Coexistence of PM$_{2.5}$ and low temperature is associated with morning hypertension in hypertensives

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Abstract

We tested the hypothesis that concentration of PM$_{2.5}$ is associated with home BP level. We analyzed home BP data for 91 consecutive days in 40 hypertensives. PM$_{2.5}$ solely was not correlated with home BP levels, but low temperature was associated with a 1.6-fold increased likelihood of morning hypertension ($p<0.001$) under the condition of high PM$_{2.5}$ concentration. In addition, coexistence of low temperature and high PM$_{2.5}$ was associated with a 2.3-fold increased likelihood of morning hypertension ($p<0.001$) compared with high temperature and low PM$_{2.5}$ condition. Environmental and meteorological factors could be important causes of enhanced home BP elevation.

Keywords

Air pollution, home BP, fine particulate matter with a diameter $<2.5 \mu m$, morning hypertension, temperature

Introduction

Air pollution, especially fine particulate matter with a diameter $<2.5 \mu m$ (PM$_{2.5}$) is one of the main environmental problems in modern society. Whole area of Japan, especially western part of Japan is faced with air pollutants transferred from continents in recent years. Because PM$_{2.5}$ can penetrate housing more easily than particulate matter with greater diameters, the concentration of PM$_{2.5}$ is used as a surrogate marker of humans’ daily exposure (1). PM$_{2.5}$ is also known to be more harmful to the human body than the other air pollutants such as particulate matter with a diameter $<10 \mu m$ (PM$_{10}$) (1). PM$_{2.5}$ can reach the alveolar space, penetrate the epithelium and might gain access to the pulmonary interstitium and systemic circulation (1). However, the toxic effect of PM$_{2.5}$ on the cardiovascular system is not well established (2).

It has been increasingly recognized that the concentration of air pollutant may contribute to BP elevation and cardiovascular diseases (CVD). An association between short-term ambient levels of PM$_{2.5}$ and high systolic BP (SBP) was reported (3). The long-term ambient levels of PM$_{10}$, sulfur dioxide, and ozone were also associated with high BP in a population study (4). PM$_{10}$ and PM$_{2.5}$ were significantly associated with a short-term increase in myocardial infarction (5). Another study revealed an association between the PM$_{10}$ level and an increased risk of stroke, especially for lacunar stroke (6).

The concentrations of air pollutants differ widely according to the season and meteorological conditions; the PM$_{2.5}$ level is elevated mostly in winter (7). Low temperature is associated with BP elevation, but an increased air pollutant level could also be a risk for BP elevation. As far as we know, there have been no studies examining the effect of air pollutants on the relationship between temperature and home BP level. Thus, we tested two hypotheses that: high concentration of PM$_{2.5}$ is associated with elevated home BP level and the combination of low temperature and high concentration of PM$_{2.5}$ results in enhanced BP elevation.

Methods

Study protocol

This was a cross-sectional study in a population-based cohort, performed in a sample of asymptomatic subjects who were seen for the evaluation of hypertension at Ohshima Clinic, Munakata Ohshima Island, Fukuoka, Japan. The study period was 91 consecutive days from 1 April to 30 June 2013.

The study subjects were 40 hypertensive adults living in a rural area of Munakata Ohshima Islands who agreed to undergo home BP monitoring. We did not include subjects undergoing hemodialysis, with a cardiac pacemaker, or a history of ischemic heart disease, congestive heart failure, stroke (including transient ischemic attacks) or other major concomitant non-CVD such as active cancer. Each subject’s body mass index (BMI) was calculated as weight (kg)/height$^2$ (m$^2$). Smoking was defined as current smoking.

At baseline, clinic BP was measured with a validated home BP monitor (HEM-7051; Omron Health Care, Kyoto, Japan). At least two clinic BP readings were taken after the subject
rested for at least 5 min while seated. Hypertension was diagnosed when the clinic SBP was \(\geq 140\) mmHg and/or diastolic BP was \(\geq 90\) mmHg on at least two occasions based on the Japanese Society of Hypertension (JSH) guideline or by a previous diagnosis of hypertension with current anti-hypertensive medication use.

