Indoor Air Quality and Cardiovascular Effects in the Taiwanese General Population: Generalized Additive Mixed Models Analysis

Wan-Yu Chuang, Lian-Yu Lin and Kai-Jen Chuang.

Abstract—**While the effects of air pollution exposure on cardiovascular morbidity and mortality are well documented, the underlying mechanisms linking indoor air quality to cardiovascular diseases are largely unknown. In order to investigate changes in blood pressure (BP) and heart rate (HR) associated with changes in exposure to indoor air pollution, we conducted nonlinear time series analysis of BP, HR and indoor air quality from the survey of health and living status of the general population in Taiwan. Associations of daily averaged indoor air pollutants [particulate matter with aerodynamic diameters < 10 μm (PM_{10}), particulate matter with aerodynamic diameters < 2.5 μm ($PM_{2.5}$), total volatile compounds (VOCs) and carbon dioxide (CO_2)] with systolic BP (SBP), diastolic BP (DBP) and HR were explored by applying generalized additive mixed models. After controlling for potential confounders, we observed that increased hourly averaged indoor $PM_{2.5}$ was associated with elevated SBP, DBP and HR. Associations of increased hourly averaged total VOCs with elevated SBP and HR were also observed. We concluded that changes in BP and HR are associated with exposure to indoor air pollutants in the Taiwanese general population.**

Index Terms—**Indoor air pollution, blood pressure, inflammation, generalized additive model, epidemiology.**

I. INTRODUCTION

Epidemiological studies have consistently demonstrated that exposure to ambient air pollution is associated with increased risk of cardiovascular disease [1], [2]. The American Cancer Society cohort study indicated that people residing in high polluted areas with particulate matter with aerodynamic diameters < 2.5 μm ($PM_{2.5}$), compared with those in low polluted areas, were more likely to die of lung cancer and cardiopulmonary diseases [3]. Such epidemiological associations have been partially supported by the association between ambient air pollution, blood pressure (BP) and heart rate (HR) [4], [5], a possible

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pathophysiologic mechanism linking ambient air pollution to increased cardiovascular events listed in the American Heart Association's statement [6].

Ambient air pollution, especially traffic-related pollution can penetrate indoors and may cause adverse effects on cardiovascular system in humans [7]. There are several indoor sources, such as cooking, cleaning, and environmental tobacco smoke [8] may worsen indoor air quality and increase the risk of cardiac events. It has been reported that exposure to indoor air pollution is associated with elevated BP, HR and decreased HR variability among healthy young subjects in panel studies [9], [10]. However, epidemiological study of associations between indoor air pollution and cardiovascular effects in general population is still lacking. The aim of this study is to investigate the association between indoor air pollution exposure and cardiovascular health data in Taiwanese general population by monitoring each voluntary participant's BP, HR and indoor air pollution concentrations in each private home.

II. METHODS

A. Study Participants and Design

The indoor air pollution and cardiovascular health data came from the survey of health and living status of 240 voluntary participants through on campus advertisement in Taipei from 2009 to 2012. Three hundred and twelve people responded to our advertisement, but only 240 people were willing to participate in our study after we explained to them our monitoring protocols (response rate = 77%). The exclusion criteria of participants were as follows: no medication that may affect cardiac rhythm; and no cardiovascular diseases, such as coronary artery disease, arrhythmia, hypertension, diabetes mellitus, and dyslipidemia. The protocol included consecutive 24-hour BP, HR, indoor air pollution and indoor weather data monitoring. A baseline screening questionnaire was administered regarding sex, age, body mass index (BMI), medications, pulmonary and cardiac symptoms, home characteristics, environmental tobacco smoke (ETS) exposure, time-activity patterns. All participants were requested to stay home during the monitoring. The study design was reviewed and approved by the human subjects committees of the St. Mary's Medicine Nursing and Management College. All participants gave written informed consent for participation.

B. Blood Pressure and Heart Rate

Participant's systolic BP (SBP), diastolic BP (DBP) and HR were continuously recorded for 24 hours by using a portable BP monitoring system (DynaPulse model 5000A; Pulse Metric, San Diego, CA). To avoid sleep effects on BP and HR, we used BP and HR measurements when the participants were awake between 7:00 AM and 11:00 PM in our data analysis. Each participant obtained 16 hourly BP and HR measurements for data analysis (3,840 hourly BP and HR measurements for all participants).

