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Association of size-fractionated indoor particulate matter and black carbon with heart rate variability in healthy elderly women in Beijing

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Abstract

Associations between size-fractionated indoor particulate matter (PM) and black carbon (BC) and heart rate variability (HRV) and heart rate (HR) in elderly women remain unclear. Twenty-nine healthy elderly women were measured for 24-hour HRV/HR indices. Real-time size-fractionated indoor PM and BC were monitored on the same day and on the preceding day. Mixed-effects models were applied to investigate the associations between pollutants and HRV/HR indices. Increases in size-fractionated indoor PM were significantly associated with declines in power in the high frequency band (HF), power in the low frequency band (LF) and standard deviation of all NN intervals (SDNN). The largest decline in HF was 19% at 5-min moving average for an interquartile range (IQR) increase (24 μg/m^3) in $PM_{0.5}$. The results showed that smaller particles could lead to greater reductions in HRV indices. The reported associations were modified by body mass index (BMI): declines in HF at 5-min average for an IQR increase in $PM_{0.5}$ were 34.5% and 1.0% for overweight (BMI $\geq$ 25 kg/m^2) and normal-weight (BMI < 25 kg/m^2) participants, respectively. Moreover, negative associations between BC and HRV indices were found to be significant in

overweight participants. Increases in size-fractionated indoor PM and BC were associated with compromised cardiac autonomic function in healthy elderly women, especially overweight ones.

Keywords: indoor exposure, size-fractionated particulate matter, black carbon, heart rate variability, cardiac autonomic function, elderly women

Practical Implications: This study found associations between exposure to indoor PM and black carbon and decreased heart rate variability (HRV) in healthy elderly women. Overweight participants showed greater reduction in HRV than normal-weight ones. In addition, particles of smaller size had greater effect on HRV indices. The results contribute further evidence that effective measures should be taken to protect people from indoor particulate pollution.

1. Introduction

Cardiovascular disease is a leading cause of mortality all over the world and accounted for more than one third of total deaths in China in 2012.[1, 2] Multiple epidemiologic studies have suggested that exposure to particulate air pollution is associated with elevated risks in cardiovascular morbidity and mortality.[3-5] It has been shown that the elderly may be especially vulnerable to the impact of air pollution.[6, 7] Exposure to ambient air pollution could result in increased morbidity and mortality from cardiovascular and respiratory diseases in the elderly.[8, 9] Furthermore, studies have suggested that exposure to ambient particulate air pollution is related to compromised cardiac autonomic function through alterations in HRV indices in the elderly.[10, 11] It has been suggested that the malfunction of the cardiac autonomic system, as reflected by a decrease in HRV, could lead to higher cardiovascular risks.[12] However, the potential effect of indoor air pollution on cardiac autonomic function in the elderly has not been adequately investigated. The number of elderly women in China exceeded 100 million in 2010, which constituted more than 10% of the whole population.[13] An aging population is becoming an increasing relevant concern for public health in China, and indeed across most of the world.

The adverse health effects of indoor PM may be equivalent to, or more serious than, that of ambient PM.[14, 15] In most societies, and especially among urban populations, people spend the majority of their time indoors, and elderly people in particular are likely to spend more time on average than others within their houses.[16, 17] Elderly women are also more likely to stay indoors for high proportions owing to the prevalence of the role of housewife in many societies.[18] Previous studies have reported that indoor air pollution is associated with compromised health status, with alterations in respiratory function and diastolic function among elderly women.[19, 20] In addition, many household activities, such as cleaning, can elevate levels of indoor air pollution.[21] Huang et al. showed that exposure to household PM was associated with detrimental decreases in HRV indices, especially during stir-frying and cleaning activities.[18] Therefore, it is important to explore the association between indoor air pollution and cardiac autonomic function in elderly women, who are potentially susceptible individuals with higher than average probabilities of exposures to indoor air pollution.

Previous research has considered the health effects of PM of different sizes.[22, 23] Fine particles may have greater health effects since these particles can penetrate deeper into the respiratory tract, and potentially into blood vessels.[24] Finer particles have larger specific surface areas for contacting lung surface and organ tissues.[25] Black carbon (BC) from combustion sources is also considered an important indoor pollutant affecting people's health,[26] and a World Health Organization report suggests that BC might be a particularly toxic component of PM.[27] Animal experiments and epidemiological studies have demonstrated that BC levels are associated with changes in cardiac autonomic function by altering HRV indices.[28-31] However, outdoor ambient PM is the focus of most research, and frequently only a single-size range of PM is considered. This study aims to investigate the association between exposure to size-fractionated indoor PM and BC and cardiac autonomic function in a group of healthy elderly women.

2. Materials and methods

2.1 Study design and participants

From November 2015 to May 2016, a group of 29 healthy elderly women (age > 50 y) was recruited to participate in a repeated-measure study. The participants were selected using the following inclusion criteria: (1) suffering from no chronic diseases such as diabetes, hypertension and other common diseases; (2) receiving no medication or drugs that could directly influence HRV; and (3) not smokers or passive smokers, and having no occupational exposure to smoke, dust or other fumes. The study protocol was approved by the Institutional Review Board of Peking University Health Science Center. All the participants gave their informed consent before the study.

