

Biomonitoring of Chemical Exposure among New York City Firefighters Responding to the World Trade Center Fire and Collapse

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The collapse of the World Trade Center (WTC) on 11 September 2001 exposed New York City firefighters to smoke and dust of unprecedented magnitude and duration. The chemicals and the concentrations produced from any fire are difficult to predict, but estimates of internal dose exposures can be assessed by the biological monitoring of blood and urine. We analyzed blood and urine specimens obtained from 321 firefighters responding to the WTC fires and collapse for 110 potentially fire-related chemicals. Controls consisted of 47 firefighters not present at the WTC. Sampling occurred 3 weeks after 11 September, while fires were still burning. When reference or background ranges were available, most chemical concentrations were found to be generally low and not outside these ranges. Compared with controls, the exposed firefighters showed significant differences in adjusted geometric means for six of the chemicals and significantly greater detection rates for an additional three. Arrival time was a significant predictor variable for four chemicals. Special Operations Command firefighters ($n = 95$), compared with other responding WTC firefighters ($n = 226$), had differences in concentrations or detection rate for 14 of the chemicals. Values for the Special Operations Command firefighters were also significantly different from the control group values for these same chemicals and for two additional chemicals. Generally, the chemical concentrations in the other firefighter group were not different from those of controls. Biomonitoring was used to characterize firefighter exposure at the WTC disaster. Although some of the chemicals analyzed showed statistically significant differences, these differences were generally small. **Key words:** antimony, biomonitoring, dioxins, disaster, firefighters, metals, PAHs, PCBs, VOCs. *Environ Health Perspect* 111:1906–1911 (2003). doi:10.1289/ehp.6315 available via <http://dx.doi.org/> [Online 9 September 2003]

The catastrophic collapse of the World Trade Center (WTC) on 11 September 2001 produced unprecedented fire-related exposures for New York City, New York, firefighters. The initial fires, building collapses, and persistent fires that burned for months, while intense rescue and recovery efforts continued, contributed to exposures from a wide variety of pyrolysis, combustion, and pulverized building materials.

Predicting the chemicals and their concentrations produced from a fire is difficult because the composition depends on the diversity of natural and synthetic fuels, fire temperature and duration, availability of oxygen, compression pressure, atmospheric conditions, and the fire's course relative to surrounding topography. Firefighters and other rescue and recovery personnel may inhale gases or vapors released during a fire or collapse and may inhale and ingest particulates. Hand-to-mouth contamination, contamination inside masks, and dermal absorption also may be important factors affecting chemical absorption. Although some chemicals are common to most fires (Austin et al. 2001), neither knowledge of the burning materials nor environmental measurements can accurately predict the absorbed dose of combustion products. Recent studies have focused on acutely toxic firefighter exposures

and specific aspects of firefighter response (Hartzell 1996); however, there has not been a comprehensive biomonitoring assessment of firefighters after a major incident.

Biomonitoring is the measurement of the internal dose of a chemical or its metabolite in body matrices (e.g., blood or urine) and provides critical information about the amount of a chemical that actually enters the body from any source—for example, air, water, dust, soil, food, and other environmental sources (Sampson et al. 1994). Biomonitoring is ideally used in conjunction with measurements of external exposure, however, because in this case personal sampling of firefighter external exposures was not possible initially and often is impractical. The purpose of this study was to characterize internal dose levels of fire-related chemicals (including ancillary exposures to petroleum-powered equipment chemicals and their exhaust products) in New York City firefighters and the relationship of those levels with firefighter activities, including firefighter job task, time of arrival at the site, and number of work days at the site.

Materials and Methods

This study was a collaborative effort of the New York City Fire Department Bureau of

Health Services (FDNY-BHS) and the Centers for Disease Control and Prevention (CDC). Disaster-related logistic limitations delayed the start of blood and urine collection until 1 October 2001. Search and rescue operations were ongoing at this time, and fires continued to burn at the WTC site. All participants gave informed consent, approved by Montefiore Medical Center's Research Review Board. The FDNY-BHS developed a medical monitoring protocol in collaboration with the CDC's National Institute for Occupational Safety and Health. In conjunction with these efforts, the CDC's National Center for Environmental Health, Division of Laboratory Sciences (DLS) developed the biomonitoring protocol to quantify 110 chemicals in firefighters' blood and urine as markers of exposure (Appendix 1).

