Coarse Particles and Heart Rate Variability among Older Adults with Coronary Artery Disease in the Coachella Valley, California

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Alterations in cardiac autonomic control, assessed by changes in heart rate variability (HRV), provide one plausible mechanistic explanation for consistent associations between exposure to airborne particulate matter (PM) and increased risks of cardiovascular mortality. Decreased HRV has been linked with exposures to PM10 (PM with aerodynamic diameter ≤ 10 µm) and with fine particles (PM with aerodynamic diameter ≥ 2.5 µm) originating primarily from combustion sources. However, little is known about the relationship between HRV and coarse particles [PM with aerodynamic diameter between 2.5–10 µm (PM2.5–10)] which typically result from entrainment of dust and soil or from mechanical abrasive processes in industry and transportation. We measured several HRV variables in 19 nonsmoking older adults with coronary artery disease residing in the Coachella Valley, California, a desert resort and retirement area in which ambient PM10 consists predominantly of PM10–2.5. Study subjects wore Holter monitors for 24 hr once per week for up to 12 weeks during spring 2000. Pollutant concentrations were assessed at nearby fixed-site monitors. We used mixed models that controlled for individual-specific effects to examine relationships between air pollutants and several HRV metrics. Decrements in several measures of HRV were consistently associated with both PM10 and PM10–2.5; however, there was little relationship of HRV with PM2.5 concentrations. The magnitude of the associations (~ 1–4% decrease in HRV per 10-µg/m3 increase in PM10 or PM10–2.5) was comparable with those observed in several other studies of PM. Elevated levels of ambient PM10–2.5 may adversely affect HRV in older subjects with coronary artery disease. Key words: cardiovascular, coarse particles, epidemiology, heart rate variability, particulate matter, PM, PM2.5, PM10, PM10–2.5.

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Many epidemiologic studies have demonstrated consistent associations between exposure to airborne particulate matter (PM) and increased risks of morbidity and mortality (Bell et al. 2004; U.S. Environmental Protection Agency [EPA] 2004). Risks of premature mortality appear to be greatest among older adults with preexisting cardiac and respiratory conditions, especially ischemic heart disease and chronic obstructive pulmonary disease (COPD). However, underlying pathophysiologic mechanisms are still unknown. It is plausible that PM-associated mortality can be explained, at least in part, by alterations in cardiac autonomic balance, as measured by heart rate variability (HRV).

HRV describes changes in successive sinus R-R intervals or in instantaneous heart rates recorded on an electrocardiogram (ECG) and has been associated with all-cause mortality (Tsuji et al. 1994), sudden cardiac death (Algra et al. 1993), and death due to heart failure (Szabo et al. 1997). HRV is decreased in survivors of acute myocardial infarction compared with healthy subjects (Bigger et al. 1995) and is altered in smokers (Hayato et al. 1990) and in individuals with COPD (Pagni et al. 1996). Decreased HRV has also been linked with conditions involving autonomic nervous system dysfunction, such as diabetes (Pfeifer et al. 1982) and Parkinson disease (Kuroiwa et al. 1983).

Several studies have linked exposure to ambient PM with decreased HRV (Creason et al. 2001; Gold et al. 2000; Holguin et al. 2003; Liao et al. 1999; Park et al. 2005; Pope et al. 1999, 2004; Schwartz et al. 2005). These investigations were conducted in areas where the mass of PM with aerodynamic diameter ≤ 10 µm (PM10) was composed primarily of fine particles [PM with aerodynamic diameter ≤ 2.5 µm (PM2.5)], which typically originate in combustion and photochemical processes. In contrast, coarse particles [PM with aerodynamic diameter between 2.5 and 10 µm (PM10–2.5)] are primarily derived from soil and from abrasive mechanical processes in transportation and industry (U.S. EPA 2004). At least two studies found no relationship between PM10–2.5 and changes in HRV (Gold et al. 2000; Liao et al. 1999); however, those investigations took place in urban areas with low PM10–2.5 levels. In contrast, our study is the first to examine the impact of PM on HRV in an area where PM10–2.5 predominates.

