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Association of Heart Rate Variability of the Elderly with Personal Exposure to PM_1, $PM_{1–2.5}$, and $PM_{2.5–10}$

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Abstract Environmental epidemiologic studies have shown that elderly people are susceptible to particulate air pollution. The decreases in heart rate variability are important indices of health effect caused by particulate matter. The objective of this study was to investigate the effects of submicron particle (PM_1), $PM_{1–2.5}$, and coarse particle ($PM_{2.5–10}$) on heart rate variability parameters in the elderly. Results of our study indicated that short-term and medium-term PM exposures were associated with the reduction of heart rate variability in the elderly, with stronger effects found for coarse particles in comparison with particles of other size ranges.

Keywords Heart rate variability · Personal exposure · PM_1 · $PM_{2.5–10}$

In the past decade, airborne particulate matter (PM) has been consistently associated with adverse cardiovascular health outcomes (Brook et al. 2004). Nevertheless, the underlying mechanism or pathway of PM-induced cardiovascular mortality and morbidity is still not fully understood. Findings from other studies suggest that PM exposure somehow interferes with regulation of cardiac action by the central nervous system, thereby precipitating adverse cardiac events (Pope and Dockery 2006). Such cardiac arrhythmic events may demonstrate stress on heart rate (HR) and heart rate variability (HRV). HRV describes the beat-by-beat changes in lengths of the intervals between beats, and has been used to assess the autonomic effects of drugs, exercise, compromised health, and other stresses, as decreased HRV marks decreased parasympathetic and increased sympathetic tones (Pumprla et al. 2002). Alternations in the autonomic balance of the heart as measured by HRV have been documented in several panel studies (Gold et al. 2000; Pope et al. 2004) and cross-sectional studies (Liao et al. 2004; Park et al. 2005) for particulate air pollution. Despite that, comparatively few studies have been conducted on the cardiovascular effects of particles with different size fractions (Pope and Dockery 2006). We previously reported a decreased HRV associated with 1- to 4-h moving averages of PM mass concentrations solely using single-pollutant models (Chuang et al. 2005). In this study, to further investigate whether PM with different size ranges have different effects on HRV, we used a panel of elderly subjects to study the HRV effects for short- and medium-term exposures to PM with aerodynamic diameters less than 1 μm (PM_1), between 1 and 2.5 μm ($PM_{1–2.5}$), and between 2.5 and 10 μm ($PM_{2.5–10}$).

Materials and Methods

We performed a panel study during the years 2003 to 2005 in Taipei County to evaluate the HRV effects of short-term and medium-term (1–8 h) personal exposure to particulate matter in 15 elderly subjects. Details of study methods including disease diagnosis and criteria of subject

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excursion have been published previously (Chuang et al. 2005). Subjects were recruited through annual health checkups at the Hsin-Chuang Health Center in metropolitan Taipei area. Each subject's sex, age, body mass index (BMI), smoking status, and medical history were collected on a questionnaire during a personal interview. The review board of the Environmental Protection Bureau of Taipei County approved the research protocol, and a written consent was obtained from each participant before the study was launched.

Each subject's 24-h electro-cardiographics (ECG) were recorded by a PacerCorder 3-channel device (model 461A, Del Mar Medical Systems LLC, USA) with a sampling rate of 250 Hz. The recorded ECG tapes were sent to National Taiwan University Hospital and were analyzed with a Delmar Avionics model Strata Scan 563 (Irvine, USA). The mean heart rate (HR) and HRV parameters were then calculated in 5-min segments throughout the recording by using the Matlab language (version 5.2; Math Works Inc., USA). The time-domain parameters of HRV included the standard deviation of normal-to-normal intervals (SDNN), and the square root of the mean of the sum of the squared differences between adjacent NN intervals (r-MSSD). The frequency-domain HRV parameters included low frequency (LF; 0.04–0.15 Hz), high frequency (HF; 0.15–0.40 Hz), and LF/HF ratio. Additionally, since HRV was found to vary with different stages of sleep (Elsenbruch et al. 1999; Villa et al. 2000), we used approximately 16-h HRV measurements when the subjects were awake between 0700 and 2300 hour to avoid the effects of sleep on HRV.

