Urinary 8-hydroxy-2'-deoxyguanosine as a biomarker of oxidative DNA damage in workers exposed to fine particulates.

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<table>
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<th>Citation</th>
<th>Kim, Jee Young, Sutapa Mukherjee, Long C. Ngo, and David C. Christiani. 2004. Urinary 8-hydroxy-2'-deoxyguanosine as a biomarker of oxidative DNA damage in workers exposed to fine particulates. Environmental Health Perspectives 112(6): 666-671.</th>
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Residual oil fly ash (ROFA) is a chemically complex mixture of compounds, including metals that are potentially carcinogenic because of their ability to cause oxidative injury. In this study, we investigated the association between exposure to particulate matter with an aerodynamic mass median diameter ≤ 2.5 µm (PM_{2.5}) and oxidative DNA damage and repair, as indicated by urinary 8-hydroxy-2′-deoxyguanosine (8-OHdG) concentrations, in a group of boilermakers exposed to ROFA and metal fumes. Twenty workers (50% smokers) were monitored for 5 days during an overhaul of oil-fired boilers. The median occupational PM_{2.5} 8-hr time-weighted average was 0.44 mg/m³ (25th–75th percentile, 0.29–0.76). The mean ± SE creatinine-adjusted 8-OHdG levels were 13.26 ± 1.04 µg/g in urine samples collected pre-workshift and 15.22 ± 0.99 µg/g in the post-workshift samples. The urinary 8-OHdG levels were significantly greater in the post-workshift samples than in the pre-workshift samples (p = 0.02), after adjusting for urinary cotinine levels, chronic bronchitis status, and age. Linear mixed models indicated a significant exposure–response association between PM_{2.5} exposure and urinary 8-OHdG levels (p = 0.03). Each 1-mg/m³ incremental increase in PM_{2.5} exposure was associated with an increase of 1.67 µg/g (95% confidence interval, 0.21–3.14) in 8-OHdG levels. PM_{2.5} vanadium, manganese, nickel, and lead exposures also were positively associated with 8-OHdG levels (p ≤ 0.05). This study suggests that a relatively young and healthy cohort of boilermakers may experience an increased risk of developing oxidative DNA injury after exposure to high levels of metal-containing particulate matter.

the 27 eligible boilermakers participated in the study, for a participation rate of 74%. The subjects were monitored during a 5-day work period in June 1999 using a repeated-measures study design. Self-administered questionnaires were used to obtain information on medical history, including respiratory symptoms and diseases, smoking history, and occupational history.

The overhaul entailed removing and replacing the interior wall panels and water-circulating tubing of the boilers and repairing the ash pit. Subjects at the overhaul site were exposed to fine particulate matter from ROFA as well as that from typical boiler-making operations such as welding, burning, and grinding.

**Particulate sample collection.** The collection of particulate samples using personal exposure monitors (PEMs) has been described previously (Kim et al. 2003b). Briefly, subjects were randomly selected to wear PEMs during their workshift. The model 200 PEM (MSP Corporation, Minneapolis, MN) with a 2.5-µm impactor cut size was used in line with a Gillain GilAir® pump (Sensidyne Inc., Clearwater, FL) calibrated at a flow rate of 4 L/min. The air sample was collected on a polytetrafluoroethylene membrane filter (Gelman Laboratories, Ann Arbor, MI). The mass collected on the filter was divided by the air volume sampled to calculate the gravimetric PM$_{2.5}$ concentration. PM$_{2.5}$ concentrations were standardized to 8-hr time-weighted averages (TWA).