We previously identified associations between daily PM10 concentrations and cardiovascular mortality in Coachella Valley, a desert resort and retirement area east of Los Angeles, California (Ostro et al. 1999, 2000). Within this valley, widespread gusty winds occur in conjunction with large pressure gradients resulting from differences between the desert and coastal air masses, generating copious quantities of windblown sand and dust. Most of the variability in PM10 in the valley is attributable to PM10–2.5 even on days without wind events. Based on concurrent PM10 and PM2.5 fixed-site monitoring during a 2.5-year period, PM10–2.5 was highly correlated with PM10 on a daily basis (r = 0.95) (Ostro et al. 2000). Chemical mass balance modeling undertaken by the South Coast Air Quality Management District (SCAQMD 1990) indicated that geologic sources contribute approximately 50–60% of PM10 on an annual basis and up to 95% during wind events. In the present study, we examined whether ambient PM10, PM2.5, and PM10–2.5 levels were associated with changes in HRV in older adults with coronary artery disease.

Materials and Methods

Subject recruitment. The study protocol was approved by the Institutional Review Board of the Public Health Institute (Oakland, California). Study participants were recruited from a large cardiology practice and through newspaper advertisements from December 1999 through February 2000. Subjects were eligible if they were ambulatory adults ≥ 60 years of age; were not current smokers; had coronary artery disease manifested by at least one of the following: a) a history of angina

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and a positive ECG, echocardiographic or nuclear stress test, or angiography (n = 12), b) prior percutaneous coronary intervention (n = 1), c) prior coronary artery bypass surgery (n = 12), or d) a history of myocardial infarction at least 6 months before recruitment (n = 16) (of the 19 subjects in the study, almost all met at least two criteria for eligibility); and residence within 5 miles of either of the two fixed-site air quality monitoring stations in Coachella Valley (located in Palm Springs and Indio).

Exclusion criteria included conditions associated with autonomic dysfunction (e.g., diabetes, chronic renal failure, Parkinsonism, and chronic alcohol abuse), cardiac transplant, cardiac pacemaker, implantable defibrillator, atrial fibrillation, or significant cognitive impairment.

**Data collection.** During the initial in-person appointment, staff obtained written informed consent and administered a baseline questionnaire, which included questions on subject demographics, medical history, current medications, usual daily activities, and any limitations on activity. The information obtained in the baseline questionnaire was supplemented by abstracting photocopies of the individuals' medical records on standardized forms. Data abstracted from the medical records included, where available, left ventricular ejection fraction (LVEF), history of myocardial infarction, and medications prescribed. During this study, the participants remained under the medical supervision of their regular personal physicians.

Staff also measured the subjects' lung function at baseline using a portable Simplicity spirometer (Mallinckrodt, Inc., St. Louis, MO). Spirometry was conducted following the guidelines of the American Thoracic Society (1995), with reproducibility criteria modified slightly to accommodate the subjects' ages (i.e., results of at least three of the forced expiratory maneuvers were required to be within 15% of one another). Briefly, the subjects were seated and wore a nose clip for the spirometric maneuvers. Each subject performed at least four expiratory maneuvers. Spirometry was rescheduled for subjects who reported a respiratory infection in the preceding 3 weeks.

Twenty-four-hour ambulatory ECGs were digitally recorded for each subject at weekly intervals from 14 February through 31 May 2000, using lightweight Trillium 3000 Holter monitors with disposable electrodes (Forest Medical, Syracuse, NY). During the Holter monitoring, subjects performed their normal daily activities, except those that would interfere with the ECG recording, such as showering. In general, Holter monitoring began at the same time and day every week for each subject. In cases of missed appointments, subjects were rescheduled for monitoring within the next 2 days, if possible.

Staff followed a standardized protocol for subject preparation and placed five electrodes (two channels) in a modified V5 and aVF configuration similar to that used by Pope et al. (1999, 2004). Each Holter monitoring session began with a 20-min resting ECG with the subject supine, during which staff remained with the subject. At each session, staff gave the subject a simple 24-hr time–activity diary to record times spent indoors or outdoors, air conditioner (AC) use (yes or no), and whether windows were open during each 2-hr period (and one 6-hr block from 2400 hr to 0600 hr).

