Insights Into the Mechanisms and Mediators of the Effects of Air Pollution Exposure on Blood Pressure and Vascular Function in Healthy Humans


Abstract—Fine particulate matter air pollution plus ozone impairs vascular function and raises diastolic blood pressure. We aimed to determine the mechanism and air pollutant responsible. The effects of pollution on heart rate variability, blood pressure, biomarkers, and brachial flow-mediated dilatation were determined in 2 randomized, double-blind, crossover studies. In Ann Arbor, 50 subjects were exposed to fine particles (150 μg/m³) plus ozone (120 parts per billion) for 2 hours on 3 occasions with pretreatments of an endothelin antagonist (Bosentan, 250 mg), antioxidant (Vitamin C, 2 g), or placebo. In Toronto, 31 subjects were exposed to 4 different conditions (particles plus ozone, particles, ozone, and filtered air). In Toronto, diastolic blood pressure significantly increased (2.9 and 3.6 mm Hg) only during particle-containing exposures in association with particulate matter concentration and reductions in heart rate variability. Flow-mediated dilatation significantly decreased (2.0% and 2.9%) only 24 hours after particle-containing exposures in association with particulate matter concentration and increases in blood tumor necrosis factor α. In Ann Arbor, diastolic blood pressure significantly similarly increased during all of the exposures (2.5 to 4.0 mm Hg), a response not mitigated by pretreatments. Flow-mediated dilatation remained unaltered. Particulate matter, not ozone, was responsible for increasing diastolic blood pressure during air pollution inhalation, most plausibly by instigating acute autonomic imbalance. Only particles from urban Toronto additionally impaired endothelial function, likely via slower proinflammatory pathways. Our findings demonstrate credible mechanisms whereby fine particulate matter could trigger acute cardiovascular events and that aspects of exposure location may be an important determinant of the health consequences. (Hypertension. 2009;54:00-00.)

Key Words: hypertension ■ endothelium ■ sympathetic nervous system ■ inflammation ■ oxidative stress

Fine particulate matter air pollution (<2.5 μm in diameter (PM_{2.5})) is a major worldwide cause of cardiovascular (CV) mortality. Although PM_{2.5} mass is related to the degree of CV risk, specific sources (eg, traffic), chemical components, and gases (eg, ozone) contribute to the health consequences. Because gas and particle pollution are typically present together, it is important to understand their individual and combined effects.

PM_{2.5} promotes CV events via several mechanisms; however, vascular dysfunction likely plays an integral role. An imbalance in vasomotor tone and/or a related prohypertensive response could trigger ischemic cardiac events and contribute to the observed risk for heart failure and stroke. Indeed, we demonstrated that a 2-hour-long exposure to concentrated ambient PM_{2.5} (CAP) plus ozone raises diastolic blood pressure (BP) and triggers vasoconstriction in healthy adults. Diesel exhaust, a mixture of particles and gases, can also instigate endothelial dysfunction and cardiac ischemia. Although the degrees of vasoconstriction and BP elevation were both associated with the concentration of organic carbon within PM_{2.5} in our original studies, some effect of ozone could not be discounted. Ozone (O₃) could have directly impaired arterial function or interacted with the particles enhancing their toxicity. Because both are targets...
for regulations, it is important to elucidate the responsible pollutant(s).\textsuperscript{15}

In addition, the mechanism underlying the CV responses remained a matter of speculation.\textsuperscript{9,10} Three pathways appeared most plausible at the time of this study design: (1) pollution-induced systemic oxidative stress/inflammation; (2) elevated endothelin (ET) levels or activity; and (3) altered autonomic nervous system (ANS) balance.\textsuperscript{2,16} The inhalation of PM\textsubscript{2.5} has been shown to cause a systemic inflammatory response (eg, elevation in proinflammatory cytokines, eg, interleukin 6 and tumor necrosis factor $\alpha$ [TNF-$\alpha$]). Previous studies suggest that particle-induced oxidative stress, within the lungs and/or systemically, likely plays a key role in initiating this response.\textsuperscript{1,2} Additional experiments show that air pollution exposure is associated with rapid changes in ANS balance, favoring sympathetic nervous system activation and parasympathetic withdrawal. Several other lines of evidence also suggest that PM inhalation can rapidly trigger an increase in circulating levels and/or bioactivity of ET within the vasculature.\textsuperscript{1,2} Each of these responses may be potentially responsible for causing systemic vascular dysfunction and increasing BP by favoring pro- and constrictive cellular signaling pathways after acute air pollution exposure.\textsuperscript{2} Therefore, we explicitly designed this experiment to test the viability of each of these putative pathways.

This study aimed to determine the responsible air pollutant(s) (ozone, PM\textsubscript{2.5}, or their combination) and the most credible mechanism underlying our previous findings.\textsuperscript{9,10} To meet these goals, we designed a controlled air pollution exposure study purposely involving well-coordinated experimental limbs performed concomitantly at 2 different sites. This design contributed to the increased sample size compared with previous studies\textsuperscript{9,11} and facilitated the investigation of the 2 different study aims along with our ability to discern whether responses differ between locations where PM\textsubscript{2.5} can be dissimilar in composition and sources.

Methods

The study was approved by the human research ethics committees of St Michael’s Hospital and the University of Toronto, as well as the institutional review board of the University of Michigan. Subjects at both locations were healthy 18- to 50-year-old nonsmokers without any CV disease or risk factor and not taking medications. We excluded subjects with a screening fasting total cholesterol $>240$ mg/dL or glucose $>126$ mg/dL.

Study Design

The overall study design is illustrated in the online Data Supplement (please see http://hyper.ahajournals.org; Figure S1). The 2 specific site locations were selected to provide exposures to fine particles that differ in source and likely also chemical composition. In Ann Arbor, exposures and CV testing were performed in the AirCare1 mobile facility adopted for humans and stationed at the University of Michigan North Campus.\textsuperscript{17} Subjects were exposed to CAP plus ozone for 2 hours on 3 separate occasions 2 to 4 weeks apart. Two hours before each exposure (1 hour before pre-exposure testing), subjects were given 1 randomized, double-blind oral pretreatment of Bosantan (250 mg), vitamin C (2000 mg), or placebo. Neither the subject nor the investigative personnel was aware of the pretreatment type during the study. In Toronto, exposures and CV testing were performed at the Gage Occupational and Environmental Health Unit in downtown Toronto.\textsuperscript{9} Subjects were exposed in a randomized, blinded fashion to 4 conditions for 2 hours (CAP plus ozone, CAP, ozone, or filtered air) without pretreatments $\geq$ 2 weeks apart. Subjects were not aware of the order and could not discern the exposure type. All of the study personnel who performed the CV outcome measurements were blinded to the exposure types during the study. Only the investigator responsible for generating the exposure was aware of its composition during the study period. Subjects arrived fasting (24 hours) to the facilities between 8:00 and 9:00 AM. Pre-exposure testing was performed first (1-hour duration). Afterward, subjects underwent the 2-hour-long exposure, followed immediately by repeat testing on completion. Subjects returned fasting the following morning for repeat testing between 8:00 and 9:00 AM. In Ann Arbor, subjects wore a 24-hour ambulatory BP monitor (SpaceLabs 90207 ABP Monitor) the day before and after all of the exposures.