This was a cross-sectional study using a stratified sample of firefighter units based on WTC arrival time. FDNY-BHS selected this sample using dispatch records, officer interviews, and a worker questionnaire (the final determinant of arrival time, if discrepancies arose). Arrival time was categorized as *a*) present at the WTC collapse, *b*) arrival on day 1 or 2 but postcollapse, and *c*) arrival on days 3–7. Arrival time was of potential interest because exposure opportunity for different chemicals could vary as a function of time from the initial collapse. We also categorized unit assignments as Special Operations Command (i.e., rescue, squad, and marine units) or other exposed firefighters (e.g., ladder, engine). This grouping was used as a surrogate for job tasks based on the expectation of different assignments for Special Operations Command personnel. Number of work days at the WTC site was categorized as 0–5 days and 6–13 days. More work days at the site could lead to higher internal dose concentrations of chemicals that persist in the body.

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Controls were FDNY firefighters who did not work at or near the WTC because of assignment to office duties as a result of prior injury. All information from the study participants and blood and urine samples were obtained during the week of 1–5 October, with nearly equal numbers of participants each day.

Sample acquisition and analytic methods. During 1–5 October 2001, firefighters received FDNY-BHS WTC medical evaluation, including a self-administered questionnaire (arrival time, work days on site, respirator and other protective equipment use, and symptoms). A DLS response team processed blood and urine samples collected at FDNY-BHS and transported them to DLS in Atlanta for biomonitoring analysis.

We analyzed samples from 370 firefighters. Because of insufficient volume collection, shortage of some precertified collection tubes, failure to pass strict chromatographic quality criteria, or overly dilute urine samples, complete analyses were not available for all participants. Specifically, volatile organic compound measurements were available for about 67% of the firefighters, and dioxin, furan, and polychlorinated biphenyl (PCB) measurements were available for about 90% of the firefighters. All analytic methods have been validated and published (Bernert et al. 1997; Calafat and Stanfill 2002; Cardinali et al. 2000; Chen et al. 1998; Miller et al. 1987; Paschal et al. 1998; Smith et al. 2002; Turner et al. 1997) and are subject to ongoing quality assurance programs. Cotinine, a nicotine metabolite, was used to assess the contribution of tobacco smoke to levels of selected volatile organic compounds (VOCs), cyanide, selected polycyclic aromatic hydrocarbons (PAHs), and selected metals. Urinary creatinine was measured to correct or exclude samples for urinary dilution by standard methods and used as a covariate for chemicals measured in urine.

Statistical analyses. We categorized the firefighters into groups based on arrival time (present during collapse, arrival day 1–2, arrival day 3–7), number of work days at WTC (0–5 days and 6–13 days), and unit assignment (Special Operations Command firefighters, other firefighters, and control firefighters who were not present at WTC). In addition, we defined another category for analysis, the exposed group, as all noncontrol firefighters. Of the 110 chemicals, 32 were detectable in more than 60% of the firefighters and were subjected to additional analysis. For these 32 chemicals, we performed nonparametric analyses (Kruskal-Wallis, $\alpha = 0.05$) testing for differences in concentrations of each chemical between any two of the firefighter groups. Chemicals that were statistically different by this test were subjected to further analysis by analysis of covariance (ANCOVA).

ANCOVA ($\alpha = 0.01$) analysis of the firefighter groups used the log-transformed chemical concentrations as the dependent variable and covariates of age, race (white and other), creatinine, and log cotinine. Number of work days at the WTC was found not to be a significant predictor of chemical concentrations and was not used in further analysis. Arrival time grouping was changed from three groups to two groups because the number of persons arriving during days 3–7 was small. So further ANCOVA analysis was done on six firefighter groups: the overall exposed group, firefighter groups defined by arrival time (present during collapse, and arrival day 1–2 since collapse), and firefighter groups defined by unit assignment [Special Operations Command firefighters, other firefighters, and control firefighters (those not present at WTC)]. As a result, we tested specific hypotheses (ANCOVA contrasts) for the effects of exposure (exposed vs. control), arrival time (present during collapse vs. days 1–2, present during collapse vs. control, days

1–2 vs. control), and unit assignment (Special Operations Command firefighters vs. other exposed firefighters, Special Operations Command vs. control, and other exposed firefighters vs. control).