We asked all subjects to measure their home BP and pulse rate (PR) every morning and evening, and we gathered all of the home BP data available measured in the above period. The self-measured home BP values were obtained using a validated upper arm cuff oscillometric device (HEM-7051), the same monitor used for measuring clinic BP. We instructed the subjects to place the cuff on the same arm throughout the measurements, and to measure their BP according to the JSH 2009 guideline. The subjects were asked to measure their home BP in the sitting position after at least 2 min of rest, more than two readings per time at 15-s intervals in both the morning and evening for 91 d. Morning BP was measured within 1 h of waking, and evening BP was measured before the subject went to bed. The BP data were noted by the subject him/herself in a notebook provided by this study, and they were instructed to bring the record when visiting the clinic. The researcher scanned their notes and created an Excel database of the subjects’ data. All available BP readings for each subject were used. Among all subjects, 76.8% of the BP readings were successfully collected in the morning and 69.5% in the evening throughout the study period.

The hourly concentrations of PM\(_{2.5}\) in the ambient air of Munakata City were obtained from a fixed-site air quality monitoring station in the city, which is a project overseen by the Prefectural Office of Fukuoka. The hourly temperature data in Munakata City were obtained from a fixed-site temperature monitoring station in the city, provided by the Japan Meteorological Agency. These data are public-access.

As the parameters for our analyses, we used the temperature of the day before, the temperature at 6 AM of the day, the mean temperature of the day, the mean PM\(_{2.5}\) concentration of the day before, and the PM\(_{2.5}\) concentration of the day.

### Statistical analysis

All statistical analyses were carried out with SPSS/Windows, version 22.0 (SPSS Inc., Armonk, NY). The data are expressed as the mean (±standard deviation [SD]) or percentages. We used Pearson’s correlation coefficients to calculate the correlations between parameters. All of the home morning and evening BP and PR data available measured in the study period were analyzed. We divided the home BP readings into four groups according to the mean temperature of the day and mean PM\(_{2.5}\) concentration of the day. As a cut-off value for temperature, we used 17°C which is the yearly mean temperature in the Fukuoka prefecture. As a cut-off value for PM\(_{2.5}\) concentration, we used 15 \(\mu\)g/m\(^3\), provided by the Japanese Basic Environment Law, from the Ministry of the Environment. The groups are as follows: the HiTempLowPM group, high temperature and low PM\(_{2.5}\); the HiTempHiPM group, high temperature and high PM\(_{2.5}\); the LowTempLowPM, low temperature and low PM\(_{2.5}\); and the LowTempHiPM, low temperature and high PM\(_{2.5}\). We compared the mean home morning SBP and DBP values between the groups by Tukey’s honestly significant difference test. The chi-square test was used to compare the percentage of morning hypertension (HT) (morning SBP \(\geq 135\) mmHg and/or diastolic BP [DBP] \(\geq 85\) mmHg). We then used a logistic regression model to test the odds ratio (OR) of subjects having morning HT after adjusting for age, sex and BMI. \(p\) Values < 0.05 were considered significant.

### Results

The baseline characteristics of the subjects are shown in Table 1. Among the total group of 40 subjects, the mean age was 74.4 ± 6.9 years, 52.5% were females, and the mean BMI was 24.2 ± 3.6 kg/m\(^2\). Among the study period, the mean temperature at 6 AM of the day was 14.8 ± 5.6 (°C), the mean temperature of the day was 18.0 ± 4.7 (°C), and the mean PM\(_{2.5}\) concentration of the day was 18.1 ± 10.7 (µg/m\(^3\)). A significant inverse correlation was observed between temperature at 6 AM of the day and the PM\(_{2.5}\) concentration of the day (\(r = -0.277\), \(p = 0.008\)). Table 2 shows the univariate correlations between the environmental data and the parameters of home BP measurements. Both the 6 AM temperature and the mean temperature of the day showed significant inverse correlations with the home morning and evening SBP, DBP and PR values. However, neither the PM\(_{2.5}\) of the day before nor the PM\(_{2.5}\) of the day was associated with any of the home BP parameters.