Exposures

Ambient PM\textsubscript{2.5} was concentrated to a target level of 150 mg/m$^3$. In Toronto, CAP exposures were produced with a 2-stage Harvard virtual impactor system.\textsuperscript{9} During filtered air exposures, a high-efficiency particulate arrestor filtering device was inserted downstream of the concentrator. In Ann Arbor, CAP exposures were produced with a 3-stage Harvard virtual impactor system.\textsuperscript{15} Ozone (120 parts per billion) was produced by an arc generator and added to the CAP airflow. Ozone was monitored continuously by using a photometric analyzer. Both human chambers were modified air-tight body plethysmographs with exposure air flows (15 to 20 L/min) entering the chamber via ducting ending in a face mask facilitating nasal inhalation. PM\textsubscript{2.5} levels were monitored during exposures by a tapered element oscillating microbalance.

A PM\textsubscript{2.5} filter sample was collected immediately upstream of the chambers on a 47-mm Gelman Teflon filter with a 2-μm pore size at an air flow of 8 L/min. The sample was analyzed gravimetrically for total mass on conditioned filters using a climate-controlled clean room.\textsuperscript{9,17}

CV Outcomes

Technicians at both sites performed all of the protocols using identical methodologies after combined training.\textsuperscript{9} Subjects rested supine for $>10$ minutes before all of the testing periods in a temperature-controlled room. In Ann Arbor, the order of testing was as follows: average of 3 supine BP levels (Omron 780), brachial artery diameter (BAD), flow-mediated dilatation (FMD), arterial compliance, nitroglycerin-mediated dilatation (NMD), and blood draws for biomarkers. In Toronto, the order of testing was as follows: average of 3 supine BP levels (Oscar-1 or -2; SunTech); supine 10-minute ECG using a Holter monitor, which subsequently recorded continuously throughout the study; BAD; FMD; NMD; and blood draws for biomarkers.

BAD, FMD, and NMD were measured using a Tersano 2000 ultrasound with a 7.5- to 10.0-mHz linear array transducer with ECG-gated image acquisition and storage of digital loops (TeraTech, Inc). Upper arm cuff inflation above the site of ultrasound image acquisition for 4 minutes was used to generate reactive hyperemia, and images were obtained continuously from 50 to 120 seconds after cuff deflation. Peak FMD within this period was used as the study outcome for “endothelial function.” Image analyses were performed using semiautomated software (Medical Imaging Applications, Inc). Arterial compliance was measured by radial artery tonometry using the CVProfiler, as described previously (Hypertension Diagnostics, Inc).\textsuperscript{18}

BP and heart rate were measured during the exposures while a subject was seated within the chamber. At both sites, subjects wore the automated BP monitors on their left upper arm (Ann Arbor: Omron 780; Toronto: Oscar-1 or -2). Readings were measured at the start, at 30-minute intervals, and immediately after exposure completion while in the chamber. At both sites, subjects showed the readings obtained by the automated devices to the investigators but were blinded to the results. The average of the second and third BP and heart rate readings was used in Toronto (7 subjects had only a single reading, which was used). In Ann Arbor, we only performed
a single BP reading at each time point during the exposure, and, therefore, only this single result was used in the analyses.

Holter monitoring was performed in Toronto with a SEER MC ambulatory digital recorder (GE Medical Systems). The 2-channel ECG data were recorded on an 8-Mb flash card and downloaded onto a MARS 8000 workstation (GE Medical Systems) to determine time and frequency domain heart rate variability (HRV). HRV measures were carried out by comparing a 10-minute epoch at the start of all of the exposures while seated within the chamber to one just before the end of the exposures.

Screening laboratory tests were analyzed for fasting lipoproteins and glucose. In Toronto, venous blood was collected before, after, and 24 hours after exposures for ET-1, cytokines, complete blood cell count, and high-sensitivity C-reactive protein. Blood samples were centrifuged and the resulting plasma (ET-1 and cytokines) and serum (C-reactive protein) stored at −70°C. Whole blood was used to make smears for complete blood cell count with an automated analyzer (Coulter, model LH755, Beckman Coulter Canada). A panel of 10 cytokines (see the online Data Supplement) that included TNF-α was analyzed using LiquiChip cytokine kits (Qiagen) and a Luminox analyzer (Luminox). C-reactive protein and lipids were analyzed using a Beckman Synchron LX analyzer (Beckman Coulter). The 2-channel plate luminometer (BMG Labtechnologies). A single BP reading at each time point during the exposure, and, therefore, only this single result was used in the analyses. Holter monitoring was performed in Toronto with a SEER MC ambulatory digital recorder (GE Medical Systems). The 2-channel ECG data were recorded on an 8-Mb flash card and downloaded onto a MARS 8000 workstation (GE Medical Systems) to determine time and frequency domain heart rate variability (HRV). HRV measures were carried out by comparing a 10-minute epoch at the start of all of the exposures while seated within the chamber to one just before the end of the exposures.

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### Results

Subject characteristics are shown in Table 1. The PM$_{2.5}$ mass and ozone concentrations were not different among the exposure limbs in Ann Arbor but significantly differed per design in Toronto (Tables 2 and 3).

#### Toronto Outcomes

FMD and NMD were not impaired immediately after exposures (Table 4). However, FMD significantly decreased 24 hours after CAP exposure compared with the baseline level (Table 4). Moreover, the change in FMD that occurred 24 hours after both exposures containing CAP (CAP and CAP plus ozone) was significantly different than the comparative change occurring after exposures without CAP (ozone and filtered air; Table 4). We defined this mixed-model analysis as a specific effect of "CAP-containing exposures" on outcomes (for other end points as well). The degree of decrease in FMD 24 hours after exposures was significantly associated only with the 2-hour integrated gravimetric PM$_{2.5}$ mass concentration (pooled results for all 4 of the exposure conditions: $\beta=-2.3\%$ per 100 $\mu$g/m$^3$; $P=0.010$; $n=117$ by mixed-model analysis accounting for ozone). Higher concen-