2.2 Pollution exposure measurements

Exposure measurement equipment was installed in a position in the residence that participants occupied most commonly. Measurement of real-time indoor air pollutants, including size-fractionated indoor PM and BC, and hygrothermal parameters, started 24 hours prior to health measurements and lasted for a total of 48 hours. To synchronize with 5-min HRV/HR segments, all the pollution data were aggregated to 5-min average values. Size-fractionated PM including $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5, and PM_{10} (PM mass concentrations for particles smaller than or equal to 0.5 μm, 1 μm, 2.5 μm, 5 μm, 10 μm in aerodynamic diameter, respectively) was measured by a real-time particulate counter (Model Handheld PC3016; GrayWolf Inc., USA). A portable microaethalometer (microAeth Model AE51; Magee Scientific, Berkeley, CA, USA) was used to monitor the concentration of BC. Real-time temperature (Temp) and relative humidity (RH) were measured by a Temp/RH meter (Model WSZY-1B; Tianjianhuayi Inc., Beijing, CHINA). During monitoring, the participants were instructed to keep indoor spaces connected between different rooms (except the kitchen) so that the monitoring data were indicative of participant exposures even when they were not present in the same rooms with installed devices.

2.3 Heart rate variability/Heart rate measurements

HRV/HR measurements were conducted using 12-channel Holter recorders (model MGY-H12; DM Software Inc., USA), which were positioned on the participants by trained investigators based on a standard protocol.[32] The participants were instructed to avoid food or drink (e.g. coffee, wine, tea) that may affect HR and avoid high intensity exercise on the day of and the day before the health measurement. All participants were measured for ambulatory 24-hour ECG on the same weekday during the study period. The participants were visited at their homes between 0800-1200 hours on Wednesdays. Participants were instructed to wear the recorders for 24 hours, during which they were told to follow their regular routines and record their activities in the formatted diaries.

The PC-based software for the Holter recorder (Holter System, version 12.net; DM Software Inc., USA) was used to process and calculate the 24-h HRV/HR data. The HRV analysis was performed in both time and frequency domains. The time-domain parameters include: SDNN, standard deviation of all NN intervals; SDANN, standard deviation of the averages of NN intervals in all 5-min segments of the entire recording; rMSSD, root mean square of successive differences between adjacent NN intervals; and pNN50, percentage of number of NN intervals with a difference ≥ 50 ms. The frequency-domain parameters include: TP, total power, the area under the spectral curve from 0.01 to 0.4 Hz; LF, power in the low frequency band, i.e., 0.04-0.15 Hz; HF, power in the high frequency band, i.e., 0.15-0.4 Hz; and LF/HF ratio, low to high frequency power ratio averaged. All indices were processed as 5-min segments in accordance with exposure data.

2.4 Statistical Analysis

We used Spearman correlations for size-fractionated PM, BC, and hygrothermal data to evaluate the relationship among these variables. Linear mixed-effects regression models with a random-term effect for participant were applied to explore the association between air pollution exposures and HRV/HR indices. Before analysis, observations were deleted if they had missing or abnormal data as the result of malfunction in study instruments, and HRV/HR indices were $\log_{10}$-transformed to improve the normality and stabilize the variance due to skewed distributions. We controlled for personal characteristics, including age and BMI, and long-term time trend, including day-of-measurement and squared day-of-measurement,[33] as fixed-effect terms. Day-of-measurement means the count of the day that the measurement was conducted over the whole study course. For instance, we coded “1” for the first day of the study course and “10” for the 10^{th} day of the study course. Squared day-of-measurement means the squared value of day-of-measurement. In addition, other potential confounding variables were included as fixed-effect terms such as hour of day, day of week, temperature, and RH.

We fitted single-pollutant models to investigate the associations between exposures to different pollutants and HRV/HR indices. Several different moving averages (5-min, 30-min, 1-, 4-, 8-, 12-, 24-hour) for size-fractionated PM and BC were calculated to examine the time-lagged effects of the pollutant exposure. Also, the same model was applied to analyze the effect of those pollutants on HRV/HR indices among participants stratified by BMI level (normal weight: BMI < 25 kg/m^2; overweight: BMI ≥ 25 kg/m^2).[34] We fitted the mix-effect model as follows:

$$Y_{it}=b_0+u_i+b_1x_1+\ldots+b_px_p+\beta \text{Pollutant}+\varepsilon_{it} \quad (1)$$

where Y_{it} is the 5-min logarithm of HRV/HR indices in subject i at time t, b_0 is the overall intercept, u_i is the specific random intercept for the subject i, x_1-x_p are covariates, b_1-b_p are regression coefficients for x_1-x_p, β is the regression coefficient for the pollutant, and ε_{it} is the error for subject i at time t.

Considering potential interactions, we also assessed models with multiplicative terms for the pollutants with each confounder at the moving average that showed greatest declines in HRV/HR indices. The results show only significant interactions between BMI and air pollutants in this study; thus, we stratified the participants into normal-weight group (BMI < 25 kg/m^2) and overweight group (BMI ≥ 25 kg/m^2) and further analyzed the associations between pollution exposure and health indices in the two groups.

