and skin aging. Fourth, further study to address dermatological issues by air pollutants in different seasons is warranted. Fifth, molecular study is lack in this study and is suggested to perform in our next study.

## 11. Conclusion

This study analyzed the relationships between air pollutants and eight skin characteristics quantitatively assessed using the VISIA Complexion Analysis System. Air pollutants such as CO, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, and NMHCs had significant negative correlations with skin quality. The novel finding in this study was that O<sub>3</sub>, by contrast, had a significant positive correlation with score of texture and pore size. It raises the possibility that air pollutants may exhibit different relationships with skin characteristics. More studies involving different populations and air pollution levels are warranted to further explore the causality between air pollutants and skin aging.

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## Author contributions

All authors have read and approved the final version of the manuscript.

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