Particulate air pollution has been associated with adverse respiratory health effects. This study assessed the utility of expired nitric oxide to detect acute airway responses to metal-containing fine particulates. Using a repeated-measures study design, we investigated the association between the fractional concentration of expired nitric oxide ($F_{ENO}$) and exposure to particulate matter with an aerodynamic mass median diameter of $\leq 2.5\ \mu m$ ($PM_{2.5}$) in boilermakers exposed to residual oil fly ash and metal fumes. Subjects were monitored for 5 days during boiler repair overhauls in 1999 ($n = 20$) or 2000 ($n = 14$). The Wilcoxon median baseline $F_{ENO}$ was 10.6 ppb (95% confidence interval (CI): 9.1, 12.7) in 1999 and 7.4 ppb (95% CI: 6.7, 8.0) in 2000. The Wilcoxon median $PM_{2.5}$ 8-hr time-weighted average was 0.56 mg/m$^3$ (95% CI: 0.37, 0.93) in 1999 and 0.86 mg/m$^3$ (95% CI: 0.65, 1.07) in 2000. $F_{ENO}$ levels during the work week were significantly lower than baseline $F_{ENO}$ in 1999 ($p < 0.001$). A significant inverse exposure–response relationship between log-transformed $F_{ENO}$ and the previous workday’s $PM_{2.5}$ concentration was found in 1999, after adjusting for smoking status, age, and sampling week. With each 1 mg/m$^3$ incremental increase in $PM_{2.5}$ exposure, log $F_{ENO}$ decreased by 0.24 (95% CI: −0.38, −0.10) in 1999. The lack of an exposure–response relationship between $PM_{2.5}$ exposure and $F_{ENO}$ in 2000 could be attributable to exposure misclassification resulting from the use of respirators. In conclusion, occupational exposure to metal-containing fine particulates was associated with significant decreases in $F_{ENO}$ in a survey of workers with limited respirator usage. Key words: air pollutants, epidemiology, nitric oxide, occupational, particulate matter. Environ Health Perspect 111:676–680 (2003). doi:10.1289/ehp.5880 available via http://dx.doi.org [Online 31 October 2002]
of oil-fired boilers. Twenty subjects were monitored in June 1999, and 14 subjects, including two from 1999, were monitored in October 2000. Self-administered questionnaires were used to obtain information on medical history, including respiratory symptoms and diseases, smoking history, and occupational history.

FENO collection. FENO samples were collected before and after work shifts each day during a 5-day sampling period. Baseline FENO samples were collected before the work shift on the first day of the work week, after 1–2 days away from work. The offline collection and measurement of FENO were in accordance with American Thoracic Society (ATS) recommendations (ATS 1999). Subjects were asked to refrain from smoking in the 1 hr preceding NO sampling. Subjects wore nose clips and tidal breathed for 30 sec through an apparatus containing two one-way valves with a NO-scrubbing filter attached to the intake limb to prevent sample contamination by ambient NO. Subjects then inhaled to total lung capacity and expired their entire vital capacity into a Mylar balloon attached to the expiratory limb while maintaining an oropharyngeal pressure of 12.5 cm H2O. The NO levels in the balloons were measured using a calibrated GilAir5 pump (Sensidyne Inc., Auburn, ME). Those who had reproducible spirometry and PM1.5 exposure were included in the model. The level of significance for all analyses was 0.05.

Results

Description of study population. Population demographic data are summarized in Table 1. The study population consisted of 32 men, 31 of whom were white (97%). Thirteen of the 32 subjects (41%) were current cigarette smokers. Their ages ranged from 18 to 59 years, with 2 weeks to 40 years of boilermaking experience. Twenty subjects were sampled in 1999, and 14 subjects, including two that were monitored in 1999, were sampled in 2000. Of the 32 subjects, six subjects entered the cohort on the second day of sampling because they had not attended work the previous day. Three subjects dropped out of the study after the fourth day of sampling; two subjects were transferred to a different work shift, and one subject did not come to work on the last day of sampling.