To adjust for autocorrelations among the measurements, we used a first-order autoregressive covariance structure in the model analysis. We estimated the percentage changes with 95% confidence intervals (CI) in HRV/HR indices per interquartile range (IQR) increase in exposure moving average of each pollutant, calculated as $[10^{(\beta\times IQR)}-1]\times 100\%$, with 95% CI $\{10^{[IQR\times(\beta\pm 1.96\times SE)]}-1\}\times 100\%$, where β and SE were the estimated regression coefficients and its standard error, respectively.[35] SAS software for Windows (version 9.2; SAS Institute Inc., Cary. NC, USA) was used to conduct all analyses and the level of significance was defined as $P < 0.05$ (two-sided).

3. Results

3.1 Descriptive statistics

A total of 29 elderly women participating in the study all completed 24-hour HRV/HR measurements successfully. The baseline characteristics of those participants are presented in Table 1. The age of the participants ranged from 51 to 79 years, with an average of 68.2 (±7.3) years. The BMI of the participants ranged from 18.8 to 33.5 kg/m^2, with an average of 25.2 (±3.5) kg/m^2. As reported in their daily diaries, all participants spent more than 90% of their time indoors each day; and all the households were equipped with central heating system, used natural gas as the energy for cooking, and did not use an air conditioner during the study period.

Table 2 shows the descriptive statistics for concentrations of BC, size-fractionated PM and hygrothermal data. The mean concentrations of indoor BC, $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5, PM_{10} were 2.7 (±2.8) μg/m^3, 17.6 (±15.0) μg/m^3, 38.0 (±38.0) μg/m^3, 55.7 (±55.4) μg/m^3, 89.8 (±77.7) μg/m^3, 134

(±130) μg/m^3, respectively. Size-fractionated PM and BC were highly correlated with each other, with Spearman correlation coefficients ranging from 0.71 to 0.99 (see Supplemental Material). Furthermore, air pollutants were also moderately correlated with hygrothermal parameters (See Supplement Material).

Table 3 shows the distribution of raw 5-min HRV/HR indices for all participants. The mean (standard deviation) levels of HF, LF and SDNN were 186 (±248) ms^2, 267 (±295) ms^2 and 44.5 (±23.9) ms, respectively.

3.2 Estimated PM and BC effect

HF, LF and SDNN showed different estimated percent changes with IQR increases in size-fractionated indoor PM and BC over different moving average periods (Figure 1). Statistically significant declines in HF and LF were found at 5-min, 30-min, 1-hour moving averages for size-fractionated PM (Figure 1A-B). Declines found in SDNN were significant only at 1-hour moving average for size-fractionated PM (Figure 1C). The largest decline in HF was 19.6% (95% CI: -27.9%, -10.2%) at 5-min moving average for an IQR increase (23.8 μg/m^3) in $PM_{0.5}$, and the largest declines in LF and SDNN were 16.2% (95% CI: -22.2%, -9.8%) and 7.6% (95% CI: -11.1%, -4.0%), respectively, at 1-hour moving average for an IQR increase (20.3 μg/m^3) in $PM_{0.5}$ (Figure 1). Similar associations were found between PM of other sizes and HF, LF and SDNN (Figure 1), with smaller particles having greater effects on HF, LF and SDNN. Similar associations were found between size-fractionated PM and TP. Almost all associations between size-fractionated PM and BC with HR and other HRV indices including LF/HF ratio, SDANN, rMSSD and pNN50 were insignificant (See Supplemental Material).

3.3 The effect modification by BMI

The participants were stratified into normal-weight group (BMI < 25 kg/m^2) and overweight group (BMI ≥ 25 kg/m^2). Before conducting the mixed-effect models in two groups, *P* values for interaction effect were calculated in targeted associations and the results all met $P < 0.05$. Figure 2 presents the estimated changes in HF, LF and SDNN per IQR increase in size-fractionated PM in two groups at the moving averages where greatest declines were found over all participants. The results show that exposure to size-fractionated PM was associated with larger reductions in HF, LF and SDNN among overweight participants. Declines in HF at 5-min average for an IQR increase in $PM_{0.5}$ were 34.5% (95% CI: -44.5%, -22.7%) for overweight participants as compared to 1.0% (95% CI: -14.3%, 14.0%) for normal-weight participants (Figure 2A). Decline in LF at 1-hour for an IQR increase in $PM_{0.5}$ was 17.1% (95% CI: -25.0%, -8.4%) for overweight participants, while an insignificant increase in LF was found in normal-weight participants (Figure 2B). Although declines in SDNN at 1-hour average for an IQR increase in $PM_{0.5}$ were similar between normal-weight participants and overweight participants, the estimated association of PM of other sizes in overweight participants were greater than those in normal-weight participants (Figure 2C).