We then compared the mean home morning SBP and DBP values among the four groups. The mean home morning SBP tended to be higher in the HiTempHiPM group than the HiTempLowPM groups \((p = 0.069)\) and the mean home morning DBP was significantly higher in the HiTempHiPM group than the HiTempLowPM groups \((p < 0.007)\). Both the mean home morning SBP and DBP were significantly higher in the LowTempLowPM and LowTempHiPM groups than in the

### Table 1. Baseline characteristics of subjects.

| N       | Age, (years) | 74.4 ± 6.9 |
|---------|--------------|------------|
| Sex female, N (%) | 21 (52.5) |           |
| Body mass index, (kg/m\(^2\)) | 24.2 ± 3.6 |           |
| Diabetes mellitus, N (%) | 1 (2.5) |           |
| Dyslipidemia, N (%) | 15 (37.5) |           |
| Clinic SBP (mmHg) | 137 ± 19 |           |
| Clinic DBP (mmHg) | 72 ± 9 |           |
| Clinic PR (bpm) | 72 ± 12 |           |
| Home morning SBP (mmHg) | 123 ± 12 |           |
| Home morning DBP (mmHg) | 71 ± 10 |           |
| Home morning PR (bpm) | 64 ± 10 |           |
| Home evening SBP (mmHg) | 118 ± 12 |           |
| Home evening DBP (mmHg) | 67 ± 9 |           |
| Home evening PR (bpm) | 67 ± 10 |           |
| Number of anti-hypertensive drugs | 1.9 ± 1.4 |           |
| Calcium channel blockers, n (%) | 29 (72.5) |           |
| Angiotensin II receptor blockers, n (%) | 24 (60) |           |
| Angiotensin-converting enzyme inhibitors, n (%) | 2 (5) |           |
| Diuretics, n (%) | 14 (35) |           |
| Alpha blockers, n (%) | 7 (17.5) |           |
| Beta blockers, n (%) | 5 (7.5) |           |

Data are expressed as mean ± SD or number (%). SBP, systolic blood pressure; DBP, diastolic blood pressure; PR, pulse rate.
the HiTempLowPM and the HiTempHiPM ($p < 0.001$, respectively) (Supplementary Figures 1 and 2). We compared the percentages of morning HT among the groups. The percentages of subjects with morning HT were significantly higher in the HiTempHiPM group than the HiTempLowPM group. In addition, the percentages of subjects with morning HT were significantly higher in LowTempLowPM and LowTempHiPM groups compared to the HiTempLowPM (both $p < 0.001$) and the HiTempHiPM groups ($p < 0.001$ and $p < 0.001$, respectively). No significant difference in morning HT was observed between the LowTempLowPM and the LowTempHiPM groups (Figure 1).

We performed multivariable logistic regression analyses to test whether the above-mentioned results of the univariate analyses would still be significant after adjusting for age, sex and BMI (Table 3). At first, when the temperature was high (i.e. the HiTempHiPM compared to the HiTempLowPM), the high concentration of PM$_{2.5}$ was associated with a 1.4-fold increased likelihood of morning HT ($p = 0.018$). However, when the temperature was low (the LowTempHiPM compared to the LowTempLowPM), a high concentration of PM$_{2.5}$ was not associated with an increased likelihood of morning HT ($p = 0.39$). Secondly, when the concentration of PM$_{2.5}$ was low (i.e. the LowTempLowPM compared to the HiTempLowPM), low temperature was associated with a 2.1-fold increased likelihood of morning HT ($p < 0.001$). When the concentration of PM$_{2.5}$ was high (the LowTempHiPM compared to the HiTempHiPM), being under low temperature was associated with a 1.62-fold increased likelihood of morning HT ($p < 0.001$). The group with low temperatures and a high concentration of PM$_{2.5}$ (i.e. the LowTempHiPM) was associated with a 2.3-fold increased likelihood of morning HT compared to the HiTempLowPM subjects ($p < 0.001$).