Six of the 32 subjects (19%) had chronic obstructive pulmonary disease (COPD), as defined by ATS (1995). Five subjects had chronic bronchitis, as diagnosed by a physician or with symptoms as defined by ATS (1995). One subject had emphysema diagnosed by a physician. None of the subjects with COPD were on medications that could influence expired NO levels. All analyses were performed initially with the total cohort, and then analyses were rerun after excluding the subjects with COPD. Because the results from the two analyses did not differ significantly, the final results included all 32 subjects. The baseline spirometry results are summarized in Table 1. Only subjects with reproducible FEV1 on both days that spirometry was performed were included in the spirometry analyses. None of the demographic information was significantly different between those who had reproducible spirometry and cigarette smoking status (yes/no), age, and sampling year. In addition, an interaction term between sampling year and PM1.5 exposure was included in the model. The level of significance for all analyses was 0.05.

Table 1. Study population characteristics by sampling year.

<table>
<thead>
<tr>
<th>Study population characteristics</th>
<th>1999</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>20</td>
<td>14*</td>
</tr>
<tr>
<td>Number (%) of current smokers</td>
<td>9 (45%)</td>
<td>5 (36%)</td>
</tr>
<tr>
<td>Number (%) of subjects with COPD</td>
<td>4 (20%)</td>
<td>2 (14%)</td>
</tr>
<tr>
<td>Age, years</td>
<td>Mean ± SD: 45.4 ± 12.0</td>
<td>41.5 ± 11.1</td>
</tr>
<tr>
<td>Range</td>
<td>18–59</td>
<td>20–55</td>
</tr>
<tr>
<td>Years as boilermaker</td>
<td>Mean ± SD: 21.7 ± 12.9</td>
<td>17.4 ± 13.5</td>
</tr>
<tr>
<td>Range</td>
<td>0.04–40</td>
<td>0.08–36</td>
</tr>
<tr>
<td>Number (%) of subjects with complete spirometry data</td>
<td>14 (70%)</td>
<td>9 (84%)</td>
</tr>
<tr>
<td>Mean ± SD baseline percent predicted FEV1</td>
<td>95.8 ± 11.3</td>
<td>92.8 ± 9.2</td>
</tr>
<tr>
<td>Mean ± SD baseline percent predicted FVC</td>
<td>95.4 ± 14.6</td>
<td>93.6 ± 8.1</td>
</tr>
<tr>
<td>Mean ± SD baseline percent FEV1/FVC</td>
<td>79.5 ± 7.0</td>
<td>79.3 ± 9.9</td>
</tr>
</tbody>
</table>

*Includes two subjects that were also monitored in 1999. Includes one subject that was also monitored in 1999. Includes only subjects with reproducible spirometric values on both days that spirometry was performed. Spirometric predictions were based on predicted normal values by Hankinson et al. (1999).
those who did not. The mean baseline percent predicted FEV\textsubscript{1} was 95.8% (SD 11.3) in 1999 and 92.8% (SD 9.2) in 2000. The mean baseline percent predicted FVC was 95.4% (SD 14.6) in 1999 and 93.6% (SD 8.1) in 2000. The mean baseline percent predicted FEV\textsubscript{1} and FVC values were not statistically different in the two sampling years (p > 0.2).

**Baseline measurements of F\textsubscript{2}NO.** The baseline measurements of F\textsubscript{2}NO are shown in Table 2. Baseline measurements were taken on average 2 days after work in 1999 and 1 day away from work in 2000. Wilcoxon confidence intervals (CIs) and corresponding medians are presented because of the positively skewed distribution of F\textsubscript{2}NO. In the 1999 cohort, the median baseline F\textsubscript{2}NO was 8.8 ppb (95% CI: 7.0, 13.6) for smokers and 12.2 ppb (95% CI: 9.8, 15.9) for nonsmokers. In the 2000 cohort, the median baseline F\textsubscript{2}NO was 7.6 ppb (95% CI: 6.5, 8.3) for smokers and 7.4 ppb (95% CI: 6.2, 8.6) for nonsmokers. The median baseline F\textsubscript{2}NO across the two sampling years was significantly different for nonsmokers (p = 0.002) but not for smokers (p < 0.20).

**Exposure assessment.** The occupational PM\textsubscript{2.5} exposures for the 1999 and 2000 survey periods are shown in Table 3. The mean sampling time was 8.8 hr (SD 1.2) in 1999 and 10.9 hr (SD 1.3) in 2000. The difference in the average time monitored in the two sampling years was due to the difference in work shift length. During the overhaul in 1999, the boilermakers worked 10-hr shifts, whereas in 2000 most of the boilermakers worked 12-hr shifts. To account for this difference in work shift length, PM\textsubscript{2.5} concentrations were standardized to 8-hr time-weighted averages (TWAs). The Wilcoxon median PM\textsubscript{2.5} 8-hr TWA was 0.56 mg/m\textsuperscript{3} (95% CI: 0.37, 0.93) in 1999 and 0.86 mg/m\textsuperscript{3} (95% CI: 0.65, 1.07) in 2000. The median PM\textsubscript{2.5} 8-hr TWAs were marginally different in the two sampling years (p = 0.06).