As significant associations were not found between indoor BC and HRV/HR indices in overall participants, we conducted mixed-effect models among normal-weight participants and overweight participants separately. Figure 3 shows the estimated changes in HF, LF and SDNN per IQR increases in BC over different moving averages in the normal-weight group and in the overweight group. In overweight participants, increases in BC were found to be significantly associated with declines in HF, LF and SDNN over several moving averages. Significant declines were found for 5-min to 12-hour moving averages in HF and SDNN, and for 5-min to 4-hour moving averages in LF. The largest declines in HF and SDNN were 30.2% (95% CI: -44.2%, -12.6%) and 23.5% (95% CI: -31.1%, -15.1%), respectively, at 12-hour moving average for an IQR increase (3.2 μg/m^3) in BC, and the largest decline in LF was 20.6% (95% CI: -28.8%, -11.4%) at 1-hour moving average for an IQR increase (2.7 μg/m^3) in BC. In the normal-weight group, associations between BC and these indices were non-significant.

4. Discussion

This study investigated the association between exposure to size-fractioned indoor PM and BC, and the changes in HRV/HR indices in a group of healthy elderly women. The results show that elevated levels of indoor PM were associated with decreased HF, LF and SDNN, the effects of which were most evident within 1 hour. We also evaluated the effect modification by BMI by stratifying the participants into normal-weight group (BMI < 25 kg/m^2) and overweight group (BMI $\geq$ 25 kg/m^2). Decreases in HF, LF and SDNN were found to be greater in overweight participants than in normal-weight participants, suggesting that overweight participants may be more sensitive to indoor PM. Moreover, elevated BC concentrations were reported to be associated with declines in HF, LF and SDNN in overweight participants within 12 hours of exposure.

In this study, real-time monitoring of indoor PM and BC was conducted one day before, and on the day of, HRV/HR measurement inside the participants' residencies, providing a more accurate assessment for participants' personal exposure compared to data from external fixed-site monitoring stations. Levels of indoor PM and BC were relatively high and had wide variation during the study period, allowing us to explore more significant exposure-response relationships.

Among the HRV indices, TP and SDNN are global indices of HRV; HF primarily reflects the parasympathetic activity; and LF reflects both sympathetic and parasympathetic activity. It has been shown that HRV indices decline rapidly in response to PM exposure as a result of decreased parasympathetic input to the heart, which is considered to allow the sympathetic drive to predominate and consequently increase cardiac arrhythmia incidence and cardiovascular risk.[36] Decreases in SDNN, HF, LF could be considered as an important indicator of malfunction of cardiac autonomic control, potentially leading to increased cardiovascular risks.[37] A review also reported that decreased HRV indices preceded the development of cardiovascular risk factors.[12] Although the relevance between reported HRV alterations and cardiovascular risks remains unclear, some studies have suggested that PM exposure is related to changes in cardiac electrophysiology.[3] Similar results were found in a cohort study of 534 elderly subjects, where increased $PM_{2.5}$ was significantly associated with declines in SDNN ($P = 0.04$) and HF ($P = 0.03$).[11] Other epidemiological studies have found similar associations between exposure to ambient PM and reduction in HRV indices among the elderly.[10, 38, 39] However, heterogeneous results were found regarding the association between PM and HRV. Several studies have reported positive associations between PM and HRV indices.[40-42] Our study adds further evidence of potential adverse cardiac effects of size-fractionated PM on elderly healthy women, contributing to insight about the association between particulate air pollution and population health.

Since the elderly women spend most of their time indoors and are involved in most household activities related to air pollutants (e.g. cleaning), it is important to study the effects of indoor air pollutants in this group. Many epidemiological studies have been conducted to explore the health effects of ambient PM, especially $PM_{2.5}$, on different populations, while indoor PM and BC have been less studied. Nevertheless, indoor air pollutants have been suggested to have equal, or even more serious effects, than outdoor PM.[14, 15] Our study focused on the association between indoor air pollutants, including size-fractionated PM and BC, and changes of HRV indices in healthy elderly women to investigate the potential cardiovascular risk brought about by exposure to indoor air pollution. Jia et al. found that a 10 $\mu g/m^3$ increase of indoor $PM_{2.5}$ could lead to increases in HF and LF by 1.3% in the elderly.[40] However, this study included both elderly men and women and was carried out during the 2008 Beijing Olympics, with considerably lower than typical ambient particulate air pollution. Another study conducted among 50 housewives indicated that an IQR increase (16.2-19.8 $\mu g/m^3$) of household $PM_{2.5}$ was associated with decreases in SDNN and rMSSD by 1.2–4.3% and 0.1–3.7%, respectively.[18] Interestingly, the effect was found to increase with household activities such as cleaning.

To our knowledge, our study is the first to investigate the effect of size-fractionated indoor PM on HRV and HR in healthy elderly women. We found that smaller particles were likely to have greater effect on HRV in the elderly women. It might be because smaller particles are more likely to pass through respiratory tract tissues and enter blood vessels; and smaller particles also have larger specific surface area to carry toxic matter into the body.[25] Previous studies support our findings by showing that smaller PM was associated with greater excess risk in cardiovascular health than larger PM.[43-45] Nevertheless, different results were found in other studies, among which one reported that $PM_{2.5-10}$ was associated with larger declines in HF, LF, SDNN than PM_1 and $PM_{1-2.5}$.[46] The heterogeneous findings may result from the differences in concentrations, sources, and constituents of PM.