Staff downloaded each subject’s monitoring data from a removable flashcard to a personal computer for storage and subsequent editing by an ECG technician. The subjects’ physicians were sent a standard Holter report within 24 hr, which resulted in the identification of three subjects during the initial monitoring sessions who had experienced asymptomatic but potentially life-threatening arrhythmias. These patients underwent procedures to implant defibrillator/pacemaker devices and were dropped from the study; no additional recordings were undertaken for these three individuals. An additional subject was found to have continuous atrial fibrillation. None of these subjects’ ECG data were included in the analysis. Thus, of the initial 23 subjects, we had multiple ECG recordings from 19 for the analysis.

Ambient pollutant data consisted of continuous measurements of PM<sub>10</sub>, PM<sub>2.5</sub>, and ozone, which were monitored at fixed-site stations operated by the SCAQMD in Indio and Palm Springs, located at either end of the population corridor in Coachella Valley. PM<sub>10</sub>-2.5 data were derived by subtracting PM<sub>2.5</sub> mass concentrations from PM<sub>10</sub>. Although the SCAQMD also monitored for carbon monoxide and nitrogen dioxide during the study period, we did not use these data for our analysis because there were many days with missing values. Sulfur dioxide was not monitored in the valley at that time. We obtained daily meteorologic data collected at two valley airports (minimum, maximum, and mean temperature, as well as dew point, relative humidity, and barometric pressure) from the National Climatic Data Center (Asheville, NC).

Data from baseline questionnaires, medical records abstraction, pulmonary function testing, daily diaries, and extracted HRV variables were entered into a SAS database, with 10% double-data entry to check for accuracy. The database was then merged with air quality and meteorologic data for analysis using SAS (version 8; SAS Institute Inc., Cary, NC).

**Data analysis.** Only normal sinus R-R intervals were used in the HRV analysis. Artifacts, ectopy (both supraventricular and ventricular), and uninterpretable complexes were excluded. We examined time-domain, frequency-domain, and geometric HRV variables. Time-domain variables included a) the standard deviation of normal sinus rhythm (“normal-to-normal” or N-N) beats (SDNN), representing the average of the standard deviations of normal beats of successive 5-min blocks over the duration of the monitoring period (SDNN estimates overall HRV); b) the standard deviation of the average N-N intervals (SDANN) within successive 5-min blocks (an estimate of long-term components of HRV); and c) the root mean square of successive differences (r-MSSD), which is the square root of the mean of the squares of differences between adjacent normal R-R intervals, which estimates short-term components of HRV and is a sensitive indicator of vagal tone (Task Force 1996).

Frequency-domain analysis delineates the heart rate signal into its frequency components and quantifies them in terms of their relative intensity or power. We examined three frequency-domain variables: high frequency (HF), low frequency (LF), and total power. HF components (0.15–0.40 Hz) provide an index of parasympathetic activity, whereas LF components (0.04–0.15 Hz) are considered to encompass both sympathetic and parasympathetic activity (Cerutti et al. 1995; Task Force 1996). Total power is an indicator of overall HRV.

Geometric methods involve analysis of the sample density histogram of R-R interval durations. A plot of the distribution typically depicts the main peak as a triangular shape. The triangular index (TRID) provides an estimate of overall HRV that is more resistant to beat-labeling errors than are its time- and frequency-domain counterparts (Task Force 1996).

Because the Holter software did not allow for downloading time-domain HRV variables

| Table 1. Characteristics of HRV study population (n = 19). |
|---------------------------------|--------------|
| Characteristic                  | Value        |
| Age (years)                     | 71.3 ± 6.0   |
| Sex (m/f)                       | Male 12, Female 7 |
| Smoking status (no.)            | Never 7, Former 12 |
| Cardiac medications (no.)       | Beta blockers 9, ACE inhibitors 7, Calcium channel blockers 2 |
| Lung function (mean ± SD)       | FEV<sub>1</sub> (L) 2.17 ± 0.58, FVC (L) 3.01 ± 0.85, PEFR<sub>25-75% (L/sec) 1.83 ± 0.98, FEV<sub>1</sub>/FVC 0.77 ± 0.02, PEFR<sub>25-75% (L) 0.64 ± 0.37, LVEF (mean ± SD) 47% ± 17 |