**Discussion**

We confirmed that temperature data were inversely associated with home SBP, DBP and PR levels. However, PM$_{2.5}$ alone was not associated with the home BP level. Low temperature and high concentration of PM$_{2.5}$ existing together was significantly associated with morning HT.

In this study, the temperature of the day before, the temperature at 6 AM of the day, and the mean temperature of the day showed significant inverse correlations with home morning SBP. The association between low temperature and high BP has been established (9). However, a few studies have investigated the association between temperature and home BP. Hozawa et al. reported an inverse association between outside temperature and BP observed only in warmer seasons (10). To the best of our knowledge, no study has shown an association between outside temperature and day-by-day home BP.

The physiological mechanism of the BP-elevating effect under low temperatures is well established. The low temperature [e.g. in a cold pressor test (11)] activates the spinal anterolateral system of ascending tracts, and the ascending fibers of the spinoreticular tract activate presympathetic rostral ventrolateral medulla (RVLM) neurons. The intermediolateral (IML) cell column is the final station involving the regulation of BP, PR, and sympathetic nerve activity, and its activation results in peripheral vasoconstriction and BP elevation. Based on this mechanism, it is possible that home BP actually elevates on every cold morning.

In the present investigation, we found that the concentration of PM$_{2.5}$ was not directly associated with elevated home BP level, which is in contrast to previous studies. We speculate that the spring season — when we performed this study — might be one of the reasons. We performed this study within a single season in order to avoid the seasonal effect on BP levels. However, as the daily temperature differs widely in spring in Japan, the temperature variability might have strongly affected the BP variability and outweighed the

![Figure 1](image)

**Figure 1.** This figure shows the percentage of those with morning HT (Morning SBP $\geq$135 and/or DBP $\geq$85 mmHg) under different condition of PM$_{2.5}$ and temperature. Chi-square test was used. Percentage of those with morning HT (Morning SBP $\geq$135 and/or DBP $\geq$85 mmHg) was high under low temperature and high PM$_{2.5}$. $^*$, $^p < 0.05$; $^**$, $^p < 0.001$; versus HiTempLowPM; $^***$, $^p < 0.001$; versus HiTempHiPM. PM$_{2.5}$, fine particulate matter with diameter <2.5 µm; CI, confidence interval.

| Table 2. Correlations between temperature, PM$_{2.5}$ concentration and home BP parameters. |
|---------------------------------------------------------------|
| **Home morning** | **Home evening** | **Home morning** | **Home evening** | **Home morning** | **Home evening** |
| SBP (mmHg) | SBP (mmHg) | DBP (mmHg) | DBP (mmHg) | PR (bpm) | PR (bpm) |
|---------------------------------------------------------------|
| Temperature of the day before (°C) | $-0.20^{**}$ | $-0.07^{*}$ | $-0.18^{**}$ | $-0.12^{**}$ | $-0.07^{**}$ | $-0.08^{**}$ |
| Temperature at 6 AM of the day (°C) | $-0.19^{**}$ | $-0.06^{*}$ | $-0.17^{**}$ | $-0.11^{**}$ | $-0.07^{**}$ | $-0.07^{**}$ |
| Temperature of the day (°C) | $-0.18^{**}$ | $-0.10^{**}$ | $-0.17^{**}$ | $-0.14^{**}$ | $-0.06^{**}$ | $-0.06^{**}$ |
| PM$_{2.5}$ of the day before (µg/m³) | $-0.01$ | $-0.004$ | $-0.006$ | $0.014$ | $0.014$ | $0.002$ |
| PM$_{2.5}$ of the day (µg/m³) | $0.002$ | $-0.03$ | $0.01$ | $-0.04$ | $0.03$ | $0.01$ |

Numbers show correlation coefficients between temperature, PM$_{2.5}$ concentration and home BP parameters. SBP, systolic blood pressure; DBP, diastolic blood pressure; PR, pulse rate; PM$_{2.5}$, fine particulate matter with diameter <2.5 µm.