Previous studies have shown that obesity is a strong modifier for the effect of exposure to PM and BC.[34, 47] In this study, we stratified the analysis by participants' BMI. Overweight participants showed greater declines in SDNN, HF and LF than normal-weight participants for PM and BC. This finding suggests that the overweight group was more susceptible to the effects of indoor PM and BC mediated by both parasympathetic activity and sympathetic activity. Our results are consistent with previous studies in different subgroups. Sun et al. found the greatest decreases in SDNN associated with exposure to BC and PM in the obese subgroup, the second largest in an overweight subgroup and the least in a normal-weight subgroup in subjects with diabetes or impaired glucose tolerance.[34] Chen et al. also provided supporting evidence that subjects with obesity had 2- to 3-fold greater $PM_{2.5}$-mediated HRV reduction in SDNN, rMSSD and HF than non-obese subjects.[47] Other studies have also suggested overweight/obesity could enhance the adverse health effect of PM in different populations with different physiological conditions.[48-50] Our study adds further evidence to the hypothesis that overweight/obese people are under higher cardiovascular risk through exaggerated

HRV alteration to particulate pollution. Therefore, special attention should be paid to the prevention of adverse health effects related to PM and BC exposure among overweight/obese populations.

Although we did not observe significant associations between BC and HRV/HR among overall participants, increases in BC were found to be significantly associated with declines in HF, LF and SDNN in overweight participants. As a product of incomplete combustion, BC is considered as one of the major toxic components in PM.[27] Animal experiments have found that BC exposure could induce significant changes in HRV indices.[28, 31] Epidemiological studies have also found similar results.[29, 30] For instance, Huang et al. found that for every 1 μg/m^3 increase in BC at 1-hour moving average, pNN50 and HF decreased by 1.9% and 2.2%, respectively, and LF/HF ratio increased by 2.9%.[30] Zanobetti et al. also found that exposure to BC was associated with declines in HF in patients with coronary artery disease.[51] Interestingly, we found significant associations between BC and HRV indices in overweight participants, but not in normal-weight participants. These results indicate that indoor BC may be partly responsible for the effects of size-fractionated indoor PM in elderly healthy women. It might suggest that multiple constituents of indoor PM lead to effects to different extent in different subgroups. Considering the effects in different populations could provide further insight for implementing certain measures to control specific sources of pollution.

We also investigated the time-lagged effects of indoor air pollutants over different moving average periods (5-min, 30-min, 1-, 4-, 8-, 12-, 24-hour). We found that higher concentrations of PM were significantly associated with decreased HF and LF at 5-min, 30-min and 1-hour moving averages, but with decreased SDNN only at 1-hour moving average. As for BC, decreases in HRV indices were found over 5-min to 12-h moving averages in overweight participants. Previous studies have examined time-lagged effects of air pollutants over different lag periods with a range from 0 min to 120 hours.[35, 52, 53] There is considerable inconsistency among the findings of these different studies. These studies focused on different populations, whose characteristics and physiological conditions varied from one to another, as well as performing investigations under different pollution scenarios, of which the concentrations, sources, and constituents varied to different extents. Our findings indicated that exposure to size-fractionated indoor PM could lead to acute decreases in SDNN, HF and LF within 1-hour of exposure. Sun et al. reported similar results among subjects with diabetes/impaired glucose tolerance in Shanghai.[34] Further studies are needed to explore the underlying physiological compensatory mechanisms related to these associations.

We note the following limitations. First, we did not monitor indoor gaseous pollutants and indoor noise. However, the levels of gaseous pollutants and noise in residential environments were not likely to be high enough to influence the results substantially in this study. Second, air pollutant monitors were not set at the personal level in this study so that we could not precisely measure the participants' exposure when they were out of home or in their kitchens. A previous study suggested different cooking activities had different effects on blood pressure.[54] Nevertheless, as participants spent more than 90% time indoors, it is unlikely that the reported associations would be altered if the outdoor and kitchen exposures were included. Third, we did not obtain adequate information, such as ventilation habits and cooking, to address indoor and outdoor origins of air pollutants and noise, which needs further exploration. Despite of these limitations, this study could still contribute to the accumulation of evidences on the health effects of indoor particulate pollution.

5. Conclusions

In conclusion, indoor PM and BC may lead to acute health impairment in the cardiovascular system through affecting cardiac autonomic function in healthy elderly women, especially in those that are overweight. In addition, this study provides evidence that PM with smaller size might contribute to greater health effects on populations. Effective measures should be taken to reduce exposures to indoor air pollution, such as operating effective air cleaners to improve the health condition of the population, and especially those at most risk.