### Table 1. Subject Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Toronto Cohort</th>
<th>Ann Arbor Cohort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>27 ± 8</td>
<td>27 ± 8</td>
</tr>
<tr>
<td>Sex, female/male</td>
<td>15/16</td>
<td>31/19*</td>
</tr>
<tr>
<td>Body mass index, kg · m$^{-2}$</td>
<td>24 ± 4</td>
<td>24 ± 3</td>
</tr>
<tr>
<td>Blood laboratory tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cholesterol, mg · dl$^{-1}$</td>
<td>169 ± 28</td>
<td>166 ± 35</td>
</tr>
<tr>
<td>LDL-C, mg · dl$^{-1}$</td>
<td>107 ± 26</td>
<td>90 ± 31*</td>
</tr>
<tr>
<td>HDL-C, mg · dl$^{-1}$</td>
<td>49 ± 12</td>
<td>59 ± 14*</td>
</tr>
<tr>
<td>Triglycerides, mg · dl$^{-1}$</td>
<td>69 ± 32</td>
<td>88 ± 58*</td>
</tr>
</tbody>
</table>

All of the values are mean ± SD. LDL-C indicates low-density lipoprotein cholesterol; HDL-C, high-density lipoprotein cholesterol. *$P<0.05$ for differences between sites.

#### Table 2. PM$_{2.5}$ Mass Concentration and Ozone Levels During Exposures in Toronto

<table>
<thead>
<tr>
<th>Exposure Measure</th>
<th>Filtered Air</th>
<th>Ozone</th>
<th>CAP</th>
<th>CAP + Ozone</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$, $\mu$g/m$^3$</td>
<td>1.3 ± 8.0</td>
<td>2.8 ± 11.7</td>
<td>148.5 ± 54.4</td>
<td>132.4 ± 38.7</td>
</tr>
<tr>
<td>Ozone, ppb†</td>
<td>10.9 ± 7.2</td>
<td>111.3 ± 6.5</td>
<td>9.7 ± 6.1</td>
<td>109.0 ± 5.6</td>
</tr>
</tbody>
</table>

Values are mean ± SD. PM$_{2.5}$ indicates gravimetric measure (post-exposure – pre-exposure conditioned filter $\Delta$ weight) over 2-h exposure; ozone, Dasibi UV photometric ozone analyzer, mean of 15-s readings over 2-h exposure; ppb, parts per billion. †ANOVA posthoc test (SAS Contrast statement).

#### Table 3. PM$_{2.5}$ Mass Concentration and Ozone Levels During Exposures in Ann Arbor

<table>
<thead>
<tr>
<th>Exposure Measure</th>
<th>Vitamin C</th>
<th>Bosentan</th>
<th>Placebo</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$, $\mu$g/m$^3$</td>
<td>133.2 ± 48.7</td>
<td>142.6 ± 51.6</td>
<td>126.9 ± 55.0</td>
</tr>
<tr>
<td>Ozone, ppb†</td>
<td>122.5 ± 5.5</td>
<td>122.3 ± 2.3</td>
<td>122.0 ± 2.8</td>
</tr>
</tbody>
</table>

Values are mean ± SD. Posthoc tests: vitamin C vs placebo, $P=0.55$; Bosentan vs placebo, $P=0.15$; and vitamin C vs Bosentan, $P=0.36$. PM$_{2.5}$ indicates gravimetric measure (post-exposure – pre-exposure conditioned filter $\Delta$ weight) over 2-h exposure; ppb, parts per billion. †ANOVA (no group differences).

*ANOVA (no group differences).
Diastolic BP significantly linearly increased during CAP-containing exposures (Figure 1), resulting in a significant 2.9-mm Hg increase in diastolic BP (slope CAP = 0.71 ± 0.21 (p=0.002)†) vs (CAP + O3 = 0.89 ± 0.22 (p=0.0003)†) in a linear mixed-model analysis (effect of CAP-containing exposures). There were no differences in outcome Δ responses to exposure when compared across exposure types except for the following: $P<0.01$ for the comparison of the (24-h post-exposure – pre-exposure) Δ values between [(CAP + O3) vs (CAP + O3 + Δ)] in a linear mixed-model analysis. This is defined as an effect of CAP-containing exposures. $P<0.05$ for the comparison of the (post-exposure – pre-exposure) Δ values between [(CAP + O3) vs (CAP + (CAP + O3))] in a linear mixed-model analysis (effect of CAP-containing exposures).

### Ann Arbor Location Outcomes

BAD, arterial compliance, FMD, and NMD were not changed after exposures (Table 6). There was no significant differential change in any outcome in response to exposures at any time point (immediately and 24 hours after exposures) when compared across the 3 different pretreatment limbs (mixed-model analysis).

Throughout the exposures, diastolic BP linearly increased (between 2.5 and 4.0 mm Hg after 2 hours) to a statistically significant increase of 3.7 mm Hg after 2 hours of exposure to CAP. This increase was not quite significant in the mixed model versus filtered air and ozone ($P=0.23$). Ozone exposure was not associated with changes in HRV or BP.

### Table 4. Vascular, Hemodynamic, and Blood Biomarker Results in Toronto (n=31)

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Filtered Air</th>
<th>Ozone Exposure</th>
<th>CAP Exposure</th>
<th>CAP + Ozone Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAD, mm</td>
<td>3.9±0.8</td>
<td>3.8±0.7‡</td>
<td>3.8±0.8</td>
<td>3.7±0.7</td>
</tr>
<tr>
<td>FMD, %</td>
<td>7.2±4.8</td>
<td>8.6±5.8</td>
<td>9.9±7.1</td>
<td>10.5±6.9</td>
</tr>
<tr>
<td>NMD, %</td>
<td>22±7</td>
<td>21±8</td>
<td>22±9</td>
<td>25±11</td>
</tr>
</tbody>
</table>

### Blood laboratory tests

- **Neutrophil, # × 10⁹**
  - Filtered Air: 3.2±1.0
  - Ozone Exposure: 3.3±0.9
  - CAP Exposure: 3.1±1.2
  - CAP + Ozone Exposure: 3.2±1.1

- **WBC, # × 10⁹**
  - Filtered Air: 5.4±1.2
  - Ozone Exposure: 5.7±1.1
  - CAP Exposure: 5.4±1.3
  - CAP + Ozone Exposure: 5.5±1.3

- **log₁₀TNF-α, pg/mL**
  - Filtered Air: 0.7±0.5
  - Ozone Exposure: 0.6±0.6
  - CAP Exposure: 0.6±0.5
  - CAP + Ozone Exposure: 0.6±0.6