Abbreviations: FEV<sub>1</sub>, FEFR<sub>25-75% , mean forced expiratory flow between 25% and 75% of the FVC; FEV<sub>1</sub>, forced expiratory volume at 1 sec; FVC, forced vital capacity; LVEF, left ventricular ejection fraction.
Continuous HRV variables and pollution
applied mixed linear regression models to the analyses. We log-transformed for the analyses. We entered individually into the models; we examined the impact of both concurrent and lagged pollutant variables to allow for the possibility of delayed and cumulative effects. Therefore, for the 24-hr measures of HRV, single-day lags and moving averages of up to 4 previous days for each pollutant were considered. For HRV variables measured on a 2-hr (time domain and TRII) or 5-min (frequency domain) basis, we examined 2-, 4-, 6-, 8-, and 24-hr pollutant moving averages. Because HRV is related inversely to heart rate, the models included the subjects’ average heart rate during the monitoring periods.

For some of the associations found, we conducted additional analyses to examine potential impacts of behavioral factors that might influence exposure. For example, for the 2-hr evening period, we examined the effect (based on responses in the daily diary) of subjects’ keeping windows open, using AC, or being outdoors for > 1 hr. Each of these factors was included separately as a dichotomous variable in models that also included a PM metric (PM$_{10}$, PM$_{10-2.5}$, or PM$_{2.5}$). We also added an interaction term between the specific factor and the PM metric to these models (e.g., the use of AC between 1800 and 2000 hr and concurrent PM$_{10}$).

Statistical methods. Most of the HRV variables were log-normally distributed and were log-transformed for the analyses. We applied mixed linear regression models to the continuous HRV variables and pollution

### Table 2. Descriptive statistics of pollutant and meteorologic variables.

| Pollutant or meteorologic variable | Mean (range) |
|-----------------------------------|--------------|
| PM$_{10}$ (µg/m$^3$, 24-hr average) | Indio: 48.1 (11.8–289.2) Palm Springs: 31.0 (9.0–140.3) |
| PM$_{2.5}$ (µg/m$^3$, 24-hr average) | Indio: 23.2 (6.3–90.4) Palm Springs: 14 (4.7–52) Ozone (ppb, 1-hr maximum) Palm Springs: 41 (19–92) |
| Maximum temperature ($^\circ$F) | Indio: 89.6 (49.8–98.4) |
| Relative humidity (%) | 44.2 (13.7–95.5) |
| Barometric pressure (mb) | Indio: 33 (12–66) |
| Precipitation (in) | 0.006 (0–0.010) |

### Table 3. Summary of HRV variables* and average heart rate.

| Variable (unit) | No. | Mean ± SD |
|----------------|-----|-----------|
| SDNN (msec)    | 168 | 73.2 ± 29.3 |
| SDANN (msec)   | 168 | 53.9 ± 22.8 |
| RMSSD (msec)   | 168 | 44.1 ± 42.5 |
| TRII           | 168 | 17.2 ± 6.1 |
| Total power (msec$^2$) | 169 | 1,216 ± 1,915 |
| HF (msec$^2$)  | 169 | 304 ± 818 |
| LF (msec$^2$)  | 169 | 221 ± 332 |
| Average heart rate (beats/min) | 168 | 76 ± 13 |

*Time domain variables, TRII, and average heart rate were measured 1800–2000 hr. Frequency domain variables were measured at 0300 hr.

### Table 4. Regression coefficients* for time-domain HRV variables measured in the evening (1800–2000 hr) in relation to different averaging times for PM$_{10}$, PM$_{10-2.5}$, and PM$_{2.5}$.