C. Indoor Air Pollution and Weather Data

Indoor particulate air pollution were measured by using a portable dust monitor (DUST-check portable dust monitor, model 1.108; Grimm Labortechnik Ltd., Ainring, Germany), which measured and recorded 1-min mass concentrations of particulate matter with aerodynamic diameters < 10 μm (PM_{10}) and $PM_{2.5}$, as well as 1-min temperature and humidity (Temperature and humidity sensor, model 1.153FH, Grimm Labortechnik Ltd., Ainring, Germany). Total VOCs was measured at 1-min interval continuously by using a total VOC monitor (ppbRAE Plus, model PGM-7240; RAE Systems, Inc., San Jose, CA, USA). Indoor carbon dioxide (CO_2) was determined with an electrochemical sensor at 1-min interval (Q-Trak monitor, model 8554, TSI, Inc., Shoreview, MN, USA). After sampling, the raw data for 1-min indoor air pollution and weather measurements were matched with the sampling time of BP and HR monitoring and then computed to 1-hour averages for data analysis.

D. Statistical Analyses

We applied generalized additive mixed models (GAMM) [11] to examine the association of indoor air pollution with BP and HR. The exposure variables were PM10, PM2.5, total VOCs and CO2 on 1-hour average, and the outcome variables were SBP, DBP and HR. Each regression model included fixed effects for sex, age, BMI and air conditioner (On vs. Off) and random effects for the participant identification number. Such mixed-effects models had the advantage of adjusting for invariate variables by fixed-effects models and accounting for individual difference by random-effects models. The final models adjusted for smooth function terms in generalized additive models as fit by penalized cubic regression spline to reflect possible nonlinear effects of continuous covariates, including monitoring date, hour, hourly temperature and humidity. All statistical analyses were performed using R Statistical Software, version 2.14.0. [12] Estimates of the effects of air pollutants were scaled to interquartile ranges (IQRs), the differences between the 25th and the 75th percentiles.

III. RESULTS

The age range of the 240 participants varied widely (20 to 65 years); 46% of the participants were male; none of the participants had ETS exposure (Table 1). Median hourly blood pressure was 134/86 mmHg, with a median HR of 81 beats/minute (Table 2). Indoor air pollution, temperature and humidity measurements are shown in Table 3. The variation

TABLE I
BASIC CHARACTERISTICS OF 240 VOLUNTARY PARTICIPANTS

Variables	
Sex, no (%)	
Female	130 (54.2)
Male	110 (45.8)
Age, years	
Mean ± SD	48.2±7.2
Range	20-65
Body mass index, kg/m^2	
Mean ± SD	23.9±1.1
Range	18.1-25.4
Smoking, no (%)	
No	240 (100)
Yes	0 (0)
Drinking, no (%)	
No	210 (87.5)
Yes	30 (12.5)
Air conditioner, no (%)	
Off	115 (47.9)
On	125 (52.1)

of indoor air pollutants was small during the study period. The indoor weather condition was pleasant with a temperature range of 18.2°C to 24.3°C and a relative humidity range of 68% to 76% during monitoring.

TABLE II
SUMMARY STATISTICS OF HOURLY BLOOD PRESSURE AND HEART RATE

	N	Mean ± SD	Range
SBP, mmHg	3840	134.1±7.4	76.2
DBP, mmHg	3840	86.2±2.5	67.5
HR, beats/minute	3840	81.4±1.6	54.0

TABLE III
SUMMARY STATISTICS OF HOURLY INDOOR AIR POLLUTION AND WEATHER DATA

	Mean ± SD	N	Range	Interquartile range
PM_{10}, μg/m^3	47.9 ± 11.4	3,840	12.0-89.2	23.5
$PM_{2.5}$, μg/m^3	23.8 ± 5.2	3,840	6.5-42.3	12.4
Total VOCs, ppb	75.5 ± 24.9	3,840	119.0-195.2	47.8
CO_2, ppm	126.0 ± 59.0	3,840	25.0-300.0	77.2
Temperature, ℃	22.3 ± 1.1	3,840	18.2-24.3	--
Relative humidity, %	71.5 ± 1.2	3,840	68.0-76.0	--

Table 4 shows increases in BP and HR for IQR increases in indoor air pollution on 1-hour average, as estimated using single-pollutant generalized additive mixed models. We observed associations of SBP, DBP and HR with increased PM2.5 and total VOCs on 1-hour average after adjustment for sex, age, BMI and air conditioner, and smooth functions of monitoring date, hour, hourly temperature and humidity. We further considered two-pollutant generalized additive mixed models for PM2.5 and total VOCs. The results showed that PM2.5 remained the strongest association with SBP, DBP and HR among PM2.5 and total VOCs after controlling other pollutants in two-pollutant models. For an IQR increase in PM2.5, we found 8.4-mmHg [95% confidence interval (CI), 1.1-15.7], 5.3-mmHg [95% confidence interval (CI), 1.2-9.4] and 1.3 beats/minute [95% confidence interval (CI), 0.1-1.4] increases in SBP, DBP and HR, respectively after controlling

total VOCs.