$p < 0.01$, ** $p < 0.001$ by Pearson’s correlation analysis.
impact of PM$_{2.5}$. In addition, as Japanese houses on the rural island where this study was conducted are often made of wood with poor home-heating equipment, the outside temperature might have directly affected the temperatures inside the subjects’ homes and the home BP level, which might have masked the effect of PM$_{2.5}$ on BP. We tested both the PM$_{2.5}$ level of the day before and the PM$_{2.5}$ of the day to investigate the association between PM$_{2.5}$ and home BP parameters, but the negative associations were similar.

We found that the coexistence of low temperature and high concentration of PM$_{2.5}$ was associated with morning HT. An association between the concentration of air pollutants and increased BP has been reported under both short-term (3) and long-term (4) exposure. The concentrations of air pollutants differ by seasons and meteorological conditions, and PM$_{2.5}$ level is elevated in the winter (7). As we hypothesized, the coexistence low temperature and high concentration of PM$_{2.5}$ was associated with morning HT. This indicates that PM$_{2.5}$ could be a modifying factor for BP elevation under low temperature.

The speculative mechanisms of the effect of PM$_{2.5}$ on the association of temperature and BP are not yet fully investigated. However, we propose two underlying mechanisms. First, as we mentioned above, inhaled particulate matter may stimulate the RVLM; for example, through sensory nerve ends or inflammation in the respiratory system (1). Male gender, drinking behavior, and low BMI were already reported as modifying factors on the association between temperature and BP (9). Based on the present study, PM$_{2.5}$ could also be one of the modifying factors on the association between temperature and BP. Second, it is reported that PM$_{2.5}$ may trigger vascular dysfunction by reducing nitric oxide synthase (3,12). It is also reported that in humans, particulate matter constricts brachial artery (13) by increasing the synthase (3,12). It is also reported that in humans, particulate matter may trigger vascular dysfunction by reducing nitric oxide synthase (3,12). It is also reported that in humans, particulate matter may trigger vascular dysfunction by reducing nitric oxide synthase (3,12). It is also reported that in humans, particulate matter may trigger vascular dysfunction by reducing nitric oxide synthase (3,12).

Table 3. Likelihood of morning hypertension by temperature and PM$_{2.5}$ concentration.

| Groups                              | Odds ratio (95%CI) | p Value |
|-------------------------------------|--------------------|---------|
| HiTempHiPM (high temperature/high PM$_{2.5}$ concentration) | 1 (reference)      |         |
| HiTempLowPM (high temperature/low PM$_{2.5}$ concentration) | 1.43 (1.06–1.92)   | 0.018   |
| LowTempLowPM (low temperature/low PM$_{2.5}$ concentration) | 2.05 (1.47–2.87)   | <0.001  |
| LowTempHiPM (low temperature/high PM$_{2.5}$ concentration) | 2.31 (1.71–3.14)   | <0.001  |

Morning hypertension was defined as SBP ≥ 135 mmHg and/or DBP ≥ 85 mmHg. Values are adjusted by age, sex and body mass index in multiple logistic regression analysis.

PM$_{2.5}$, fine particulate matter with diameter <2.5 μm; CI, confidence interval.

Conclusion

Although PM$_{2.5}$ alone was not associated with high BP level, low temperature and high concentration of PM$_{2.5}$ existing together was associated with morning HT. The meteorological relationship between low temperature and PM$_{2.5}$ could be one of the underlying mechanisms of this association. As a factor of morning hypertension, PM$_{2.5}$ concentration under the cold weather should be considered.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the article. The first author (Y. I.) and the second author (K. E.) equally contributed to the writing process.

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Supplementary material available online
Supplementary Figures 1 and 2