| PM moving average | SDNN | Coefficient (SE) | p-Value | SDANN | Coefficient (SE) | p-Value | TRII | Coefficient (SE) | p-Value |
|-------------------|------|-----------------|---------|-------|-----------------|---------|------|-----------------|---------|
| PM$_{10}$         |      |                 |         |       |                 |         |      |                 |         |
| 1800–2000 hr      | 0.71 (0.268) | 0.009 | -0.99 (0.366) | 0.008 | -0.72 (0.252) | 0.005 |
| 1600–2000 hr      | 1.03 (0.433) | 0.019 | -1.38 (0.590) | 0.021 | -1.1 (0.406) | 0.008 |
| 1400–2000 hr      | 1.45 (0.54) | 0.008 | -1.80 (0.738) | 0.016 | -1.41 (0.51) | 0.007 |
| 1200–2000 hr      | 1.21 (0.60) | 0.021 | -1.53 (0.621) | 0.064 | -1.46 (0.563) | 0.011 |
| 24 hr             | 0.51 (0.77) | 0.510 | -0.71 (1.072) | 0.51 | -1.00 (0.725) | 0.17 |

| PM$_{10-2.5}$     |      |                 |         |       |                 |         |      |                 |         |
| 1800–2000 hr      | 0.72 (0.296) | 0.017 | -0.96 (0.444) | 0.034 | -0.61 (0.303) | 0.046 |
| 1600–2000 hr      | 1.19 (0.516) | 0.024 | -1.53 (0.765) | 0.049 | -0.89 (0.531) | 0.096 |
| 1400–2000 hr      | 1.84 (0.649) | 0.006 | -2.37 (0.986) | 0.019 | -1.23 (0.691) | 0.08 |
| 1200–2000 hr      | 1.4 (0.767) | 0.074 | -2.02 (1.159) | 0.087 | -1.62 (0.833) | 0.056 |
| 24 hr             | 0.23 (0.923) | 0.61 | -0.42 (1.433) | 0.77 | -0.37 (1.148) | 0.75 |

| PM$_{2.5}$        |      |                 |         |       |                 |         |      |                 |         |
| 1800–2000 hr      | 0.37 (1.01) | 0.72 | -1.26 (1.375) | 0.36 | -0.76 (0.957) | 0.43 |
| 1600–2000 hr      | 0.55 (1.176) | 0.64 | -1.66 (1.60) | 0.30 | -0.55 (1.067) | 0.61 |
| 1400–2000 hr      | 1.21 (1.034) | 0.24 | -1.74 (1.391) | 0.21 | -0.43 (0.956) | 0.65 |
| 1200–2000 hr      | 1.25 (1.122) | 0.27 | -1.54 (1.429) | 0.28 | -0.26 (1.018) | 0.8 |
| 24 hr             | 1.63 (2.38) | 0.49 | -2.20 (3.135) | 0.31 | -0.96 (2.129) | 0.65 |

*All coefficients and SE = 1.000. Regression model includes pollutant variable and average heart rate. Coefficient represents relationship between exposure and ln(SDNN) in msec.

Results

Table 1 presents demographic and medical data for the 19 participants. The average number of HRV monitoring sessions per subject was 8.8 (range, 4–12). Descriptive statistics for the pollutant and meteorologic variables during the study period are presented in Table 2, and the time- and frequency-domain HRV variables used in the analysis are summarized in Table 3.

Evaluation of potential time-variant confounders through both simple correlation analysis and univariate regressions indicated that the pollutant variables were not confounded by any meteorologic variables. Although barometric pressure was often associated with the HRV measures, it had little impact on the associations of ambient pollutants with HRV. Therefore, the results presented are from fixed-effects models that included only the pollutant term and average heart rate as predictor variables.

Results of the analysis of time-domain HRV variables measured during the evening period (1800–2000 hr) are displayed in Table 4. These results indicated associations between decrements in SDNN, SDANN, and TRII in relation to increases in both PM$_{10}$ and PM$_{10-2.5}$. The magnitude of the associations between SDNN and PM$_{10}$ or PM$_{10-2.5}$ increased as the averaging time increased up to 6 hr but began to decrease at 8 hr and diminished to nonsignificance when the averaging time was extended to the prior 24 hr. A similar pattern was observed for SDANN, whereas for TRII the coefficients for both PM$_{10}$ and PM$_{10-2.5}$ continued to increase modestly at 8 hr relative to an averaging time of 6 hr. There was no evidence of an association between PM$_{2.5}$ or ozone and these HRV variables. There was no association
between any pollutant variable and r-MSSD, except for a marginally significant but positive association with PM$_{10-2.5}$ averaged over the preceding 24 hr.