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Filtered Air</th>
<th>Ozone Exposure</th>
<th>CAP Exposure</th>
<th>CAP + Ozone Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBP (mm Hg)</td>
<td>72±1</td>
<td>76±2</td>
<td>72±1</td>
<td>76±3</td>
</tr>
<tr>
<td>DIA (mm Hg)</td>
<td>60±2</td>
<td>65±3</td>
<td>60±2</td>
<td>65±3</td>
</tr>
<tr>
<td>BAD, mm</td>
<td>3.9±0.8</td>
<td>3.8±0.7‡</td>
<td>3.8±0.8</td>
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<td>9.9±7.1</td>
<td>10.5±6.9</td>
</tr>
<tr>
<td>NMD, %</td>
<td>22±7</td>
<td>21±8</td>
<td>22±9</td>
<td>25±11</td>
</tr>
</tbody>
</table>

### Endothelial function

- **BAD, mm**
  - Filtered Air: 3.9±0.8
  - Ozone Exposure: 3.8±0.7‡
  - CAP Exposure: 3.8±0.8
  - CAP + Ozone Exposure: 3.7±0.7

- **FMD, %**
  - Filtered Air: 7.2±4.8
  - Ozone Exposure: 8.6±5.8
  - CAP Exposure: 9.9±7.1
  - CAP + Ozone Exposure: 11.5±6.5

- **NMD, %**
  - Filtered Air: 22±7
  - Ozone Exposure: 21±8
  - CAP Exposure: 22±9
  - CAP + Ozone Exposure: 23±10

### Blood laboratory tests

- **WBC indicates white cell count. Values are mean±SD.**
- $*P<0.001$ vs pre-exposure value for same visit (paired t test).
- $†P<0.01$ vs pre-exposure value for same visit (paired t test).
- $‡P<0.05$ vs pre-exposure value for same visit (paired t test).

### Ann Arbor Location Outcomes

BAD, arterial compliance, FMD, and NMD were not changed after exposures (Table 6). There was no significant differential change in any outcome in response to exposures at any time point (immediately and 24 hours after exposures) when compared across the 3 different pretreatment limbs (mixed-model analysis).

Throughout the exposures, diastolic BP linearly increased (between 2.5 and 4.0 mm Hg after 2 hours) to a statistically significant increase of 3.7 mm Hg after 2 hours of exposure to CAP. This increase was not quite significant in the mixed model versus filtered air and ozone ($P=0.23$). Ozone exposure was not associated with changes in HRV or BP.
comparable degree in each pretreatment limb (Figure 2). Although there was a slight blunting of the response, the slope of the diastolic BP increase was not statistically different in the Bosentan limb compared with the other 2 pretreatments limbs. Heart rate (slope: bpm per 30 minutes) significantly increased to a statistically similar degree (P<0.05 by linear mixed-model analysis) during all of the exposure limbs (placebo: 1.05±0.24, P=0.001; Bosentan: 0.78±0.27, P=0.003; vitamin C:0.99±0.27, P=0.001). Systolic BP did not significantly increase.

### Table 5. Associations Between HRV Measures and 2-h Change in Diastolic BP (per 1 mm Hg) During Exposures in Toronto

<table>
<thead>
<tr>
<th>HRV Exposure End—Start Δ</th>
<th>HRV Measurement</th>
<th>β Estimate</th>
<th>95% CI</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency domain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>log10 LF, ms^2</td>
<td>−4.5</td>
<td>−8.3 to −0.7</td>
<td>0.0218</td>
<td></td>
</tr>
<tr>
<td>log10 HF, ms^2</td>
<td>−5.2</td>
<td>−8.4 to −1.9</td>
<td>0.0022</td>
<td></td>
</tr>
<tr>
<td>log10 LF/HF ratio</td>
<td>1.9</td>
<td>−1.6 to 5.5</td>
<td>0.2782</td>
<td></td>
</tr>
<tr>
<td>Time domain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDNN, ms</td>
<td>−0.09</td>
<td>−0.14 to −0.04</td>
<td>0.0006</td>
<td></td>
</tr>
<tr>
<td>rMSSD, ms</td>
<td>−0.07</td>
<td>−0.12 to −0.02</td>
<td>0.0043</td>
<td></td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>0.01</td>
<td>−0.22 to 0.24</td>
<td>0.9216</td>
<td></td>
</tr>
</tbody>
</table>

All of the models included all 4 exposures (97 observations), a random intercept for subject, and the PM2.5 mass concentration during exposure. The original models included ozone ( dichotomous) and the interaction of ozone*PM2.5 concentration, but neither were significant, and thus were removed from the final models. Only 27 subjects had HRV data and were included in these analyses. PM2.5 mass concentration indicates integrated gravimetric measure of PM2.5 in CAP airstream delivered to subject over 2-h exposure; LF, low frequency; HF, high frequency; SDNN, SD of all normal RR intervals; rMSSD, root mean square successive difference in heart rate interval.

### Discussion

This study provides several novel insights into the acute CV effects of air pollution exposure. First, PM2.5, not ozone, was responsible for raising diastolic BP and only transiently during the actual period of inhalation. Second, the results implicate ANS imbalance as the most plausible mechanism underlying this prohypertensive response. Third, PM2.5, not ozone, can additionally impair endothelial function 24 hours after exposure. However, certain aspects of exposure location are major determinant of this response, because it occurred only in downtown Toronto. Fourth, the endothelial dysfunction was triggered via a slower biological pathway, the most likely being systemic inflammation.

### Responsible Air Pollutant and the Importance of Exposure Location

This is the first controlled human exposure study to investigate the effect of ozone on the vasculature, moreover to compare the responses to those induced by PM2.5. The results provide clear evidence that it is PM2.5, not ozone, that causes both the endothelial dysfunction (Toronto) and prohypertensive response (both locations) within minutes to hours of exposure.9–11 Ozone did not cause any adverse CV effects by itself, nor did it augment those induced by PM2.5. Furthermore, higher levels of PM2.5 exposure were associated with larger elevations in diastolic BP and greater reductions in FMD, supporting the linear dose-response relationship between exposure and CV risk.12

Our findings support the concept that aspects of exposure location (eg, PM2.5 composition or sources) critically influence the breadth of CV responses. Particle exposures caused a similar diastolic BP elevation at both sites. On the other hand, only the fine particles from downtown Toronto, which are heavily influenced by local traffic, were capable of...
additionally triggering endothelial dysfunction despite the fact that mass concentrations were nearly identical between sites. Congruent with our findings, particles in Northern Scotland (low in combustion-derived compounds) were shown to have a neutral effect, whereas diesel exhaust (high in combustion particles and gases) was capable of triggering endothelial dysfunction.11