**Metal analysis of particulate samples.** Metal analysis of particulate filter samples has been described previously (Kim et al. 2003a). Briefly, filter samples were digested using a modified acid digestion procedure originally developed by Loring and Rantala (1992). The digestion protocol allowed for the determination of total metal concentration, including metal oxides. The filter was placed in a Teflon liner (Parr Instrument Co., Moline, IL), and 5 mL nitric acid (OPTIMA, Seastar Chemical Inc., Pittsburgh, PA) and 400 µL hydrofluoric acid (OPTIMA, Seastar Chemical Inc.) were added to the liner. The Teflon liner was placed in a Parr bomb (Parr Instrument Co.) and heated in a microwave oven for 3 min at 750 watts. After cooling, 10 mL of 1.5% boric acid (ULTREX, J.T. Baker, Phillipsburg, NJ) was added to the liners, and the sample was reheated for 3 min. After an additional cooling period, the digestate was transferred into a 50-mL polypropylene tube and diluted to 50 mL with ultrapure deionized water.

Samples were analyzed using inductively coupled plasma–mass spectrometry (ICP-MS; Perkin-Elmer/SCIEX ELAN model 5000 and model 6100; Perkin-Elmer Inc., Norwalk, CT). Elements analyzed were vanadium, chromium, manganese, nickel, copper, and lead. Quality assurance and control procedures were performed to ensure the accuracy and precision of the metal analysis data.

The limit of detection (LOD) was determined as three times the standard deviation of 10 replicate measurements of the filter blank samples. None of the metal concentrations were below the LOD. The mass of each metal was calculated after adjusting for the blank filter metal concentration. The PM$_{2.5}$ metal concentrations were calculated by dividing the metal mass by the air volume sampled. The PM$_{2.5}$ metal contents were calculated by dividing the PM$_{2.5}$ metal mass by the total PM$_{2.5}$ mass.

**Urine sample collection.** The collection of urine samples began on the first day of the work week before work had begun. Urine samples were collected pre- and post-workshift each day during the 5-day sampling period. After samples were collected in sterile 120-mL urine collection cups, they were aliquoted into 15-mL polypropylene tubes. Specimens were stored at −20°C until analysis.

**Urine analysis for creatinine.** A polypropylene tube containing 5 mL frozen urine was sent to ESA Laboratories, Inc. (Chelmsford, MA) for creatinine analysis. The creatinine level in the urine sample was measured with a Shimadzu model UV-1601 spectrophotometer (Shimadzu Corporation, Nakagyou-ku, Kyoto, Japan) using the Jaffé reaction (Jaffé 1886).

**Urine analysis for cotinine.** Urinary analysis of cotinine also was performed at ESA Laboratories. Urinary cotinine was determined using reverse-phase high-performance liquid chromatography with ultraviolet spectrophotometry detection (Hariharan and VanNoord 1991).

**Urine analysis for 8-OHdG.** Urine analysis for 8-OHdG was performed by Genox Corp. (Baltimore, MD). Urinary 8-OHdG was determined using a competitive enzyme-linked immunosorbent assay (Japan Institute for the Control of Aging, Fukuroi, Shizuoka, Japan; Erhola et al. 1997; Leinonen et al. 1997). Briefly, 50 µL of urine samples and standards were added to precoated 8-OHdG protein conjugate microtiter plates, followed by 50 µL of the primary antibody, anti-8-OHdG monoclonal antibody solution, and incubated for 1 hr at 37°C. The plates were washed and the enzyme-labeled horseradish peroxidase-conjugated secondary antibody (100 µL) was applied for 1 hr at 37°C. After washing, 100 µL of the chromatic substrate, (3,3′,5,5′)-tetramethylbenzidine, was added to the plate and allowed to react at room temperature for 15 min. The intensity of color produced for each sample was measured at an optical density of 490 nm. Pooled urine samples were randomly placed among the unknown samples. The measured QC values were averaged and compared with previously established values. Acceptable QC values were defined as mean ± 2 SDs. The LOD for 8-OHdG was 0.64 ng/mL. For each subject sample, either a duplicate or triplicate measurement was performed. The mean, SD, and coefficient of variation (percent) were calculated. Any sample with a coefficient of variation equal to or greater than 20% was retested. The urinary 8-OHdG concentration was adjusted to the urinary concentration of creatinine (micrograms 8-OHdG/grams creatinine) to control for the variability in urine dilution.