Of the 110 chemicals, 78 had detection rates of < 60% among individuals tested and were therefore considered as dichotomous variables (i.e., detected or not detected). These chemicals were examined initially for differences in detection rates among the six firefighter groups described above with chi-square tests ($\alpha = 0.05$). Chemicals that were statistically significant were further analyzed by logistic regression ($\alpha = 0.01$) for effects of the six firefighter groups, including the same covariates listed above [age, race (white and other), creatinine, log cotinine]. The two probabilities used for type I error rejection are considered lenient because of multiple comparisons at both stages of statistical analysis.

Cotinine from tobacco smoke exposure was an important covariate in most analyses. Tables 1 and 2 report the results of 102 statistical tests examining group differences for each of the chemicals. Only five of the tests required adjustment for interaction terms among the covariates. Statistical analyses were performed using SAS software, version 8.0 (SAS Institute, Cary, NC).

Results

A total of 370 firefighters (321 exposed, 47 controls, and 2 with missing data) participated in the biomonitoring study, with 368 firefighters having chemical measurements. Of the participating firefighters, 148 were present during the WTC towers collapse, and 142 arrived postcollapse on days 1–2. A significantly greater percentage of Special Operations Command firefighters were present on days 1 and 2 (90.7%) versus other exposed firefighters (48.2%).

Table 1. Adjusted geometric mean chemical concentrations and ANCOVA results.

Chemical	Units	Exposed, all except controls (n = 318)	Control (n = 47)	Arrival time			Unit assignment		
				Day 1 present at collapse (n = 148)	Days 1–2 present after collapse (n = 142)	p-Value, present at collapse vs. 1–2 days	Special Operations Command (n = 95)	Other firefighters (n = 195)	p-Value, special vs. other
1-Hydroxypyrene	ng/L urine	93.2*	62.5	110*	113*	NS	159*	77.9	< 0.01
1-Hydroxyphenanthrene	ng/L urine	186	158	197	206	NS	248*	164	< 0.01
2-Hydroxyphenanthrene	ng/L urine	164	119	163	191*	NS	211*	147	< 0.01
3-Hydroxyphenanthrene	ng/L urine	162	127	168	185*	NS	214*	145	< 0.01
1,2,3,4,6,7,8-HCDBD	pg/g lipid	27.8*	19.2	30.1*	26.4*	NS	30.6*	25.9*	NS
1,4-Dichlorobenzene	µg/L blood	0.235	0.165	0.274	0.289	NS	0.343*	0.231	< 0.01
meta/para-Xylenes	µg/L blood	0.066*	0.051	0.066	0.071	NS	0.081*	0.057	< 0.01
Methyl tert butyl ether	µg/L blood	0.124	0.101	0.129	0.138	NS	0.166*	0.107	< 0.01
Lead	µg/dL blood	2.76*	1.93	3.08*	2.98*	NS	3.77*	2.43*	< 0.01
	µg/L urine	1.17	1.01	1.44*	1.19	NS	1.77*	0.96	< 0.01
Antimony	µg/L urine	0.203*	0.165	0.271*	0.238*	< 0.01	0.381*	0.169	< 0.01
Cadmium	µg/L urine	0.324	0.377	0.355	0.299	< 0.01	0.351	0.303*	< 0.01
Uranium	µg/L urine	0.00611*	0.00752	0.00643	0.00576*	NS	0.00610*	0.00607*	NS

Abbreviations: HCDBD, heptachlorodibenzodioxin; NS, not significant. To be listed in this table, a chemical had to show a difference between any two of the groups by Kruskal-Wallis testing ($p < 0.05$). All chemicals listed in the table were significant by ANCOVA at $p < 0.01$, except 1-hydroxyphenanthrene ($p = 0.0246$) and uranium ($p = 0.0273$), for differences between any two of the six exposure groups adjusted for covariates of age, race, creatinine, and log cotinine.

*Significantly different from controls, $p < 0.01$.