At present we can only speculate about the specific particle constituents or sources accountable for the differential responses between locations, although we can rule out a role played by gases or ozone. The exposure inlet in Toronto faces a downtown urban roadway experiencing 30 000 vehicles per day. The site is surrounded by a dense road network for several kilometers in all directions, and exposures were conducted in the morning when the impact of fresh rush-hour emissions on particle mass and composition was expected to be important.22 In contrast, Ann Arbor is a smaller urban area with much less traffic density in the vicinity of the north campus location. The region surrounding the exposure site quickly becomes rural in the prevailing wind directions, and, thus, the fine particles used in the experiments were more likely derived from long-range transport of background-aged aerosols.23 Future analyses of the filters collected during exposures will provide more specific information regarding the particulate constituents and sources responsible. Nonetheless, the present findings provide compelling evidence that PM2.5 derived from different locations poses varying degrees of risk to the CV system.12

**Biological Mechanisms**

Our findings implicate acute ANS imbalance as the most plausible mechanism for the prohypertensive response. It initiated and terminated rapidly and was associated with an increase in heart rate. The magnitude of diastolic BP elevation during exposures was also most strongly associated with decreases in HRV markers of parasympathetic ANS withdrawal (eg, SD of normal-to-normal intervals; Table 5).19,24 This hypothesis is supported by the fact that human airways are lined with receptors and nerve endings that, after stimulation by inhaled PM2.5, may be capable of altering reflex ANS pathways leading to a blunting of CV parasympathetic tone and a relative favoring of sympathetic activity.24 Indeed, a recent study with dogs has corroborated that diastolic BP acutely increases during 5-hour–long CAP inhalation. This response was mitigated by α-adrenergic receptor antagonism, thus further supporting the central mechanistic importance of the ANS.25 On the other hand, the later-onset elevation in BP (eg, occurring 1 to 5 days postexposure) observed in epidemiological studies is likely elicited by different slower mechanistic pathways (eg, inflammation-induced vascular dysfunction) unrelated to the acute ANS imbalance that increases BP within minutes-to-hours.

Although we had alternatively hypothesized that PM2.5 could raise BP attributed to a systemic oxidative stress-mediated impairment in basal NO-dependent bioavailability (favoring vasoconstriction),9–11 the BP change was unrelated to inflammatory biomarkers (Toronto) and not mitigated by a pretreatment dosage of vitamin C (Ann Arbor) previously shown capable of acutely obviating tobacco smoke–induced oxidative stress and endothelial dysfunction.26 Moreover, the time courses of the endothelial dysfunction and BP elevation were discordant in Toronto. Diastolic BP also increased in Ann Arbor without any change in FMD or arterial compliance. Therefore, it is not likely that the later-onset endothelial dysfunction was mechanistically responsible for the earlier BP increase or that oxidative stress was centrally involved. It has also been speculated that increased ET-1 bioactivity could be responsible.27 However, the nonsignificant changes in plasma ET-1 (Toronto) were unrelated to the BP elevation. Moreover, the relatively large pretreatment dose of Bosentan (Ann Arbor) effectively lowered pre-exposure diastolic BP, suggesting that it achieved physiologically relevant ET-A and -B receptor blockade that should have significantly attenuated any hemodynamic actions of CAP exposure if they had occurred via this pathway. Finally, ET-mediated vasoconstriction is typically of slower onset and of more prolonged duration than the corresponding BP changes observed.28

The mechanisms responsible for the endothelial dysfunction after the CAP-containing exposures in Toronto are less...
clear. However, our findings could most plausibly be interpreted to mean that the dysfunction was triggered by a systemic proinflammatory cascade. It had the expected slower onset of occurrence than responses induced by the ANS. Moreover, the decrease in FMD was associated with an increase in postexposure TNF-α levels. Epidemiological and animal studies support this hypothesis in that PM$_{2.5}$ exposure can cause an increase in a variety of inflammatory cytokines/mediators within the circulation and vasculature. Although C-reactive protein and other measured blood cytokines remained largely unchanged by PM$_{2.5}$, white blood cell count and neutrophils (also blunt markers of inflammation) increased after the CAP-containing exposures that provoked endothelial dysfunction. It is possible that unmeasured proinflammatory factors derived from circulating leukocytes (eg, myeloperoxidase, as demonstrated elsewhere), the increase in TNF-α itself, or other facets of inflammation that we did not measure (or accurately quantify by the cytokine tests) were responsible for impairing FMD. Nevertheless, our results corroborate that ambient PM$_{2.5}$ exposure, at least in some urban locations, is capable of triggering vascular endothelial dysfunction within a day.

**Clinical Implications**

It is important to highlight in the context of short-term and rather low-dose exposures performed on healthy humans that the adverse, yet modest, CV responses observed in this study are actually at the very least on par with past reports. Nevertheless, the observed small degree of diastolic BP elevation and endothelial dysfunction pose little risk to healthy people. However, both are plausible instigators of ischemic events in susceptible individuals by triggering pre-existing atherosclerotic plaque instability and/or by impairing myocardial perfusion. The BP increase could also help explain the associations between PM$_{2.5}$ with strokes and heart failure exacerbations. Moreover, these responses could very conceivably occur in an exaggerated manner in patients with CV risk factors or disease who have a pre-existing ANS imbalance or endothelial dysfunction that renders counterbalancing mechanisms less effective. For example, subjects with hypertension have been shown to have a greater increase in BP in response to ambient PM$_{2.5}$ exposures than normotensives. Diabetics are at greater risk for air pollution–mediated endothelial dysfunction than healthy patients. These findings agree with observations that PM$_{2.5}$ poses much greater acute risks to vulnerable individuals with pre-existing heart disease. Together with our present results, the evidence supports that even short-term PM$_{2.5}$ averages (eg, hourly levels) than are currently regulated may need to be minimized to optimally protect vulnerable individuals from an acute CV event.

**Strengths and Limitations**

This study was the largest human-controlled air pollution exposure protocol yet completed (274 total exposures). Our well-coordinated design and uniform methods between the 2 sites provided us the unique ability to compare CV responses with air pollution from different locations.

It is unclear why we did not replicate previous findings of brachial artery vasoconstriction after CAP plus ozone exposures. We either failed to identify its occurrence, or this vascular territory behaved in a discordant manner between experiments. It is also uncertain why exposures elicited a greater effect on diastolic rather than systolic BP. Additional studies are required, but perhaps the underlying hemodynamic changes responsible reflected a predominant vasoconstriction without changes in cardiac output or arterial compliance (as suggested by the results in Table 6).