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Characteristics	
Number	29
Age, years	
Mean ± SD	68.2 (±7.3)
Median	69
Range	51-79
Body Mass Index, kg/m^2	
Mean ± SD	25.2 ± 3.5
Median	25.4
Range	18.8 - 33.5
Smoking	
No	29

Abbreviation: SD, standard deviation

Table 1 Baseline demographic characteristics for the study participants

Pollutants	N[a]	Mean ± SD	Minimum	25th	Median	75th	Maximum	IQR
Black Carbon, μg/m^3	7309	2.7±2.8	0.1	0.8	1.8	3.7	19.1	2.9
$PM_{0.5}$[b], μg/m^3	5902	17.6±15.0	1.2	4.6	11.5	28.4	52.0	23.8
$PM_{1.0}$, μg/m^3	5902	38.0±38.0	1.9	7.3	21.0	59.5	179	52.2
$PM_{2.5}$, μg/m^3	5902	55.7±55.4	3.6	12.5	31.1	85.6	401	73.1
$PM_{5.0}$, μg/m^3	5902	89.8±77.7	5.5	27.6	64.0	136	1136	109
PM_{10}, μg/m^3	5902	134±130	5.9	46.7	109	178	3052	132
Relative Humidity, %	7141	37±12	11	30	37	44	79	14
Temperature,℃	7141	23.1±2.7	9.7	21.0	22.8	24.8	30.4	3.8

Abbreviation: IQR, interquartile range; SD, standard deviation.

[a] Number of observations corresponding to the simultaneously measured 5-min health outcomes and after excluding all missing values and abnormities. All pollutants and meteorological parameters were calculated in 5-min average.

[b] Although PC3016 can measure PM with an aerodynamic diameter equal to or less than 0.3 μm ($PM_{0.3}$), we did not include this band due to few $PM_{0.3}$ mass concentration values above the detection limit of the instrument.

Table 2 Distribution of indoor exposure variables and meteorological parameters during the study in 2015-2016

Variables	N[a]	Mean ± SD	Median	Range
TP, ms^2	6866	1661±1709	1083	71-10985
LF, ms^2	6942	267±295	173	10.5-2451
HF, ms^2	6954	186±248	95	5.1-1992
LF/HF	6865	16.6±21.7	8.7	0.5-159
SDNN, ms	7336	44.5±23.9	39.0	10.0-189
SDANN, ms	7141	28.3±9.8	29.0	6.0-51.0
rMSSD, ms	7383	30.8±21.6	24.0	6.0-177
pNN50	4978	14.1±15.3	8.0	1.0-88.0
HR, bpm	6882	70.8±13.4	70.0	43.0-128

Abbreviation: SD, standard deviation.

[a] Observation after excluding all missing values and abnormities.