Personal exposures to PM were measured simultaneously with ECG in real-time for twenty-four hours by using a personal dust monitor (DUSTcheck portable dust monitor, model 1.108, Grimm Labortechnik Ltd., Germany), which recorded 1-min mass concentrations of PM_1, $PM_{2.5}$, and PM_{10}, as well as ambient temperature and relative humidity. The DUSTcheck monitor measured number concentrations by using light-scattering technology to derive mass concentrations. Our previous results of collocating the DUSTcheck monitor with the TEOM (tapered-element oscillating microbalance monitor, model 1400a, Thermo Electron Corp., USA) showed good association for PM levels measured by both monitors simultaneously, with R^2 values of 0.90, 0.91, and 0.79 for PM_{10}, $PM_{2.5}$, and PM_1, respectively (Chuang et al. 2005). The DUSTcheck monitor was calibrated by the manufacturer with reference methods before and after field sampling seasons.

Table 1 Personal characteristics of study subjects

Characteristic	Statistics
Gender (n) (male/female)	9/6
Age (years)	66.2 ± 6.5 (53.0–75.0)
BMI (kg/m^2)	24.3 ± 1.9 (21.5–28.8)
Health status	
Coronary heart disease (n) (%)	7 (47%)
Hypertension (n) (%)	9 (60%)
Hypercholesterolemia (n) (%)	4 (27%)

Values are mean ± SD (range) unless otherwise noted

Table 2 Summarized statistics for HRV indices, personal PM exposures, and meteorological variables during the study period

Variable	N	Mean ± SD	IQR*	Min	Max
Log_{10} Heart rate (beats/min)	2,300	1.97 ± 0.31	–	1.68	3.05
Time-domain HRV					
Log_{10} SDNN (ms)	2,300	1.54 ± 0.25	–	0.79	2.53
Log_{10} r-MSSD (ms)	2,300	0.93 ± 0.27	–	0.45	2.16
Frequency-domain HRV					
Log_{10} LF (ms^2)	2,300	2.21 ± 0.57	–	0.56	4.63
Log_{10} HF (ms^2)	2,300	1.93 ± 0.64	–	0.39	4.72
LF/HF	2,300	3.19 ± 3.23	–	0.04	26.41
Personal PM exposures					
PM_{10} (μg/m^3)	2,207	40.7 ± 31.3	23.8	3.8	300.9
$PM_{2.5-10}$ (μg/m^3)	2,207	9.5 ± 9.9	6.4	0.2	145.4
$PM_{2.5}$ (μg/m^3)	2,207	31.3 ± 27.3	20.2	3.4	252.1
$PM_{1-2.5}$ (μg/m^3)	2,207	6.0 ± 5.9	3.0	0.4	82.7
PM_1 (μg/m^3)	2,207	25.3 ± 22.9	17.9	2.4	208.2
Microenvironmental meteorological variables					
Temperature (°C)	2,300	24.3 ± 2.7	4.1	18.2	30.7
Relative humidity (%)	2,300	63.3 ± 10.1	15.3	37.1	83.8