In contrast to the regressions for the evening monitoring period, there were few associations during the morning monitoring period between pollutant metrics and time-domain variables (data not shown). PM$_{10-2.5}$ was associated with both SDNN and SDANN at lags up to 4 hr but not at 24 hr. PM$_{10}$, PM$_{2.5}$, and ozone were not associated with any HRV metrics in the morning session. In addition, there was again a marginally significant positive association between PM$_{10-2.5}$ averaged over 24 hr and r-MSSD.

Analysis of the frequency-domain variables during sleep (0300 hr) also indicated sporadic associations between HRV and PM metrics (Table 5). For this monitoring period, the unlagged pollutant variables were measured over the prior hour (i.e., 0200–0300 hr). Total power was associated with all three particular metrics. The strongest associations for PM$_{10}$ and PM$_{10-2.5}$ were averaged over the prior 4 hr, whereas for PM$_{2.5}$, only the measurement in the prior hour was statistically significant. There were also several modest associations with changes in the HF and LF components, with no obvious patterns. Ozone was also associated with decreases in all three frequency-domain measures, although the coefficients were of borderline significance ($p=0.08$ to 0.10). The daytime postcheckup frequency-domain variables also showed no pattern of association with the pollutant metrics (data not shown).

Adding variables representing exposure-related behaviors (e.g., use of AC) to the models generally resulted in modest increases in the magnitude and significance of the coefficients for PM$_{10}$ and PM$_{10-2.5}$ (data not shown). However, neither these behavioral variables nor the interactive term coefficients were statistically associated with the HRV metrics. The use of exposure adjustment factors did not alter the generally null to modest findings for PM$_{10}$.

Several constitutional and clinical variables [age, sex, lung function, use of beta-blockers or angiotensin-converting enzyme (ACE) inhibitors, prior smoking status] did not exhibit an association with SDNN, nor did they have much, if any, effect on the magnitude or significance of PM$_{10-2.5}$ coefficients. In contrast, inclusion of LVEF in the model increased the absolute magnitude of the PM$_{10-2.5}$ coefficient by 36% [from $-0.00072$ ($p=0.02$) to $-0.00098$ ($p=0.007$)], whereas the LVEF coefficient was of borderline statistical significance ($p=0.09$).

**Discussion**

We found consistent associations of several PM metrics, notably PM$_{10}$ and PM$_{10-2.5}$, with short-term decrements in several measures of HRV in a panel of older adults with coronary artery disease. The strongest associations were detected when PM measurements were taken within a few hours before the HRV measures. These associations, however, were no longer present when the PM averaging time was extended to 24 hr or longer. These observations suggest that if there are causal relationships between PM exposures and decreases in HRV, the effects likely occur in close temporal proximity to the exposures.

These findings accord with some previous epidemiologic studies of HRV (Gold et al. 2000; Pope et al. 2001), although others have reported more prolonged effects (Creason et al. 2001; Pope et al. 2004). Gold et al. (2000) conducted 25-min ECG measurements in 21 older Boston residents weekly over a 3-month period. They reported significant associations of r-MSSD and SDNN with PM$_{2.5}$ within a few hours of obtaining the ECG data. No associations between PM$_{2.5}$ and HRV were seen at lags longer than 24 hr.

In a subsequent study, however, the same researchers found somewhat stronger associations with 24-hr PM metrics than with 4-hr averages (Schwartz et al. 2005). Pope et al. (2004) reported decrements in several HRV metrics associated with 24-hr averages of PM$_{2.5}$ measured up to 2 days before Holter monitoring, although the strongest associations were with same-day measurements. A recent study of 10 elderly subjects involving 2-hr controlled exposures to either filtered air or concentrated PM$_{2.5}$ also reported significant decreases in several HRV measures immediately postexposure, which tended to persist (albeit somewhat attenuated) at 24 hr postexposure (Devlin et al. 2003). In contrast, other investigators found that a 48-hr PM averaging time had the strongest associations with decrements in HRV (Park et al. 2005).