**Statistical analysis.** Statistical analyses were performed using SAS version 6.12 (SAS Institute Inc., Cary, NC). The medians and interquartile ranges (25th–75th percentiles; Q$_{25}$–Q$_{75}$) of the occupational total PM$_{2.5}$ concentration and of the vanadium, chromium, manganese, nickel, copper, and lead concentrations in PM$_{2.5}$ were determined for all subjects. Medians are presented for the PM$_{2.5}$ exposures because of the positively skewed distribution of the data. Wilcoxon rank-sum tests were performed to compare the occupational PM$_{2.5}$ concentrations in smokers and nonsmokers. The Spearman rank correlation coefficient was used to determine the correlation between total PM$_{2.5}$ and the individual PM$_{2.5}$ metal concentrations, and the correlations among the individual PM$_{2.5}$ metal concentrations.

Urinary creatinine-adjusted 8-OHdG concentrations (micrograms/grams creatinine) were used in all analyses. Because of the repeated measurements design, linear mixed models were used to calculate the mean pre-workshift and post-workshift measurements. Pre-workshift measurements served as baseline measurements. A cross-shift change in 8-OHdG level was calculated by subtracting the pre-workshift concentration from the post-workshift concentration. Linear mixed models were used to compare the pre-workshift 8-OHdG levels in smokers and nonsmokers and to compare pre-workshift and post-workshift 8-OHdG concentrations.

Linear mixed regression models were constructed to investigate the association between urinary 8-OHdG concentrations and total PM$_{2.5}$ and PM$_{2.5}$ metal concentrations. To adjust for total PM$_{2.5}$ exposure, analyses also were performed using PM$_{2.5}$ metal content as the exposure of interest. Although urinary 8-OHdG data collection was complete, some PM$_{2.5}$ exposure data were missing at random because subjects were randomly selected each day to wear exposure monitors. Therefore, all analyses were restricted to subjects who had both urinary 8-OHdG and the corresponding PM$_{2.5}$ concentrations on a given day. A generalized autoregressive covariance structure was used because it resulted in the best Akaikes
Information Criterion compared with models with other covariance structures (Verbeke and Molenberghs 1997). A generalized autoregressive structure assumes that the correlation function decays exponentially as the interval between the measurements increases (Verbeke and Molenberghs 1997). Restricted maximum likelihood was used to estimate the covariance parameters. Regression models were adjusted for tobacco smoking, chronic bronchitis status (yes/no), and age because previous studies have found these variable to be significantly associated with urinary 8-OHdG levels (Igishi et al. 2003; Loft et al. 1992; Pilger et al. 2001). According to the American Thoracic Society (ATS) criteria, chronic bronchitis is defined as the presence of a productive cough most days of the week for 3 months or more in at least 2 consecutive years (ATS 1995).

The effect of smoking was evaluated using self-reported current smoking status (yes/no) and creatinine-adjusted urinary cotinine concentrations (micrograms/grams creatinine). In addition, to study effect modification by smoking, an interaction term between PM$_{2.5}$ exposure and a smoking variable was included in the model. The level of significance for all analyses was set at 0.05.

**Results**

**Study population demographics.** The study population demographic data are presented in Table 1. The study population consisted of 20 men, all of whom were white. Their ages ranged from 18 to 59 years, with a mean ± SD of 45.5 ± 12.0 years. On average, the subjects had 21.7 ± 12.9 years of boilermaking experience. Four of the 20 subjects (20%) had chronic bronchitis as defined by ATS (ATS 1995). Ten of the 20 subjects (50%) were current cigarette or cigar smokers. The median urinary creatinine-adjusted cotinine levels were 414 µg/g creatinine (range, 5–2,373) for smokers and 12 µg/g creatinine (range, 3–72) for nonsmokers. None of the demographic characteristics significantly differed between the 20 subjects who participated and the 7 nonparticipants ($p > 0.25$).