Of the 110 chemicals, 32 were treated as continuous variables, and Kruskal-Wallis analysis showed 13 chemicals had statistically significant differences between any two of the six firefighter groups. Results of the ANCOVA analysis for these 13 chemicals are presented in Table 1. For 11 of the 13 chemicals, firefighters in the Special Operations Command had concentrations that were higher ($p < 0.01$) than those of the other firefighter group. A 12th chemical (1,2,3,4,6,7,8-heptachlorodibenzodioxin) had higher levels ($p < 0.01$) for firefighters in the Special Operations Command compared with controls, and also for firefighters in the other firefighter group compared with controls. For only 2 of the 13 chemicals (urinary antimony and urinary cadmium), levels were higher ($p < 0.01$) in firefighters present at the collapse compared with those who arrived after the collapse during day 1–2.

Of the 110 chemicals, 78 had detection rates $< 60\%$ and were therefore analyzed as dichotomous variables (i.e., detected or not detected). Chi-square testing showed that four of these 78 chemicals had significantly different detection rates between any two of the six firefighter groups (see Table 2). All four of these chemicals were more likely to be detected in firefighters of the Special Operations Command than in firefighters in the other firefighter group. Two of the four chemicals were more likely to be detected in firefighters present at the collapse compared with those who arrived after the collapse during days 1–2.

Discussion

This was the only biomonitoring study performed after the WTC collapse and during rescue operations. It is also the most extensive biomonitoring study ever performed on any occupational group during the first weeks of exposure to a major fire, building collapse, or urban disaster. We measured up to 110 chemicals in 368 firefighters. As expected, known products of combustion, such as represented by PAH metabolites, were present in greater amounts in exposed firefighters.

Unanticipated increases in urinary antimony, serum heptachlorodibenzodioxin, and heptachlorodibenzofuran also were associated with exposure. Unit assignment was the most predictive variable for the internal dose chemical levels. Arrival time was associated with levels of a few chemicals; duration at the site was not predictive. None of the measured chemicals is presumed to be specific to the WTC and might be seen in firefighters exposed to any structural fire (and collapse) as well as from exposures in the general environment. Although statistically significant elevations were found, their magnitude was not high enough to be of immediate clinical concern.

Interpretation of biomonitoring measurements is most straightforward when recognized guidelines are available that define elevated levels associated with health effects (e.g., blood lead levels $\geq 10 \mu\text{g/dL}$ for children, or $\geq 40 \mu\text{g/dL}$ for adults). Concentration-related health effects are not established for most chemicals measured in this study. Biomonitoring results of firefighters can be compared with levels observed in other occupational groups or reference ranges for the general population, when available. Reference ranges and tentative occupational guidelines are available for 1-hydroxypyrene, some of the metals, and some volatile organic compounds. Interpretation is also most straightforward when a single known exposure is followed by analysis. In this study, exposures may have continued at varying levels after the initial incident.

We compared exposed firefighters to a firefighter control group (all in New York City) to determine how levels compared with those in persons in the same occupation but who did not respond to the WTC disaster. Although firefighters may have similar fire exposure backgrounds, those assigned to Special Operations Command more often respond to fires of greater intensity and have different job tasks, all of which may have led to greater exposure to combustion products before and during the WTC disaster. However, it remains unclear for some chemicals whether differences

between Special Operations Command firefighters and other exposed firefighters reflect WTC exposures alone or cumulative exposure occurring before the WTC events, or both. Kinetic considerations may be useful in making these distinctions.

Polycyclic aromatic hydrocarbons. The burning of carbonaceous fuels (any organic matter) produces gases and soot containing PAHs. Our analytic method measured 14 hydroxylated metabolites in urine. The most common PAH metabolite used for biomonitoring exposure is 1-hydroxypyrene, having been studied in a variety of environmental settings (Bouchard et al. 2001; Gilbert and Viau 1997; Gundel et al. 1996; Scherer et al. 2000; Viau et al. 2000), aluminum refining (Levin et al. 1995; Ny et al. 1993; Ovrebø et al. 1995b; Van Schooten et al. 1995), and coke production (Mielynska et al. 1997; Ovrebø et al. 1995a; Pan et al. 1998; van Delft et al. 2001; Van Rooij et al. 1993; Wu et al. 1998).