As expected, elevation in hourly temperature and relatively humidity were associated with increases in SBP,

TABLE IV

CHANGES (95% CI) IN BLOOD PRESSURE AND HEART RATE FOR INTERQUARTILE RANGE INCREASES IN HOURLY INDOOR AIR POLLUTION ESTIMATED BY SINGLE-POLLUTANT GENERALIZED ADDITIVE MIXED EFFECTS MODELS.

	SBP (mmHg)	DBP (mmHg)	HR (beats/minute)
PM_{10} ($\mu g/m^3$)	3.3 (-0.1, 3.4) †	-0.7 (-1.7, 0.3)	1.2 (-3.8, 6.2)
$PM_{2.5}$ ($\mu g/m^3$)	5.2 (1.6, 8.8) *	3.9 (1.4, .6.4) *	1.8 (0.3, 3.3) *
Total VOCs (ppb)	1.5 (1.0, 2.0) *	1.2 (-0.1, 1.3) †	0.7 (0.1, 1.3) *
CO_2 (ppm)	1.40 (-5.9, 8.7)	2.3 (-10.6, 15.2)	0.5 (-6.8, 7.8)

† $P < 0.10$.

* $P < 0.05$.

§ All models adjusting for sex, age, BMI and air conditioner, and smooth functions of monitoring date, hour, hourly temperature and humidity.

DBP and HR. No significant association of BP and HR was observed with PM_{10}, and CO_2.

IV. DISCUSSION

We found that short-term exposure to indoor $PM_{2.5}$ and total VOCs was associated with high BP and elevated HR, representing increased risk of cardiovascular disease [13] in the Taiwanese general population. Such findings provide an epidemiological evidence of a link between high BP and elevated HR to indoor air pollution exposure and support the hypothesized mechanisms of ambient air pollution effects on cardiovascular system through alterations in vascular tone [6]. High BP and HR reflect a systemic increase in vascular tone, with its adverse implications for the increased risk for cardiovascular disease [14]. It has been reported that exposure to ambient PM_{10} was associated with elevated SBP and DBP among subjects with chronic obstructive pulmonary disease [15]. A chamber study of healthy adults reported increased DBP in response to controlled exposure to $PM_{2.5}$ [16]. Our panel study of young adults demonstrated increased SBP, DBP and HR in response to indoor exposure to PM_{10} and $PM_{2.5}$ [9]. Another panel study of young adults showed decreased HR variability in response to indoor exposure to total VOCs [10]. These studies highlight the importance of altering vascular tone in the pathophysiologic pathways underlying adverse cardiovascular effects of air pollution exposure.

Modulation of the autonomic function plays an important role in alteration of BP and HR [17]. Our findings related to indoor air pollution exposure on BP and HR in this study suggests that indoor air pollution can have adverse effects on autonomous nervous system in human subjects. Previous study has also shown that vascular endothelial perturbation [18] altered sympathetic nerve activity and blood pressure [19] after air pollution exposures in human subjects. Taken together, we believe indoor air pollution can indirectly result in BP and HR changes after indoor air exposure. However, the association of indoor air pollution on increased BP and HR found in the study could be confounded by unavailability of indoor exposure data for other air pollutants, such as ozone, sulfur dioxide, and particle compositions, such as elemental contents, carbon contents, or soluble ions. As these unmeasured air pollutants are usually correlated with indoor $PM_{2.5}$ and total VOCs, the outcomes of this study may be bias [20]. Moreover, it is still unclear whether short-term and small fluctuations of BP and HR are associated with higher risks of cardiovascular diseases clinically. Further studies are needed to investigate whether the effects of indoor air pollution on BP and HR fluctuations observed in this panel study will have meaningful implications of cardiovascular diseases clinically in the Taiwanese general population.

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