**Particulate exposure assessment.** The personal occupational PM$_{2.5}$ exposure data are shown in Table 2. Workplace particulate samples were collected from 19 of the 20 subjects. The number of workdays each subject wore the PEM varied from 4 days to none. The subjects, on average, worked 10-hr shifts at the power plant. Particulate samples were collected for 8.9 ± 1.3 hr. The median total PM$_{2.5}$ 8-hr TWA concentration was 0.44 mg/m$^3$, with an interquartile range of 0.29–0.76 mg/m$^3$ for all subjects. The total PM$_{2.5}$ 8-hr TWA concentrations were not significantly different between smokers and nonsmokers ($p = 0.74$).

Of the six metals, the subjects had the highest exposure to vanadium (median, 1.23 µg/m$^3$; Q$_{25}$–Q$_{75}$, 0.47–3.53) and the lowest exposure to chromium (median, 0.11 µg/m$^3$; Q$_{25}$–Q$_{75}$, 0.05–0.27). Each of the constituent metal concentrations were moderately to highly correlated with the total PM$_{2.5}$ concentrations, ranging from a Spearman correlation coefficient of 0.48 ($p = 0.002$) for PM$_{2.5}$ manganese to 0.78 ($p = 0.001$) for PM$_{2.5}$ nickel. The individual metal concentrations also were moderately to highly correlated with one another (0.52 <$r$ < 0.92; $p < 0.001$).

**Urinary 8-OHdG analysis.** Day 1 pre-workshift urine samples were collected after an average of 2 days away from work. The mean urinary creatinine-adjusted 8-OHdG concentrations (± SE) for each pre- and post-workshift sampling time are shown in Figure 1. The mean ± SE pre-workshift 8-OHdG concentration was 13.26 ± 1.04 µg/g creatinine for all subjects (Table 3). Current smokers had a mean baseline 8-OHdG concentration of 12.09 ± 0.65 µg/g creatinine, whereas nonsmokers had a mean baseline 8-OHdG concentration of 14.84 ± 2.07 µg/g creatinine. The mean pre-workshift 8-OHdG concentrations were not significantly different between smokers and nonsmokers ($p = 0.20$).

The pre-workshift 8-OHdG concentrations were compared with the post-workshift samples. The mean ± SE of the cross-shift change was 1.88 ± 0.74 µg/g creatinine for all subjects. The pre-workshift samples were found to be significantly different compared with the post-workshift samples ($p = 0.02$). The cross-shift changes in urinary 8-OHdG concentrations were not significantly different in smokers compared with nonsmokers ($p = 0.83$).

**Association between urinary 8-OHdG concentrations and PM$_{2.5}$ exposure.** Linear mixed regression models were constructed to investigate the association between urinary 8-OHdG concentrations and PM$_{2.5}$ exposure. Crude analyses indicated a significant association between PM$_{2.5}$ 8-TWA concentrations and urinary 8-OHdG concentrations ($p = 0.02$). Each 1 mg/m$^3$ of PM$_{2.5}$ exposure was associated with a 1.68 µg/g creatinine [95% confidence interval (CI), 0.24–3.12] increase in urinary 8-OHdG concentration.

The effects of tobacco smoking, chronic bronchitis status, and age were investigated. Both self-reported smoking status (yes/no; $p = 0.85$) and urinary cotinine levels ($p = 0.28$) were not found to be significant predictors of urinary 8-OHdG in the models adjusted for chronic bronchitis status and age. In addition, smoking was not found to be a confounder of the association between urinary 8-OHdG and PM$_{2.5}$ exposure. However, both age and having chronic bronchitis were found to be statistically significant predictors of urinary 8-OHdG in the adjusted model. Each year of age was associated with a 0.18 µg/g creatinine (95% CI, 0.02–0.35) increase in urinary 8-OHdG concentrations, after adjusting for PM$_{2.5}$ exposure, urinary cotinine levels, and chronic bronchitis status. In addition, the urinary 8-OHdG concentrations in subjects with chronic bronchitis were, on average, 8.37 µg/g creatinine (95% CI, 3.41–13.33) greater than subjects without chronic bronchitis in the adjusted model.