In 1999, 85% of the subjects stated in the questionnaires that they wore respirators while performing boiler maintenance and repair. However, it was noted by the field team that the actual use of respirators while working was limited because of the high temperatures and limited ventilation inside the power plant. Data from the National Weather Service, Boston Weather Forecast Office (Taunton, MA), indicated that the maximum temperature in Boston, Massachusetts, was 92°F (33°C) to 97°F (36°C) during the first half of the 1999 sampling period. In the 2000 sampling period, 85% of the subjects also stated that they wore respirators while working. In contrast to 1999 observations, the field team observed that respirator use was more common in 2000. The maximum temperature in Boston during the 2000 sampling period ranged from 53°F (12°C) to 65°F (18°C). The cooler temperature may have made use of respirators more tolerable. The respirators typically used were the half-mask particulate respirators equipped with a high-efficiency particulate air (HEPA) filter, which has a particle filter efficiency of 99.97% for particles with an aerodynamic mass median diameter of 0.3 μm (NIOSH 1996).

**Changes in F\textsubscript{2}NO and spirometric parameters.** The changes in F\textsubscript{2}NO and spirometric parameters after occupational particulate exposure were calculated as the difference in the prework measurements from baseline (day 1) to day 5 of sampling. Measurements from day 5 were used to compare with the baseline levels because day 5 was the only workday during which both spirometry and F\textsubscript{2}NO samples were collected. The changes in F\textsubscript{2}NO and spirometric measurements are shown in Table 4. The mean change in F\textsubscript{2}NO was −5.5 ppb (95% CI: −8.8, −2.1) for 1999 subjects and +1.0 ppb (95% CI: −0.2, 2.2) for 2,000 subjects. The changes in F\textsubscript{2}NO for each individual are shown in Figure 1.

A similar trend was seen in the mean change in FEV\textsubscript{1} and FVC. The mean change in FEV\textsubscript{1} was −0.17 L (95% CI: −0.24, −0.09) for 1999 and −0.05 L (95% CI: −0.19, 0.09) for 2000. Likewise, the mean change in FVC was −0.14 L (95% CI: −0.23, −0.04) for 1999 subjects and +0.02 L (95% CI: −0.18, 0.22) for 2000 subjects. Compared with baseline levels, the F\textsubscript{2}NO, FEV\textsubscript{1}, and FVC values were significantly lower on day 5 in the 1999 subjects (p < 0.01). In contrast to 1999 data, the F\textsubscript{2}NO, FEV\textsubscript{1}, and FVC values from day 5 did not differ statistically from the baseline measurements in 2000. The changes in F\textsubscript{2}NO, FEV\textsubscript{1}, and FVC values did not differ by smoking status.

Baseline-adjusted changes were used to determine the correlation between F\textsubscript{2}NO and spirometric parameters. In both 1999 and 2000, the changes in F\textsubscript{2}NO were significantly correlated to the changes in FEV\textsubscript{1} (p = 0.51, p = 0.01) and moderately correlated with changes in FVC (p = 0.39, p = 0.07).

**Association between F\textsubscript{2}NO and PM\textsubscript{2.5} exposure.** There was a weak correlation between PM\textsubscript{2.5} 8-hr TWA exposure and the postshift F\textsubscript{2}NO on the same day (r = −0.06, p = 0.60). Furthermore, the linear models did not indicate a significant association between postshift F\textsubscript{2}NO and PM\textsubscript{2.5} exposure from the previous workday (r = −0.22, p = 0.03). Therefore, analyses were restricted to regressing postshift F\textsubscript{2}NO on PM\textsubscript{2.5} exposure the previous day.