In our study population of individuals with coronary artery disease, we identified PM-associated decreases in SDNN, SDANN, and TR1, but little relationship with r-MSSD. Others have found decreases in SDNN and SDANN, with mixed results regarding r-MSSD (Pope et al. 1999, 2004). It is possible that the variable results with the latter metric are caused partly by the effects of a variety of common cardiovascular medications on r-MSSD. Liao et al. (1999) examined HRV in 26 elderly residents of a Baltimore retirement home, reporting significant decreases in HF, LF, and SDNN in relation to indoor and outdoor PM$_{2.5}$ only among subjects with preexisting cardiovascular disease. Recently, Schwartz et al. (2005) reported stronger associations of PM$_{2.5}$ (especially black carbon) with HRV decrements in subjects with a prior myocardial infarction ($n=3$) relative to the other subjects ($n=25$), although this observation must be interpreted cautiously because of small numbers. Other studies have reported that subjects with cardiovascular disease may be at increased risk of PM-associated changes in HRV (Holguín et al. 2003; Park et al. 2005). Holguín et al. (2003) reported decrements in HF and LF variables among 34 elderly nursing home residents with both PM$_{2.5}$ and ozone in Mexico City, especially among individuals with hypertension. However, we found little relationship between frequency-domain variables and any of these pollutant factors, nor did we observe that a history of hypertension affected the PM–HRV associations. However, the levels of both PM$_{2.5}$ and ozone were substantially greater in the Mexican study (means of 37.2 µg/m$^3$ PM$_{2.5}$ and 149 ppb ozone in Mexico City vs. 18.6 µg/m$^3$ and 37 ppb, respectively, in our study, representing the averages of the values recorded at Indio and Palm Springs). In addition, all of the subjects in our study had documented coronary artery

![Table 5. Regression coefficients for frequency-domain HRV variables in relation to PM metrics and ozone.](image-url)
Coarse particles and heart rate variability

Table 6. Comparisons of particle-associated decreases in SDNN per 10 µg/m³ increase in PM.

| Reference          | Mean of SDNN (averaging time) | PM metric (averaging time) | Effect estimate (msec; 95% CI) | Percent change |
|--------------------|--------------------------------|-----------------------------|--------------------------------|----------------|
| Pope et al. 1999   | 129.6 (24 hr)                  | PM₁₀ (24 hr)                | −1.8 (−1.1 to −2.5)            | −1.4           |
| Gold et al. 2000   | 72.7 (25 min)                  | PM₂.₅ (4 hr)                | −2.6 (−0.8 to −4.4)            | −3.6           |
| Pope et al. 2001   | 74.7 (1.75 hr)                 | RSP (1.75 hr)               | −1.1 (−0.5 to −1.7)            | −1.5           |
| Pope et al. 2004   | 131.4 (24 hr)                  | PM₁₀ (24 hr)                | −3.5 (−1.9 to −5.1)            | −2.7           |
| Park et al. 2005   | 31.6 (4 min)                   | PM₂.₅ (24 hr)               | −0.9 (−3.0 to 1.4)             | −2.9           |
| Sullivan et al. 2005 | 49 (20 min)                  | PM₁₀ (24 hr)                | 0.5 (−2.4 to 3.9)              | 1.0            |
| Chuang et al. 2005 | 33.9 (16 hr)                   | PM₁₀–₂.₅ (4 hr)             | −1.4 (−3.0 to 0.2)             | −4.2           |
| Present study      | 73.2 (2 hr)                    | PM₁₀ (2 hr)                 | −1.2 (−0.3 to −2.1)            | −1.6           |
| Present study      | 73.2 (2 hr)                    | PM₂.₅ (6 hr)                | −2.4 (−0.7 to −4.1)            | −3.3           |
| Present study      | 73.2 (2 hr)                    | PM₁₀–₂.₅ (2 hr)             | −1.2 (−0.2 to −2.2)            | −1.6           |
| Present study      | 73.2 (2 hr)                    | PM₁₀–₂.₅ (6 hr)             | −3.0 (−1.0 to −5.1)            | −4.1           |

Abbreviations: CI, confidence interval; RSP, respirable particles (<3 µm) from environmental tobacco smoke. *Subjects with cardiovascular disease.
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