The association between urinary 8-OHdG levels and PM$_{2.5}$ exposure remained statistically significant, after adjusting for urinary cotinine levels, chronic bronchitis status, and age (Table 4). Each 1 mg/m$^3$ increase in total PM$_{2.5}$ 8-hr TWA concentration was associated with an increase in urinary 8-OHdG concentrations by 1.67 µg/g creatinine (95% CI, 0.21–3.14), after adjusting for urinary cotinine levels, chronic bronchitis status, and age. PM$_{2.5}$ vanadium, manganese, nickel, and lead concentrations also showed a statistically significant association with 8-OHdG concentrations ($p < 0.05$). Each 1 µg/m$^3$ increase in PM$_{2.5}$ vanadium exposure was associated with an increase of 0.23 µg/g creatinine (95% CI, 0.05–0.53).

### Table 1. Study population characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>No. of subjects</th>
<th>No. (%) of current smokers</th>
<th>No. (%) with chronic bronchitis</th>
<th>Mean ± SD</th>
<th>Range</th>
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<td>No. of subjects</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No. (%) of current smokers</td>
<td>10 (50)</td>
<td></td>
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</tr>
<tr>
<td>No. (%) with chronic bronchitis</td>
<td>4 (20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td></td>
<td></td>
<td></td>
<td>45.5 ± 12.0</td>
<td>18–59</td>
</tr>
<tr>
<td>Years as boilermaker</td>
<td></td>
<td></td>
<td></td>
<td>21.7 ± 12.9</td>
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### Table 2. Summary of occupational total PM$_{2.5}$ and PM$_{2.5}$ metal 8-TWA concentrations ($n = 39$).

<table>
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<th>Median</th>
<th>Q$<em>{25}$–Q$</em>{75}$</th>
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<tr>
<td>Total (mg/m$^3$)</td>
<td>0.44</td>
<td>0.29–0.76</td>
</tr>
<tr>
<td>Vanadium (µg/m$^3$)</td>
<td>1.23</td>
<td>0.47–3.53</td>
</tr>
<tr>
<td>Chromium (µg/m$^3$)</td>
<td>0.11</td>
<td>0.05–0.27</td>
</tr>
<tr>
<td>Manganese (µg/m$^3$)</td>
<td>0.81</td>
<td>0.12–2.67</td>
</tr>
<tr>
<td>Nickel (µg/m$^3$)</td>
<td>0.96</td>
<td>0.31–1.88</td>
</tr>
<tr>
<td>Copper (µg/m$^3$)</td>
<td>0.86</td>
<td>0.25–2.53</td>
</tr>
<tr>
<td>Lead (µg/m$^3$)</td>
<td>0.17</td>
<td>0.04–0.53</td>
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0.04–0.42) in 8-OHdG concentrations, after adjusting for urinary cotinine levels, chronic bronchitis status, and age. Likewise, with each 1-µg/m³ increase of PM$_{2.5}$ manganese, nickel, and lead exposure, 8-OHdG concentrations increased by 0.47 µg/g creatinine (95% CI, 0.05–0.89), 0.33 µg/g creatinine (95% CI, 0.01–0.64), and 1.64 µg/g creatinine (95% CI, 0.02–3.26), respectively. PM$_{2.5}$ chromium exposure was marginally associated with urinary 8-OHdG concentrations ($p = 0.09$).