Arrival time, when controlled for other factors (Table 1), was not an independent predictor for urinary 1-hydroxypyrene. However, Special Operations Command firefighters had more than twice the level of urinary 1-hydroxypyrene as did other exposed firefighters or control firefighters. The urinary concentrations in the other exposed firefighters were similar to controls. Because of the short half-lives (Heikkilä et al. 1995), higher urinary concentrations of 1-hydroxypyrene or other PAHs in the Special Operations Command firefighters may reflect either ongoing higher exposure, larger exposures earlier in the WTC response, or both. The adjusted geometric mean of urinary 1-hydroxypyrene in the Special Operations Command group was 159 ng/L or $0.72 \mu\text{mol/mol creatinine}$. This value is similar to median values in another firefighter study (Caux et al. 2002), much less than mean values seen in other occupational studies (Heikkilä et al. 1997; Van Schooten et al. 1995; Van Rooij et al. 1992; Venier et al. 1985), and similar to reported levels in firefighters during a training exercise (Feunekes et al. 1997). The

Table 2. Adjusted odds ratios (95% CIs) for the detection of significant chemicals.

Chemical	Arrival before collapse		Arrival on days 1–2 versus control ^a	Special operations		Other versus control ^b	All exposed firefighters versus control ^c
	Versus arrival on days 1–2 ^a	Versus control ^a		Versus other exposed firefighters ^b	Versus control ^b		
1,2,3,4,6,7,8-HCDBF	1.48 (0.81–2.70)	6.48 (2.30–18.22)	3.81 (1.39–10.46)	3.25 (1.70–6.21)	9.15 (3.12–26.80)	2.70 (1.02–7.10)	3.54 (1.39–9.01)
Tetrachloroethylene	1.89 (1.04–3.42)	2.86 (1.17–6.94)	2.06 (0.89–4.79)	2.13 (1.12–4.03)	3.23 (1.30–8.03)	1.82 (0.80–4.13)	2.28 (1.04–5.02)
Blood cadmium	2.44 (1.42–4.20)	0.72 (0.30–1.73)	0.31 (0.13–0.73)	2.19 (1.23–3.90)	0.70 (0.28–1.71)	0.32 (0.14–0.74)	0.43 (0.19–0.94)
Ethylbenzene	0.71 (0.36–1.41)	5.85 (1.57–21.83)	8.04 (2.14–30.19)	6.25 (2.99–13.08)	18.14 (4.55–72.28)	2.59 (0.73–9.20)	4.04 (1.25–13.03)

Abbreviations: CI, confidence interval; HCDBF, heptachlorodibenzofuran. Listed chemicals in this table were initially significant at $p < 0.05$ for differences between any of the six exposure groups using the chi-square test. All chemicals listed were also significant at $p < 0.01$ for differences between any of the six exposure groups by logistic regression adjusted for covariates of age, creatinine, and log cotinine.

^aAdjusted for job task and other covariates. ^bAdjusted for arrival time and other covariates; the group having arrival times from 3 to 7 days was too small for statistical comparison.

^cAdjusted for covariates of age, creatinine, and log cotinine.

Special Operations Command values were slightly greater than reported general population background levels (CDC 2003; Jongeneelen 2001), and only 13 (4.1%) firefighters had values above the 95th percentile of a nationally representative sample 20 years and older (CDC 2003). The values were below a recommended occupational guideline of 2.3 $\mu\text{mol/mol}$ creatinine (Lauwerys and Hoet 2001).