*IQR (Interquartile range) = Q3 – Q1

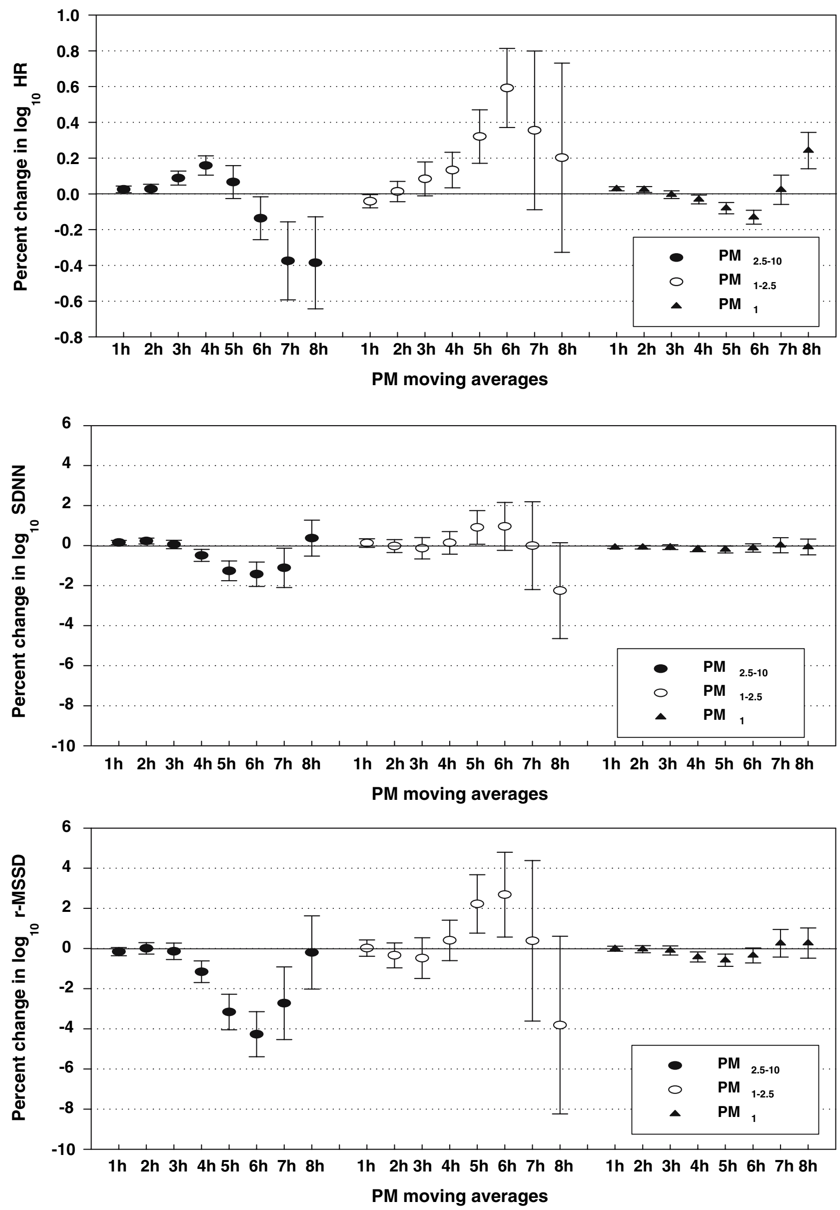

Fig. 1 Estimated percent changes in HR and time-domain HRV by increase in PM exposures (per 1 μg/m^3) at 1- to 8-h moving averages for 15 subjects using mixed-effects models. Error bars indicate mean ± 95% confidence interval

To measure subjects' personal PM exposures, all subjects were instructed to keep the DUSTcheck monitor with them at all times. Mass concentrations of $PM_{2.5–10}$ were obtained by the subtraction of $PM_{2.5}$ fractions from the concurrent PM_{10} levels. A similar approach was applied to derive the data of $PM_{1\text{-}2.5}$ concentrations. In addition, a diary was given to each subject to record activities and environmental factors in order to control confounding factors. The quality of diary entries was assured by the field staff immediately after daily sampling.

The linear mixed-effects regression model was applied to estimate the effects of PM concentrations on heart rate, time-domain, and frequency-domain HRV indices, adjusted for personal and meteorological variables. Such mixed-effect models have the advantage of adjustment for invariant variables by fixed-effect models and accounting for individual differences by random-effect models (Diggle et al. 2002). To evaluate the interval of effects of different size PM exposures, moving PM averages were calculated from 1 to 8 h and the regression coefficient on HRV parameters analyzed. Regression coefficients were presented as percentage changes to indicate the magnitude of the correlation of PM with the HRV. To improve normality and stabilize the variances, the HR, SDNN, r-MSSD, LF, and HF were log10-transformed. In mixed-effects models, we treated each subject's sex, age, BMI, temperature, relative humidity, disease status, time (hour of day), and moving PM averages as fixed effects and each subject as a random effect. Since people in the real world are exposed to PM_1, $PM_{1–2.5}$, and $PM_{2.5–10}$ simultaneously, exposures