We also limited blood biomarker interpretation to the Toronto results because this was where we could account for any filtered air (placebo) effect on these secondary outcomes. The Ann Arbor site did not have a filtered air control; therefore, the blood biomarkers were not analyzed after it was apparent from the results in the Toronto study that controlling for filtered air responses was essential for proper data interpretation. It is unclear why we did not observe the expected decreases in HRV after CAP-containing exposures, despite the fact that reductions in HRV during all of the exposures pooled together were associated with the diastolic BP elevation. Perhaps the sample size was inadequate for discerning dichotomous HRV differences because the study was not powered for this outcome, or the young subjects were less susceptible than studies showing such changes in elderly patients. Future studies that investigate the effect of exposures on baroreflex sensitivity and/or direct microneurography measurement of sympathetic activity are warranted to help further corroborate our findings. A lack of adequate sample size and the very healthy nature of our subjects may also explain why there were no observed increases in cytokines after CAP exposures, although the increase in TNF-α correlated with a reduction in FMD in the pooled analysis. Although the PM$_{2.5}$ concentration was greater than that typically observed over 24 hours, levels $>150 \mu g/m^3$ can occur for 1- to 2-hour periods in many North American locations and are commonly encountered over even longer durations throughout developing nations.

It is a possible limitation that gaseous pollutants (eg, CO, nitrogen oxides, and sulfur oxides) were not measured during all of the exposures. However, these gases, along with any volatile vapor phase pollutants, are at (or below) ambient levels in the concentrator system. As such, per our study design, the concentrations of these pollutants were expected to be at similar and ambient levels during all of the exposures at both sites. They were, thus, not likely to differ between exposures to any meaningful degree, nor are they, therefore, likely to explain any of the responses. Although it is not impossible that these other pollutants (eg, gases or vapor phase compounds) could have played a small role, the sum of our findings (particularly the independent statistical associations of BP and FMD with PM$_{2.5}$ mass) along the concentrator systems used makes it much more likely that the fine particles were principally responsible for the observed results.

There were small differences in triglycerides, low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, and the female: male ratio of subjects between sites (Table 1). However, the values were all well within the normal range, and all of the subjects were healthy without overt CV disease,
risk factors, and/or any parameter known to alter the risk of air pollution exposure.\textsuperscript{1,2} At both sites, these parameters were not associated with the FMD responses to exposures. In addition, even overt hyperlipidemia has not been shown to be a risk-effect modifier to air pollution exposure.\textsuperscript{1,2} Therefore, we do not believe that these small differences account for the observed FMD response differences between sites.

**Conclusions**

Our findings provide plausible mechanisms whereby even brief contact with high levels of real-world ambient PM\textsubscript{2.5} can promote acute CV events. They also illustrate that aspects of exposure location and, hence, particle source and/or composition can play a critical role in determining the breadth of the adverse reactions. We believe it important to examine whether shorter (eg, hourly) time frames of ambient PM\textsubscript{2.5} reductions beyond existing 24-hour–long hour standards can have a positive impact on the health of vulnerable populations.\textsuperscript{3,4}

**Perspectives**

PM\textsubscript{2.5} air pollution is a leading cause of worldwide mortality. Exposure to ozone is also associated with an increased risk of premature death. We demonstrated that PM\textsubscript{2.5} exposure, not ozone, causes a significant increase in diastolic BP and impairs endothelial function, but only from particles derived from an urban environment. The results implicate changes in ANS activity as the cause for the acute increase in BP, whereas the slower impairment in vascular function was likely attributable to systemic inflammatory responses. These are important new insights into the mechanisms whereby air pollution impairs biological harm. The findings confirm that even transient contact with relevant concentrations of PM\textsubscript{2.5} can rapidly instigate physiological responses potentially capable of triggering acute CV events in susceptible individuals. In addition to bolstering the veracity of the epidemiological associations linking air pollution with excess CV-related mortality, the findings suggest that the characteristics of the particles are likely to be important determinants of the health consequences after exposure. Overall, these study results further strengthen the justification for environmental regulations on ambient PM\textsubscript{2.5}.

**Acknowledgments**

HRV analyses were generously carried out at the Beth Israel Deaconess Medical Center (Boston) under the direction of Dr Murray Mittleman with support from the National Institutes of Environmental Health grant P01 ES009825.

**Sources of Funding**

This project was supported by a grant from the US Environmental Protection Agency, 2002-STAR-G1 (CR830837), and from a National Institutes of Health General Clinical Research Center Grant (M01-RR000042), as well as support from Natural Resources Canada and Air Quality Health Effects Research Section, Government of Canada (Toronto Study).

**Disclosures**

None.

**References**


Insights Into the Mechanisms and Mediators of the Effects of Air Pollution Exposure on Blood Pressure and Vascular Function in Healthy Humans

Hypertension. published online July 20, 2009;
Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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Insights into the Mechanisms and Mediators of the Effects of Air Pollution Exposure on Blood Pressure and Vascular Function in Healthy Humans

Online Supplement


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Supplemental Methods

At both locations, Institutional Review Board-approved advertisements (newspapers, fliers, web-sites) were used locally to recruit potential subjects. In the Toronto sub-study, a blinded block randomization protocol with balanced exposure order sequence was generated by the study investigators. We screened a total of 56 people for the study. There were 18 potential subjects that did not meet inclusion criteria or did not want to enroll into the study. Among study participants, 30 subjects completed all 4 exposures. One subject completed only 3 exposures. One subject’s data were not adequate for technical reasons for use in analyses.

In the Ann Arbor sub-study, a blinded randomization protocol with balanced pre-treatment order sequence was generated by the University of Michigan General Clinical Research Center Statistical Core and by the Investigative Pharmacy Services. There were 56 subjects who underwent screening but only 50 subjects were randomized and underwent exposures. Five subjects did not participate because of scheduling conflicts and one subject did not meet the inclusion criteria requirements. Of the 50 randomized subjects, 49 subjects completed the entire study (3 exposures) and one only completed 2 exposures because of a missed appointment and an inability to reschedule the appointment.

The study was designed to have a sample size of 50 subjects in Ann Arbor with each participant receiving 3 exposures (150 exposures). The design was for 30 subjects in Toronto with each participant receiving 4 exposures (120 exposures). The sample size was set a priori based upon feasibility of performing this number of exposures over the study period. Previous studies performed by the investigators have demonstrated an ability to observe meaningful alterations in the cardiovascular outcomes (blood pressure and vasoconstriction) with similar (or even fewer) subjects. Based upon this feasible study sample size, we estimated potential observable effect sizes for changes in flow-mediated dilatation (FMD) as the primary outcome. If changes in FMD were plausibly observable, then changes in the other vascular outcomes (brachial artery diameter and blood pressure) would also be observable given the same sample size. These outcomes have much smaller variability in relation to their mean effect sizes and the study would be adequately powered for these outcomes as well. Therefore, the more conservative outcome of FMD was chosen as the primary variable to estimate feasibility of observing effects with the fixed sample sizes at each site.