Table 3 Distributions of 5-min health outcomes during the study in 2015-2016

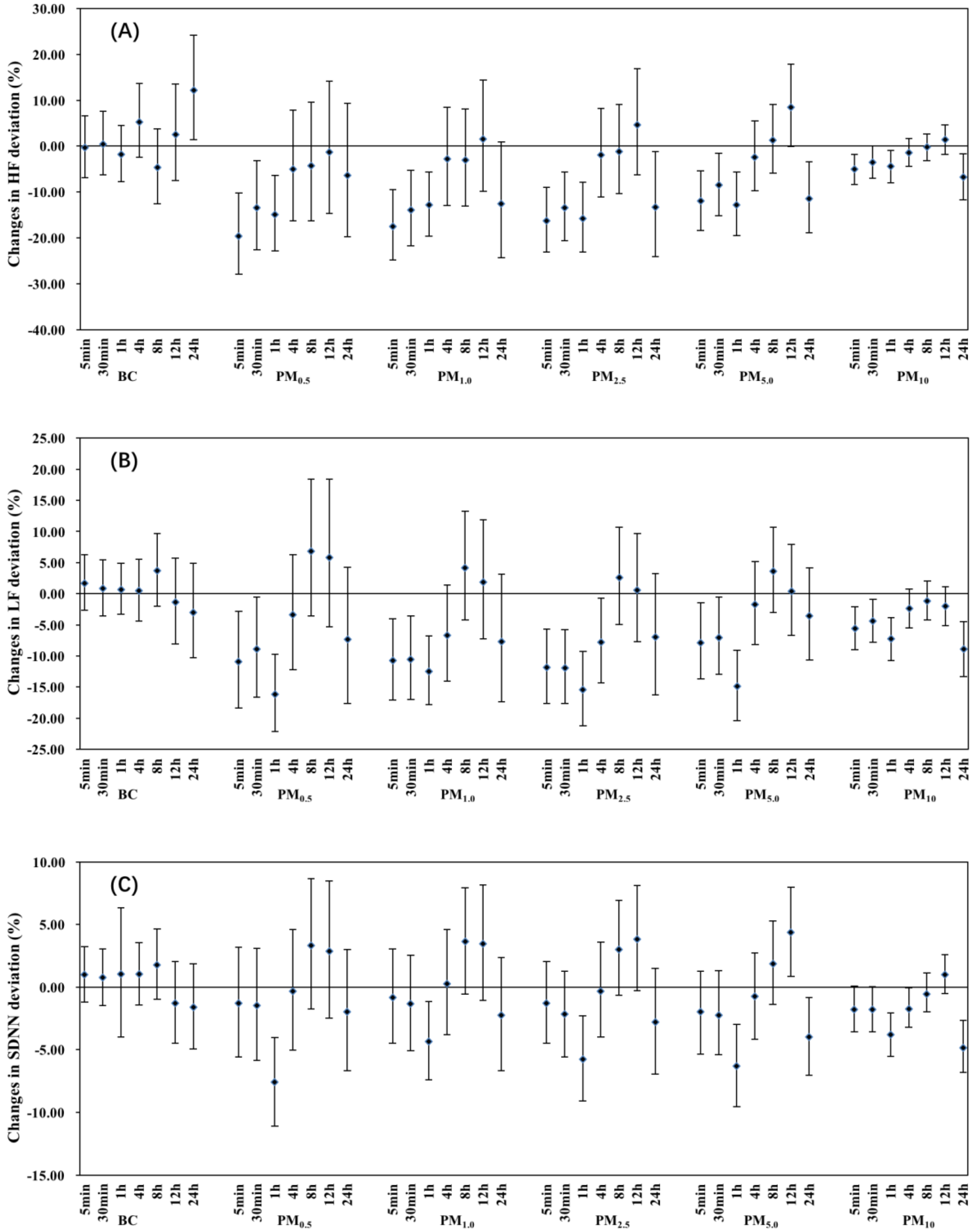

Figure 1 Estimated percent changes with 95% confidence intervals in HF, LF and SDNN per IQR increases in size-fractionated PM and BC over different moving averages. (A) HF; (B) LF; (C) SDNN.