Linear models indicated that PM\textsubscript{2.5} exposure was associated with a decrease in log F\textsubscript{2}NO in the sampling year 1999. With each 1 mg/m\textsuperscript{3} increase in PM\textsubscript{2.5} exposure, log F\textsubscript{2}NO decreased by 0.24 (95% CI: −0.38, −0.10) after adjusting for dichotomized cigarette smoking status, age, and sampling year. Cigarette smoking was significantly associated.
with a change of −0.22 (95% CI: −0.36, −0.08) in log F_{E,NO}. Residual analysis indicated that there were two subjects with standardized residuals greater than 2. After excluding the two potential statistical outliers, log F_{E,NO} decreased by 0.19 (95% CI: −0.32, −0.05) for each 1 mg/m³ of PM_{2.5} exposure. Although the two outlying subjects increased the magnitude of the association between PM_{2.5} exposure and log F_{E,NO}, their influence was marginal.

For the subjects sampled in year 2000, there was no association between PM_{2.5} exposure on the previous workday and preshift log F_{E,NO}. After adjusting for cigarette smoking status, age, and sampling year, the PM_{2.5} regression coefficient was 0.02 (95% CI: −0.15, 0.18).

**Discussion**

In the present study, short-term occupational exposure to particulates was associated with a significant decrease in F_{E,NO} and spirometric indices. A significant inverse exposure–response association between log F_{E,NO} and PM_{2.5} 8-hr TWA exposure was found. However, these associations were seen only in subjects tested in 1999. In the group of boilermakers sampled in 2000, there was no change in F_{E,NO} or spirometric indices, and no exposure–response relationship between log F_{E,NO} and PM_{2.5} exposure.

A possible explanation for the lack of change in F_{E,NO} and spirometric parameters, and lack of an exposure–response relationship between PM_{2.5} exposure and F_{E,NO} in the 2000 subjects could be attributable to respirator use. During the sampling week in June 1999, temperatures neared 100°F (38°C) inside the power plant because of a heat wave and limited ventilation. The difficult environmental conditions might have prevented the boilermakers from wearing their respirators. In contrast, the climate was much cooler during the sampling period in October 2000, making the use of respirators more tolerable. Because the half-mask respirators used by the boilermakers had a particle filter efficiency greater than 99% for particles with an aerodynamic mass median diameter of 0.3 μm, respirator use would have significantly decreased the exposure to particulates during the sampling year 2000. The reduced particulate exposure might explain the lack of a difference between baseline F_{E,NO}, FEV_{1}, and FVC measurements and measurements taken during the work week in 2000.

During both sampling years, the PEMs were placed on the lapels of the subjects, near their breathing zones. Based on observations made in 1999, no modifications were made in the exposure assessment procedure to adjust for respirator use in 2000. Because the subjects in 2000 were more likely to wear respirators, the PM_{2.5} measurements during this sampling year were less likely to represent true exposure. The PM_{2.5} measurement error might be responsible for the lack of an exposure–response relationship between PM_{2.5} and F_{E,NO} in 2000. We were unable to estimate the effect of respirator use on PM_{2.5} exposure because usage was inconsistent and the fit of the respirators was unknown because of factors such as the presence of facial hair.

Changes in F_{E,NO} from baseline to day 5 were strongly correlated with changes in FEV_{1} (r = 0.51, p = 0.01) and moderately correlated with changes in FVC (r = 0.39, p = 0.07) in subjects from both sampling years 1999 and 2000. Other studies have also examined the relationship between F_{E,NO} and spirometric indices. Jones et al. (2001) showed a negative correlation between changes in F_{E,NO} and changes in FEV_{1} (r = −0.35, p < 0.002) across weeks. The conflicting results between the Jones et al. study and our study may be attributable to the difference in the study populations. The population in our study generally consisted of healthy subjects, whereas Jones et al. studied asthmatics. The relationship between expired NO and FEV_{1} may be dependent on the subjects' states of airway inflammation. Although an increase in F_{E,NO} indicates loss of asthma control in asthmatics (Kharitonov et al. 1994; Massaro et al. 1996), a decrease in F_{E,NO} from normal levels in healthy individuals may be considered an adverse response, as in the case of smokers (Kharitonov et al. 1995). In the present study, a decrease in F_{E,NO} was associated with a decrease in FEV_{1}, both adverse respiratory responses in healthy individuals.

In our study, a significant inverse exposure–response association between the previous workday's PM_{2.5} 8-hr TWA exposure and the next day's preshift log F_{E,NO} was found in the subjects in 1999. With the median PM_{2.5} exposure of 0.56 mg/m³, F_{E,NO} declined by 13% from baseline after adjusting for current cigarette smoking status, age, and sampling year.