<table>
<thead>
<tr>
<th>Chart of estimated effects sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ann Arbor</strong></td>
</tr>
<tr>
<td>n=50 (3 cross-over)</td>
</tr>
<tr>
<td>Power=80%</td>
</tr>
<tr>
<td>Alpha=.05</td>
</tr>
<tr>
<td>OUTCOME</td>
</tr>
<tr>
<td>FMD</td>
</tr>
<tr>
<td>DBP</td>
</tr>
<tr>
<td>BAD</td>
</tr>
<tr>
<td>r (within subject correlation)</td>
</tr>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
</tr>
<tr>
<td>Detectable Effect Size (F)</td>
</tr>
<tr>
<td>0.25</td>
</tr>
<tr>
<td>0.12</td>
</tr>
<tr>
<td>0.08</td>
</tr>
<tr>
<td>medium</td>
</tr>
<tr>
<td>small</td>
</tr>
<tr>
<td>small</td>
</tr>
</tbody>
</table>

| **Toronto**                      |
| n=30 (4 cross-over)              |
| Power=80%                        |
| Alpha=.05                        |
| OUTCOME                          |
| r (within subject correlation)    |
| 0.05                             |
| 0.8                              |
| 0.9                              |
The data demonstrate that with the sample size of n=50 in Ann Arbor and n=30 in Toronto we will have 80% power to detect a medium-sized effect size for FMD and very small effect sizes for DBP and BAD. Thus, we have adequate power to determine moderate size changes in endothelial function, and the power to detect very small changes in blood pressure and brachial diameter (vasoconstriction). These are based upon a priori data related to each outcome. Post hoc analyses confirm the power calculations.

References

Table S1. Hemodynamic Results in Toronto Exposures Outside the Chamber (before and after exposures).

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Filtered Air</th>
<th>Ozone Exposure</th>
<th>CAP Exposure</th>
<th>CAP+Ozone Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>24 hr pst</td>
<td>Pre</td>
</tr>
<tr>
<td>Ambulatory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>112.5 ± 12.3</td>
<td>114.7 ± 8.5</td>
<td>112.2 ± 11.2</td>
<td>112.6 ± 9.2</td>
</tr>
<tr>
<td>DBP (mm Hg)</td>
<td>71.0 ± 7.4</td>
<td>73.9 ± 8.6†</td>
<td>66.7 ± 8.5†</td>
<td>70.9 ± 7.1</td>
</tr>
<tr>
<td>HR (beats•min⁻¹)</td>
<td>71.6 ± 12.6</td>
<td>74.4 ± 11.8</td>
<td>74.8 ± 10.9</td>
<td>75.3 ± 11.7</td>
</tr>
</tbody>
</table>

Means ± SD. N=31 subjects (114 observations for BP and 99 for HR).

SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate.

* p<0.001 versus pre-exposure value for same visit.
† p<0.01 versus pre-exposure value for same visit.
‡ p<0.05 versus pre-exposure value for same visit.

Mixed Model Results: no CAP or Ozone effects for SBP, DBP or HR.
There were no significant differences in the Δ responses for any outcome by mixed model between exposure types.
## Table S2. Heart Rate Variability Results in Toronto.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Filtered Air Exposure</th>
<th>CAP Exposure</th>
<th>CAP+Ozone Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>Δ</td>
</tr>
<tr>
<td>HRV: Time-Domain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDNN (msec)</td>
<td>69.8 ± 35.0</td>
<td>75.5 ± 29.5</td>
<td>5.7 ± 23.1</td>
</tr>
<tr>
<td>rMSSD (msec)</td>
<td>55.6 ± 44.2</td>
<td>46.3 ± 30.4</td>
<td>-9.3 ± 39.2</td>
</tr>
<tr>
<td>HRV: Frequency-Domain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log LF</td>
<td>2.96 ± 0.45</td>
<td>3.06 ± 0.38</td>
<td>0.10 ± 0.33</td>
</tr>
<tr>
<td>Log HF</td>
<td>2.75 ± 0.64</td>
<td>2.69 ± 0.55</td>
<td>-0.05 ± 0.47</td>
</tr>
<tr>
<td>Log LF/HF</td>
<td>0.22 ± 0.44</td>
<td>0.37 ± 0.39</td>
<td>0.15 ± 0.34†</td>
</tr>
<tr>
<td>HRV: Heart Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. HR (beats/min)</td>
<td>69.8 ± 8.8</td>
<td>73.2 ± 8.5</td>
<td>3.4 ± 4.7†</td>
</tr>
</tbody>
</table>

Means ± SDs. N=27 subjects. Frequency domain values (msec²) log₁₀-transformed to normalize.

HRV, heart rate variability assessed during first (start) and last (end) five minutes of 2-hr exposure; SDNN, standard deviation of all NN intervals; rMSSD, square root of the mean of the squared differences between adjacent NN intervals; LF, low frequency power (0.05-0.15 Hz); HF, high frequency power (0.15-0.4 Hz); LF/HF, ratio of LF to HF power; Avg. HR, average heart rate.

*p<0.001, Δ= end - start exposure value for same visit.
†p<0.01, Δ= end - start exposure value for same visit.
‡p<0.05, Δ= end - start exposure value for same visit.