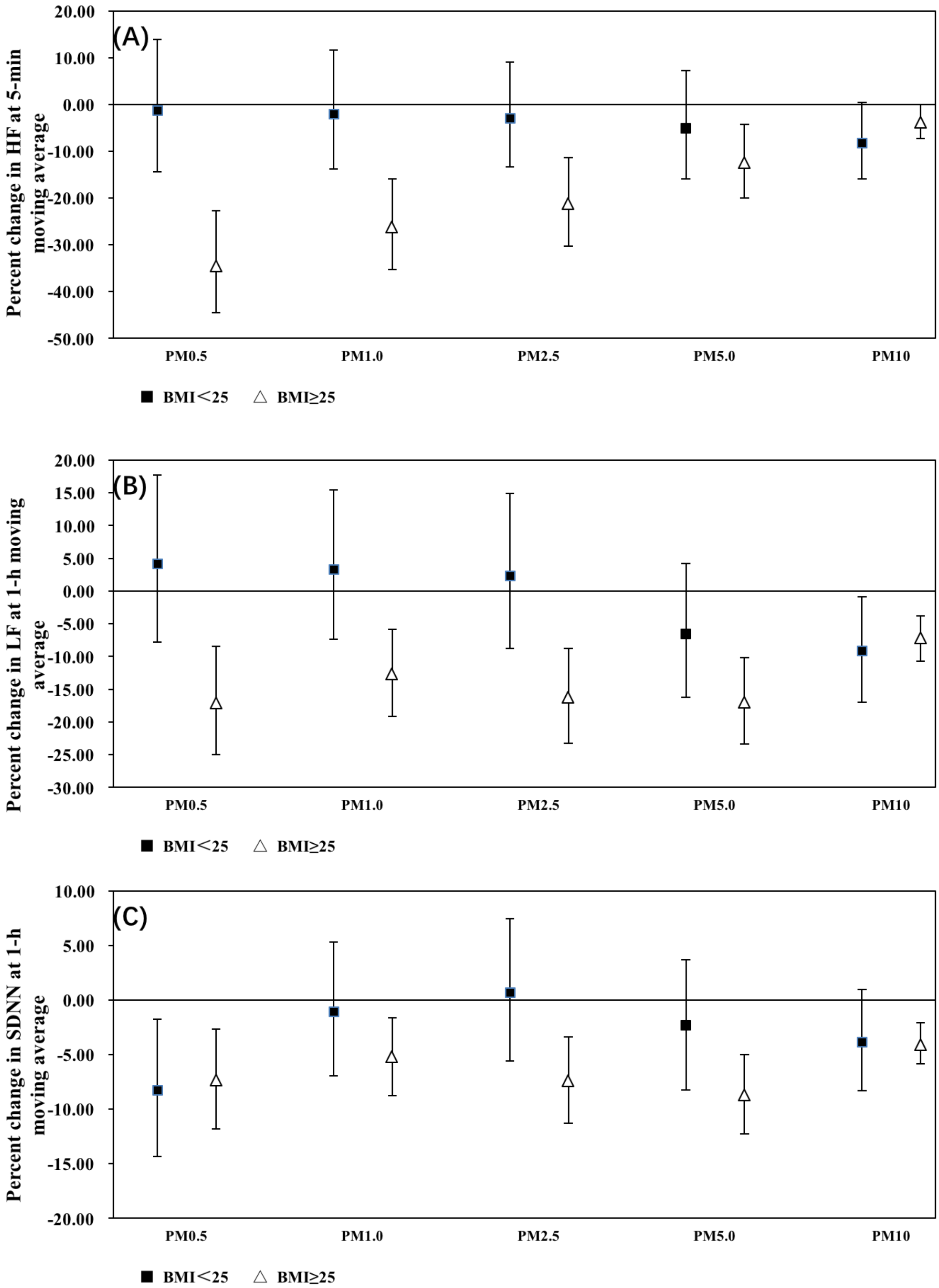

Figure 2 Estimated percent changes with 95% confidence intervals in HF, LF and SDNN per IQR increases in size-fractionated PM and BC at selected moving average in normal-weight (BMI<25) and overweight (BMI≥25) groups. Solid squares: effect estimates for normal-weight participants; vacant triangles: effect estimates for overweight participants. (A) HF; (B) LF; (C) SDNN.

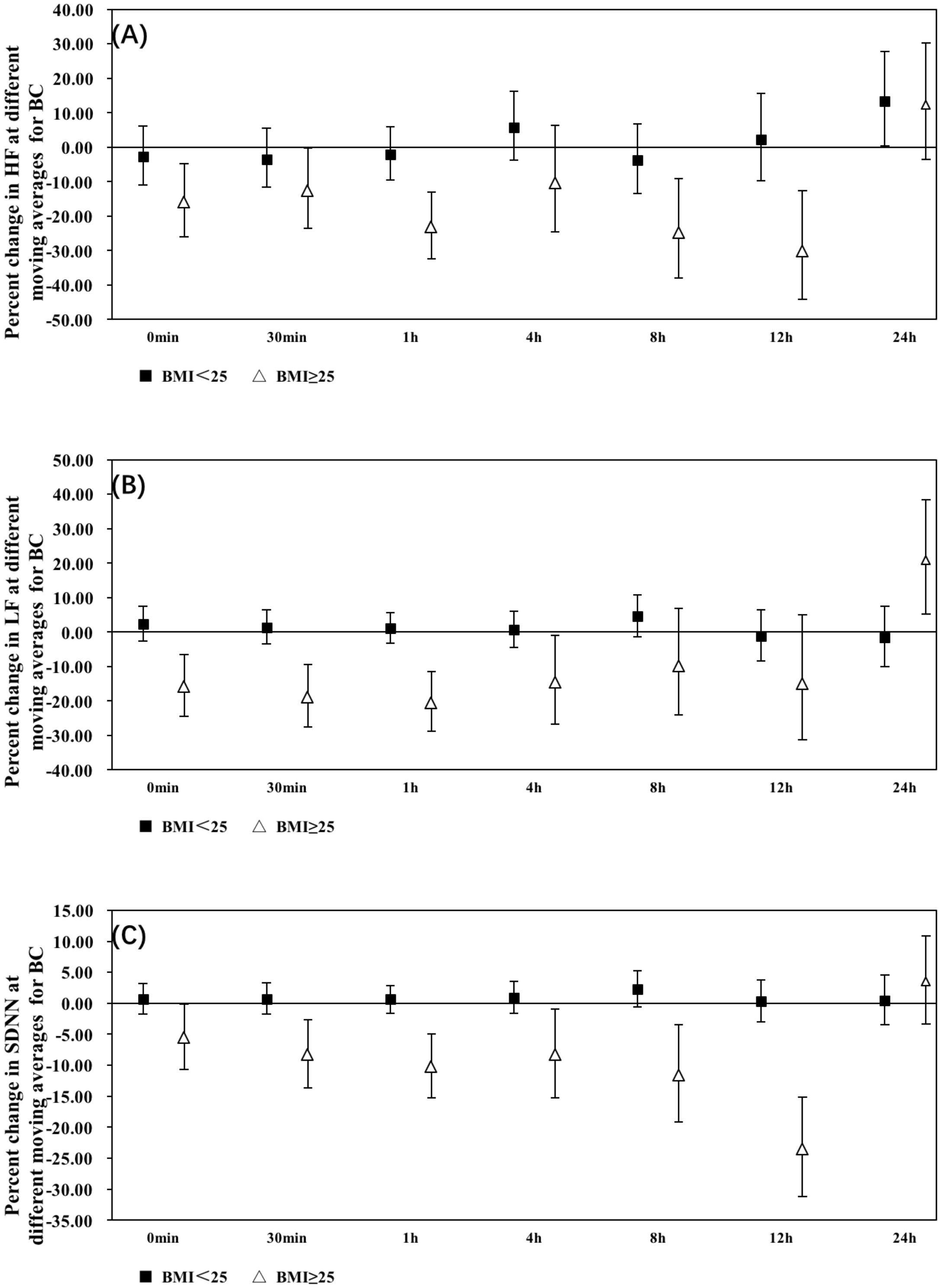

Figure 3 Estimated percent changes with 95% confidence intervals in HF, LF and SDNN per IQR increases in size-fractionated PM and BC at different moving averages in normal-weight (BMI<25) and overweight (BMI≥25) groups. Solid squares: effect estimates for normal-weight participants; vacant triangles: effect estimates for overweight participants. (A) HF; (B) LF; (C) SDNN