Previous studies have shown that particulate air pollution is associated with an increase in expired NO levels (Steerenberg et al. 2001; Van Amstel et al. 1999). In a study by Steerenberg et al. (2001), exposure to particulate air pollution was associated with an increase in F_{E,NO}. Although the results of our study are inconsistent with the results from Steerenberg et al., there are several important differences in the two studies. First, Steerenberg et al. used particulate matter with an aerodynamic mass median diameter of ≤ 10 μm (PM_{10}) as the marker for particulate exposure, whereas we used PM_{2.5}. Our study chose PM_{2.5} because fine particles have been found to have a stronger association with respiratory health effects than coarse particles with larger aerodynamic mass median diameters (Schwartz and Neas 2000). Another difference between the studies is that Steerenberg et al. studied the effects of particulate exposure from urban air pollution, whereas we studied the effects of particulates from ROFA and various boilermaking tasks such as welding and burning. Unlike ambient air, ROFA and metal fumes contain significant amounts of transition metals, including vanadium, nickel, and iron. In addition, the levels of exposure from the two aerosols were different. Typical urban air has a PM_{2.5} concentration of approximately 10–30 μg/m³, whereas the median PM_{2.5} level from the occupational particulate exposure in our study was 560 μg/m³.

Other studies have observed that exposure to DEP, another component of ambient air, was associated with increased expired NO levels in mice (Lim et al. 1998; Sagai and Ichinose 1995). Lim et al. found that DEP exposure increased the level of constitutive NOS in the airway epithelium and inducible NOS in the macrophages of mice. However, another study observed that DEP reduced endothelial NOS activity in the bronchi of healthy rabbits (Muto et al. 1996). The source of the increased NO is relevant because the effect of NO may differ depending on whether it is produced by inducible or constitutive NOS. Takano et al. (1999) showed that NO produced from inducible NOS might enhance the DEP-induced inflammatory response, whereas NO derived from constitutive NOS might play a protective role against airway inflammation.

Exposure to cigarette smoke also is known to induce acute airway inflammation. However, in contrast to the results from air pollution and DEP, cigarette smoking consistently results in decreased expired NO levels (Kharitonov et al. 1995; Yates et al. 2001). One hypothesis for the reduction in expired NO is that the levels of NOS are reduced from decreased transcription of NOS. A study by Su et al. (1998) observed that cigarette smoke specifically affected constitutive NOS activity. After exposure to cigarette smoke extract, the presence of endothelial NOS and endothelial NOS mRNA was reduced in the pulmonary artery endothelial cells from pigs. The decrease in endothelial NOS activity caused by cigarette smoke extract was found to be time and dose dependent.

A recent study by Huang et al. (2002) found that ROFA instilled intratracheally into isolated perfused rabbit lungs resulted in reduced NO production, as determined by decreases in nitrite/nitrate accumulation. Huang et al. also observed that NO production was reduced after exposure to vanadium, indicating that the transition metal component of ROFA may be responsible for the decreased NO production. Huang et al.
hypothesized that the inhibition of NO production by ROFA might be related to reduced NOS activity, as shown in studies with cigarette smoke exposure. Therefore, the decrease in \( F_{ENO} \) observed in the boilermakers in our study might be due to a reduction in constitutive NOS activity resulting from ROFA and other metal-containing fine particulate exposure. Given the potential protective role of NO from constitutive NOS, the decreased NO levels might have been a contributing factor to the increased airway inflammation and respiratory symptoms seen in our previous studies on boilermakers exposed to ROFA and other particulates (Hauser et al. 1995a; Woodin et al. 2000).

In conclusion, we found an inverse exposure—response relationship between \( F_{ENO} \) and PM\(_{2.5}\) in exposed workers. The results from our study show greater consistency with the studies on exposure to cigarette smoke than to those of ambient air pollution. Cigarette smoke contains a significant concentration of transition metals, similar to ROFA and metal fumes (Chiba and Masironi 1992; Dreher et al. 1997). Further studies are needed to determine if the metal component of PM\(_{2.5}\) is specifically responsible for the decline in \( F_{ENO} \).

Expired NO previously has been found to be a sensitive and practical marker in the assessment of inflammatory lung diseases in a clinical setting. This study shows that \( F_{ENO} \) can be used to detect acute airway responses to metal-containing fine particulate matter in an occupational setting.

**References**