Mixed Model Results: no CAP or Ozone differential effects for any HRV measures. There were no significant differences in the Δ responses for any outcome by mixed model between exposure types.
Table S3. Blood Cytokine and C-Reactive Protein Results in Toronto.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Pre</th>
<th>Filtered Air Post</th>
<th>24 hr pst</th>
<th>Pre</th>
<th>Ozone Exposure Post</th>
<th>24 hr pst</th>
<th>Pre</th>
<th>CAP Exposure Post</th>
<th>24 hr pst</th>
<th>Pre</th>
<th>CAP+Ozone Exposure Post</th>
<th>24 hr pst</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-1β</td>
<td>-0.60 ± 1.47</td>
<td>-0.53 ± 1.40</td>
<td>-0.64 ± 1.50</td>
<td>-0.44 ± 1.36</td>
<td>-0.46 ± 1.31</td>
<td>-0.55 ± 1.47</td>
<td>-0.55 ± 1.42</td>
<td>-0.43 ± 1.29</td>
<td>-0.60 ± 1.40</td>
<td>-0.53 ± 1.37</td>
<td>-0.49 ± 1.42</td>
<td>-0.57 ± 1.34</td>
</tr>
<tr>
<td>IL-2</td>
<td>0.05 ± 0.93</td>
<td>-0.11 ± 0.99</td>
<td>-0.05 ± 0.99</td>
<td>-0.11 ± 0.96</td>
<td>-0.06 ± 0.99</td>
<td>-0.21 ± 1.00</td>
<td>-0.11 ± 1.02</td>
<td>-0.09 ± 0.99</td>
<td>-0.22 ± 0.96</td>
<td>-0.06 ± 0.95</td>
<td>-0.26 ± 0.95</td>
<td>-0.15 ± 0.96</td>
</tr>
<tr>
<td>IL-4</td>
<td>0.18 ± 1.11</td>
<td>0.11 ± 1.29</td>
<td>0.30 ± 1.03</td>
<td>0.08 ± 1.23</td>
<td>0.13 ± 1.24</td>
<td>0.29 ± 1.17</td>
<td>0.22 ± 1.10</td>
<td>0.16 ± 1.13</td>
<td>0.02 ± 1.22</td>
<td>0.23 ± 1.06</td>
<td>0.20 ± 1.12</td>
<td>0.21 ± 1.12</td>
</tr>
<tr>
<td>IL-6</td>
<td>0.50 ± 0.93</td>
<td>0.51 ± 1.01†</td>
<td>0.62 ± 0.93</td>
<td>0.51 ± 0.99</td>
<td>0.50 ± 1.02</td>
<td>0.52 ± 1.00</td>
<td>0.51 ± 0.99</td>
<td>0.47 ± 1.00</td>
<td>0.48 ± 1.04</td>
<td>0.47 ± 1.01</td>
<td>0.43 ± 1.06</td>
<td></td>
</tr>
<tr>
<td>IL-10</td>
<td>-0.25 ± 0.80</td>
<td>-0.45 ± 0.86</td>
<td>-0.26 ± 0.81</td>
<td>-0.28 ± 0.81</td>
<td>-0.28 ± 0.88</td>
<td>-0.27 ± 0.90</td>
<td>-0.27 ± 0.79</td>
<td>-0.30 ± 0.78</td>
<td>-0.39 ± 0.71</td>
<td>-0.46 ± 0.74</td>
<td>-0.38 ± 0.83</td>
<td>-0.52 ± 0.81</td>
</tr>
<tr>
<td>IL-12</td>
<td>0.75 ± 0.98</td>
<td>0.74 ± 0.96</td>
<td>0.85 ± 0.93</td>
<td>0.70 ± 0.93</td>
<td>0.77 ± 1.00</td>
<td>0.70 ± 1.02</td>
<td>0.66 ± 0.91</td>
<td>0.64 ± 0.90</td>
<td>0.51 ± 0.91</td>
<td>0.52 ± 0.97</td>
<td>0.57 ± 0.94</td>
<td>0.56 ± 0.97</td>
</tr>
<tr>
<td>GM-CSF</td>
<td>0.85 ± 0.90</td>
<td>0.96 ± 0.78</td>
<td>0.82 ± 0.95</td>
<td>0.89 ± 0.96</td>
<td>1.00 ± 0.94</td>
<td>0.99 ± 1.00</td>
<td>0.90 ± 0.70</td>
<td>0.91 ± 0.78</td>
<td>0.78 ± 0.81</td>
<td>0.83 ± 0.82</td>
<td>0.82 ± 0.89</td>
<td>0.87 ± 0.84</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>1.05 ± 0.71</td>
<td>1.02 ± 0.81†</td>
<td>1.05 ± 0.75</td>
<td>1.07 ± 0.94</td>
<td>1.01 ± 0.76</td>
<td>0.84 ± 0.95</td>
<td>0.95 ± 0.80</td>
<td>0.85 ± 0.99</td>
<td>0.94 ± 0.82</td>
<td>0.97 ± 0.69</td>
<td>0.91 ± 0.84</td>
<td>0.88 ± 0.92</td>
</tr>
<tr>
<td>TNF-α</td>
<td>0.65 ± 0.51</td>
<td>0.57 ± 0.53</td>
<td>0.60 ± 0.55</td>
<td>0.61 ± 0.52</td>
<td>0.60 ± 0.53</td>
<td>0.55 ± 0.59</td>
<td>0.54 ± 0.53</td>
<td>0.51 ± 0.49</td>
<td>0.38 ± 0.55</td>
<td>0.51 ± 0.58</td>
<td>0.54 ± 0.62</td>
<td>0.57 ± 0.57</td>
</tr>
<tr>
<td>CRP (mg•L⁻¹)</td>
<td>1.32 ± 1.83</td>
<td>1.48 ± 2.45</td>
<td>1.35 ± 1.73</td>
<td>1.00 ± 1.36</td>
<td>1.04 ± 1.54</td>
<td>1.09 ± 1.47</td>
<td>0.93 ± 1.25</td>
<td>0.97 ± 1.32</td>
<td>1.04 ± 1.65</td>
<td>1.73 ± 3.25</td>
<td>1.68 ± 3.03</td>
<td>1.73 ± 2.40</td>
</tr>
</tbody>
</table>

Means ± SDs. Cytokines: Values ≤ 0 not included; N=33 subjects (86-125 observations); values (pg/ml) log₁₀-transformed to normalize.

Note: IL-8 only had 10 observations with values > 0.

CRP: Values below the detection limit (0.2 mg/mL) were assigned a value of 0.1 mg/dL; N=31 (123 observations).

IL, interleukin; GM-CSF, granulocyte-macrophage colony stimulating factor; IFN-γ, interferon gamma; TNF-α, tumor necrosis factor alpha; CRP, C-reactive protein.

†p<0.01 versus pre-exposure value for same visit (paired t-test).
‡p<0.05 versus pre-exposure value for same visit (paired t-test).

ap=0.016; for the comparison of the (24 hr post - pre-exposure) Δ values between [(FA Δ + O₃ Δ) versus (CAP Δ + CAP+O₃ Δ)] in a linear mixed model analysis. This is defined as an “effect of CAP-containing exposures” due to the large number of comparisons (all exploratory secondary analyses) and the unusually low IL-4 value 24 hours post-CAP, we believe and interpret this result to be a chance finding.

There were no other significant differences in the Δ responses for any outcome by mixed model between exposure types.
Figure S1  Study protocol outlines

Toronto Study

- HEF 2-hour exposure to:
  1. CAP + O₃
  2. CAP
  3. O₃
  4. Filtered Air

- 2 weeks later Cross-over to alternative exposure-type

- 31 subjects

- Vascular Studies
  Brachial FMD, NMD
  Blood draw

- 30 min BP

- 1 day

Ann Arbor Study

- Vascular Studies
  Brachial FMD, NMD
  Arterial Compliance (HDI)
  Blood draw

- Placebo

- 50 Subjects

- Vitamin C 2000 mg

- Bosentan 250 mg

- 2 hours

- 24 hour AMBP monitoring

- 30 min BP

- 2 weeks later Crossover to alternative pretreatment prior to next exposure.

- AirCare 1
  CAP (~150 μg/m³) + O₃ (120 ppb)

- 24 hour AMBP monitoring

HEF, Human exposure facility; FMD, flow mediated dilatation; NMD, nitroglycerin mediated dilatation; CAP, concentrated ambient particles; O₃, ozone