Because of the high correlation between the total PM$_{2.5}$ concentration and the individual PM$_{2.5}$ metal concentrations, total PM$_{2.5}$ exposure could not be directly adjusted for in the models investigating the association between PM$_{2.5}$ metal concentrations and urinary 8-OHdG levels. To adjust for total PM$_{2.5}$ exposure, analyses were performed using PM$_{2.5}$ metal contents, calculated by dividing the mass of the individual metal by the total PM$_{2.5}$ mass. The regression coefficients for the PM$_{2.5}$ metal contents are summarized in Table 4. Analyses using PM$_{2.5}$ metal contents, in general, indicated results similar to analyses from PM$_{2.5}$ metal concentrations. The PM$_{2.5}$ metal contents of vanadium, manganese, and nickel were significantly associated with urinary 8-OHdG concentrations, after adjusting for urinary cotinine levels, chronic bronchitis status, and age ($p \leq 0.03$). Each 1,000-µg/g increase in PM$_{2.5}$ vanadium, manganese, and nickel content was associated with a 0.19-µg/g creatinine (95% CI, 0.05–0.33), 0.22-µg/g creatinine (95% CI, 0.05–0.39), and 0.21-µg/g creatinine (95% CI, 0.02–0.41) increase in 8-OHdG concentration, respectively. Chromium, which had been marginally significant in the analysis using metal concentration, almost reached statistical significance ($p = 0.05$) when its metal content was used in the analysis. In contrast, lead, which had previously been statistically significant became marginally significant ($p = 0.10$) when analysis was performed using its metal content. In both analyses using metal content and metal concentration, copper was not found to be significantly associated with urinary 8-OHdG concentrations.

Analyses using self-reported smoking status (yes/no) suggested that the association between 8-OHdG levels and total PM$_{2.5}$ exposure might be modified by tobacco smoking ($p = 0.12$). However, regression analysis using urinary cotinine concentrations found that smoking did not significantly modify the association between urinary 8-OHdG levels and total PM$_{2.5}$ concentrations ($p = 0.66$).

**Discussion**

The proportion of lung cancer attributable to occupational exposure to recognized carcinogens ranges from 8.8 to 40%, after controlling for confounding by smoking (Simonato et al. 1988). Among the occupational exposures, lung cancer is most frequently associated with asbestos, radon, and metal exposures (Nemery 1990). The carcinogenicity of metals may derive from their ability to induce oxidative DNA damage through the generation of ROS (Hartwig 2000; Knaapen et al. 2002; Pritchard et al. 1996). In this study, we investigated a urinary biomarker for oxidative DNA damage and repair, 8-OHdG, in boilermakers exposed to ROFA and metal fumes.

The particulate exposure in our cohort of boilermakers was higher than levels typically experienced by the general population. The median occupational PM$_{2.5}$ exposure in our study was 440 µg/m³, compared with PM$_{2.5}$ concentrations ranging from 10 to 30 µg/m³ in typical U.S. urban air (Dockery et al. 1993). Despite the high exposure in this study, the PM$_{2.5}$ levels were much lower than the Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs) of 5 mg/m³ for respirable fraction particulates (OSHA 1997). In addition, none of the particulate samples had vanadium, chromium, manganese, nickel, copper, or lead concentrations exceeding the OSHA PELs (OSHA 1997). Among all the PM$_{2.5}$ metal concentrations, only one sample for nickel exceeded the more stringent National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (NIOSH 2003).

Previous studies provide evidence that occupational exposure to certain metals may be associated with increased risk of cancer. Mancuso (1997) found an exposure–response relationship between chromium exposure and age-specific lung cancer death rates in workers previously employed at a chromate plant. In a study at a nickel refinery, workers with the highest cumulative soluble nickel exposures had a 3-fold increase in relative risk of lung cancer compared with the control population (Andersen et al. 1996). Other epidemiologic studies also found an excess of lung cancer deaths in battery plant workers chronically exposed to lead (Cooper et al. 1985; Wong and Harris 2000). However, most studies did not effectively control for other confounding factors such as smoking and coexposure to other potential carcinogens. In our study, potential confounding by smoking was adjusted for using urinary cotinine concentrations. Urinary cotinine is a reliable biomarker that provides an accurate measure of smoking dose in smokers and environmental tobacco smoke exposure in nonsmokers (Husgafvel-Pursiainen 2002).