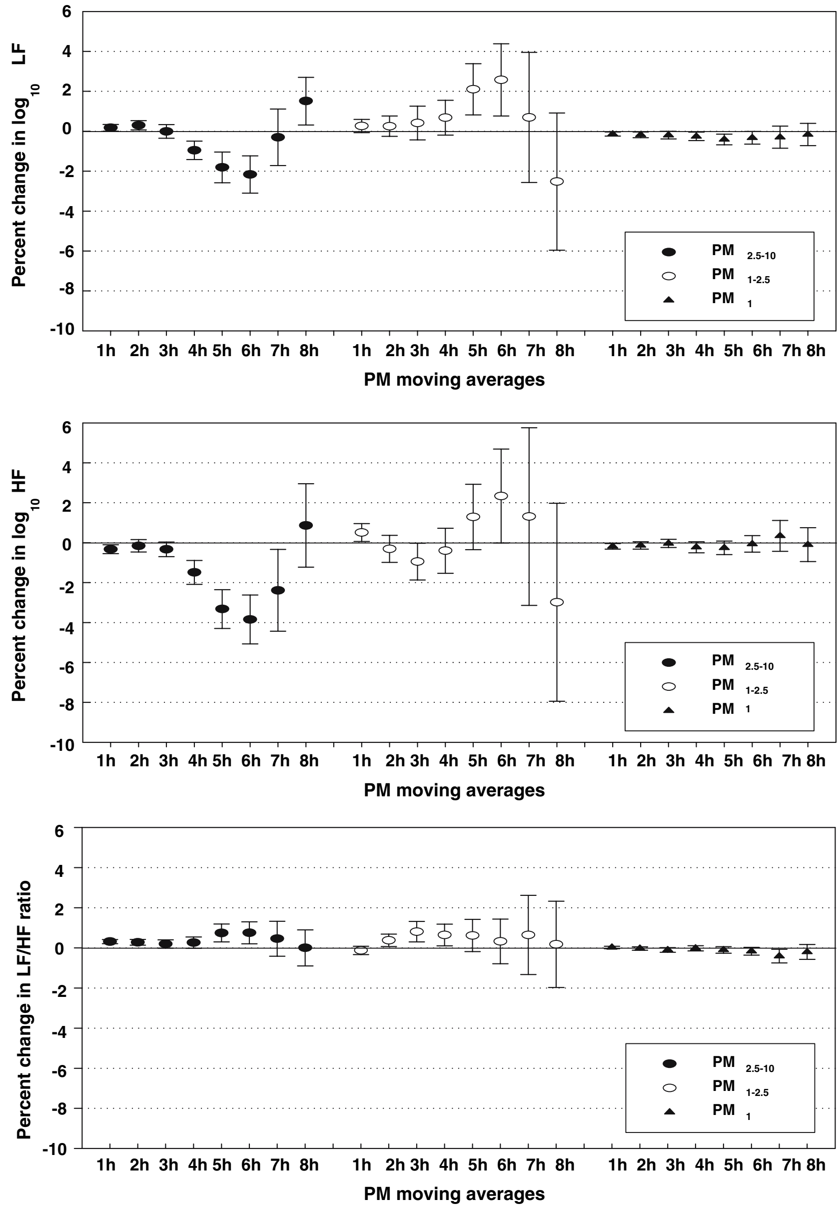

Fig. 2 Estimated percent changes in frequency-domain HRV by increase in PM exposures (per 1 μg/m^3) at 1- to 8-h moving averages for 15 subjects using mixed-effects models. Error bars indicate mean ± 95% confidence interval

to these three size fractions of PM were treated as co-pollutants in our multi-pollutant models. Statistical analyses were performed using the MIXED procedure in the S-Plus 2000 program (MathSoft Inc., Cambridge, MA, USA). Model selection was based on minimizing Akaike's information criterion (AIC) (Akaike 1974).

Results and Discussion

The study population consisted of 15 subjects, 9 male and 6 female. All subjects (mean age 66; range 53–75 years) were residents of Taipei County and all were current non-smokers. Among them, approximately 47% had a history of coronary heart disease, 60% were hypertensive, and 27% were hypercholesterolemic (Table 1). During the study period, the heart rate of the subjects was 76.4 ± 14.4 (mean ± SD) beats per minute. In addition, average personal exposures to PM_1, $PM_{1-2.5}$, and $PM_{2.5-10}$ were 25.3 (±22.9), 6.0 (±5.9), and 9.5 (±9.9) μg/m^3, respectively. The levels of PM_1 accounted for more than 60% of PM_{10} exposure measurements. Finally, the microenvironmental meteorological conditions were an average temperature of 24.3 (±2.7)°C and a relative humidity of 63.3 (±10.1)% (Table 2).

Investigative results of our multi-pollutant mixed-effects models are listed in Figs. 1 and 2. In general, increase was observed with PM for HR and the LF/HF ratio, where the strongest significant effects on HR were found at short-term intervals (1–4 h) for $PM_{2.5-10}$ and at medium-term duration (5–8 h) for particles smaller than 2.5 μm in diameter. On the other hand, among the different-sized particles, $PM_{2.5-10}$ exposures showed the strongest significant association with decreases in time-domain (SDNN, r-MSSD) and frequency-domain parameters (LF, HF) in most averaging periods. Especially for the longer duration of 5–8 h, the strongest association was found for the 6-h moving average of $PM_{2.5-10}$ exposures. For example, after adjusting for potential confounders in our mixed-effects models, an increase of 1 μg/m^3 in the 6-h $PM_{2.5-10}$ moving average was associated with a 1.43% decrease (95% confidence interval, –2.03 to –0.82%) in SDNN and a 4.27% decrease (–5.39 to –3.15%) in r-MSSD, respectively.