In this study, we found a significant exposure–response relationship between total PM$_{2.5}$ and urinary 8-OHdG levels in workers exposed to ROFA and welding fumes. With each 1-mg/m³ increase in total PM$_{2.5}$ exposure, urinary 8-OHdG concentrations increased by 1.67 µg/g creatinine, a 13% increase from baseline levels. Similarly, statistically significant associations were seen between urinary concentrations of 8-OHdG and PM$_{2.5}$ vanadium, manganese, nickel, and lead concentrations ($p \leq 0.05$). PM$_{2.5}$ chromium exposure was marginally associated with increased urinary 8-OHdG ($p = 0.09$). Similar results were observed using PM$_{2.5}$ metal contents as the exposure of interest, suggesting that the metal...
component, independent of the total PM$_{2.5}$ concentration, was associated with increased urinary 8-OHdG concentrations. Increased urinary levels of 8-OHdG after metal-containing PM$_{2.5}$ exposure may indicate an increase in oxidative DNA damage and repair. Other epidemiologic studies also have indicated a positive association between particulate or metal exposure and oxidative DNA damage (Merzenich et al. 2001; Sörensen et al. 2003). Sörensen et al. (2003) found that ambient particulate air pollution was significantly associated with increases in lymphocyte levels of 7-hydro-8-oxo-2′-deoxyguanosine, another biomarker of oxidative DNA damage, in students living in central Copenhagen, Denmark. A cross-sectional study by Merzenich et al. (2001) examined the association between metals and oxidative DNA damage in the residents of Bremen, Germany. Although urinary concentrations of cadmium, chromium, and lead were not found to be significantly associated with oxidative DNA damage, Merzenich et al. (2001) found a statistically significant dose–response relationship between urinary nickel levels and oxidative DNA lesions in lymphocytes.

In a study by Prahalad et al. (2000), oil fly ash exposure was observed to induce a dose-dependent increase in oxidative DNA damage, as determined by the formation of 7,8-dihydro-8-oxo-2′-deoxyguanosine in calf thymus DNA. Hydroxylation of 2′-deguanosine was significantly enhanced after exposure to individual metals present in the oil fly ash, including vanadium and nickel (Prahalad et al. 2000). These findings by Prahalad et al. (2000) indicate that metals may contribute to the DNA damage caused by oil fly ash, as observed in our study.

In this study, we focused on the metal component of PM$_{2.5}$ exposure from ROFA and metal fumes. However, there may be other components of PM$_{2.5}$ that may contribute to the increased oxidative DNA damage observed in our study, including carcinogenic polycyclic aromatic hydrocarbons (PAHs). We investigated the association between urinary 8-OHdG levels and exposure to PAHs, as determined using urinary 1-hydroxypyrene (1-OHP), and found that occupational ROFA exposure is responsible for the oxidative DNA damage. Previous occupational studies in which workers were exposed to various carcinogens, including PAHs and asbestos, found that smoking status was not a significant predictor of urinary 8-OHdG levels (Tagesson et al. 1993; Torason 1999; Torason et al. 2001).

In conclusion, this study shows that levels of urinary 8-OHdG, a biomarker of oxidative DNA damage and repair, increased after occupational exposure to fine particulate matter. We found a positive exposure–response relationship between urinary 8-OHdG concentrations and PM$_{2.5}$ exposure, specifically the PM$_{2.5}$ metal component. Results from this study suggest that a relatively young and healthy cohort of boilers exposed to high levels of metal-containing particulate matter may experience an increased risk of developing oxidative DNA injury.

REFERENCES

Jaffé MR. 1986. Über den niederenschlag, welchen pikrinsäure in normalen harn erzeugt und über eine neue reaktion des kreatinins (About the precipitation caused by picric acid in normal urine and about a new reaction of creatinine) in German, Physiol Chem 10:391–400.

670 VOLUME 112 | NUMBER 6 | May 2004 • Environmental Health Perspectives