In brief, to our knowledge, few studies have reported the short-term effects of $PM_{2.5-10}$ on cardiovascular health (Brunekreef and Forsberg 2005). Some researchers have observed that acute exposure to concentrated ambient coarse particles appeared to alter the autonomic nervous system of the heart in adult volunteers (Gong et al. 2004). This is one of the first studies presenting that $PM_{2.5-10}$, compared to PM_1, had stronger effects on reducing HRV among elderly people. Lately, one panel study also reported that small temporal increases in ambient $PM_{2.5-10}$ are sufficient to affect important cardiopulmonary and lipid parameters in adults with asthma (Yeatts et al. 2007). Previous studies have provided evidence that PM-related changes in cardiac autonomic function are not independent of pathways involving pulmonary and systemic oxidative stress (Pope and Dockery 2006). Observations of altered HR or HRV in relation to particulate air pollution would help piece together the causal chain linking air pollution and heart function. Therefore, future studies are needed to determine if $PM_{2.5-10}$ has underappreciated health effects in susceptible populations.

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References

Akaike H (1974) A new look at the statistical model identification. IEEE Trans Auto Control 19:716–723

Brook RD, Franklin B, Cascio W, Hong Y, Howard G, Lipsett M, Luepker R, Mittleman M, Samet J, Smith SC Jr, Tager I (2004) Air pollution and cardiovascular disease: a statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. Circulation 109:2655–2671

Brunekreef B, Forsberg B (2005) Epidemiological evidence of effects of coarse airborne particles on health. Eur Respir J 26:309–318

Chuang KJ, Chan CC, Chen NT, Su TC, Lin LY (2005) Effects of particle size fractions on reducing heart rate variability in cardiac and hypertensive patients. Environ Health Perspect 113: 1693–1697

Diggle PJ, Heagerty P, Liang KY, Zeger SL (2002) Analysis of longitudinal data. Oxford University Press, New York

Elsenbruch S, Hamish MJ, Orr WC (1999) Heart rate variability during waking and sleep in healthy males and females. Sleep 22:1067–1071

Gold DR, Litonjua A, Schwartz J, Lovett E, Larson A, Nearing B, Allen G, Verrier M, Cherry R, Verrier R (2000) Ambient pollution and heart rate variability. Circulation 101: 1267–1273

Gong H, Linn WS, Terrell SL, Clark KW, Geller MD, Anderson KR, Cascio WE, Sioutas C (2004) Altered heart-rate variability in asthmatic and healthy volunteers exposed to concentrated ambient coarse particles. Inhal Toxicol 16:335–343

Liao D, Duan Y, Whitsel EA, Zheng ZJ, Heiss G, Chinchilli VM, Lin HM (2004) Association of higher levels of ambient criteria pollutants with impaired cardiac autonomic control: a population-based study. Am J Epidemiol 159:768–777

Park SK, O'Neill MS, Vokonas PS, Sparrow D, Schwartz J (2005) Effects of air pollution on heart rate variability: the VA Normative Aging Study. Environ Health Perspect 113:304–309

Pope CA, Dockery DW (2006) Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc 54: 709–742

Pope CA III, Hansen ML, Long RW, Nielsen KR, Eatough NL, Wilson WE, Eatough DJ (2004) Ambient particulate air pollution, heart rate variability, and blood markers of inflammation in a panel of elderly subjects. Environ Health Perspect 112:339–345

Pumprla J, Howorka K, Groves D, Chester M, Nolan J (2002) Functional assessment of heart rate variability: physiological basis and practical applications. Int J Cardiol 84(1):1–14

Villa MP, Calcagnini G, Pagani J, Paggi B, Massa F, Rochetti R (2000) Effects of sleep stage and age on short-term heart rate variability during sleep in healthy infants and children. Chest 117:460–466

Yeatts K, Svendsen E, Creason J, Alexis N, Herbst M, Scott J, Kupper L, Williams R, Neas L, Cascio W, Devlin RB, Peden DB (2007) Coarse particulate matter ($PM_{2.5-10}$) affects heart rate variability, blood lipids, and circulating eosinophils in adults with asthma. Environ Health Perspect 115:709–714