Polychlorinated dibenzofurans, dibenzodioxins, and biphenyls. These chemicals are produced when carbon and chlorine combine at high temperatures. Heptachlorodibenzodioxins and heptachlorodibenzofurans were the only polychlorinated dibenzofuran and dibenzodioxin found statistically significant in exposed firefighters when compared with control firefighters. Marklund et al. (1986), found that heptachlorinated dibenzofurans were the most abundant pyrolytic products in residues of burned plastic material (polyvinylidene chloride, Saran plastic wrap). They found the content of heptachlorinated dibenzofurans and dibenzodioxins were several orders of magnitude greater than other total congeners (tetra, penta, hexa, octa); however, congener-specific data within the hepta class were not reported. Similar findings have been found in Japanese incinerator workers (Kumagai et al. 2000, 2002). Our results demonstrating differences for the two hepta congeners were not anticipated but are consistent with other published data and suggest that these analytes may be useful for detecting exposures to burning plastics containing chlorine. Further kinetic data are needed to understand the relationship of exposure to burning plastics under various exposure conditions with internal dose levels. One report of firefighters after exposures to a transformer fire found 1,2,3,4,6,7,8-heptachlorodibenzofuran and 1,2,3,4,6,7,8-heptachlorodibenzodioxin to have the highest average blood levels, with the exception of the fully chlorinated octa class compounds (Kelly et al. 2002). These findings are also consistent with the general U.S. population data showing the octa and hepta congeners to be among the most detectable (CDC 2003).

Metals. Antimony is generally present in the environment in very low concentrations and has been used in glass as a coloring agent, in nonlead solders, metallurgy, electronics, manufacture of plastics, and other applications. Firefighters present at the collapse had urinary antimony levels that were statistically higher than those of firefighters arriving on days 1–2 postcollapse or of controls (Table 1). The urinary antimony–adjusted geometric mean for the Special Operations Command group was two times higher (Table 1) than that for the other exposed firefighters or controls. Eighteen percent of exposed firefighters had values greater than the 95th percentile of the control group.

Differences between firefighter groups with respect to antimony were unexpected. Antimony in plastics is an integral part of fire-retardant formulations (Einhorn 1975; Landrock 1983; Liepins and Pearce 1976) as a charring agent, and acts with halogenated hydrocarbons to suppress fire. Plastics may have 7–30% antimony by weight. Combustion of plastics or particulate dusts containing antimony from the WTC collapse probably explains this increase in exposed firefighters. Although antimony concentrations were significantly higher in firefighters present during the collapse and in Special Operations Command firefighters, they were well below recommendations for maximum exposure guidelines for workplace antimony exposures (35 $\mu\text{g/g}$ creatinine) or the general population (3 $\mu\text{g/g}$ creatinine; Lauwerys et al. 2001) and were less than reported industrial exposures (Kentner et al. 1995; Luderndorf et al. 1987).

Lead levels were statistically higher in exposed firefighters than in control firefighters. Time of arrival was not a significant predictor of adjusted geometric mean blood lead concentrations, whereas job task group was predictive. For the entire cohort, the highest value was 12.7 $\mu\text{g/dL}$, with none exceeding the 40 $\mu\text{g/dL}$ adult workplace standard set by U.S. Occupational Safety and Health Administration (U.S. Department of Labor 2001). Because lead is a cumulative toxic metal in the body, blood lead represents a combination of long-term exposure, compartmental equilibration, and exposure several weeks precollection. Although exposed firefighters showed elevations that were statistically significant compared with control firefighters, the increase was small, far below clinically significant levels.

Mercury levels were not higher in exposed firefighters but are mentioned because of heightened concern about exposure at WTC (Worth 2002). One control and three exposed firefighters had total blood mercury levels > 20 $\mu\text{g/L}$, a conservative upper reference limit. Because blood inorganic mercury was < 1.7 $\mu\text{g/L}$ for all exposed firefighters, these elevated total blood mercury concentrations represent organic mercury contributions from dietary sources (e.g., fish consumption) rather than from exposure at WTC.

We believe our results are comparable to those of our source population of about 11,000 FDNY firefighters because similar levels were found for blood lead in 9,660 firefighters analyzed by an independent FDNY-BHS contract laboratory. For example, 96% of the firefighters had detectable blood lead, with a geometric mean of 3.21 $\mu\text{g/dL}$ (Prezant D. Personal communication). Neither study identified clinically significant concentrations of metals in firefighters.

Cyanide and volatile organic compounds. A major cause of mortality from smoke

inhalation at structural fires is cyanide intoxication (Baud et al. 1991). Because cyanide kinetics dictate that blood cyanide levels reflect exposure mainly within the 24 hr before testing, our study shows only that firefighters were not exposed to significant amounts of cyanide proximate to sampling. VOCs also tend to have rapid elimination from the blood. The results for VOCs are presented in Tables 1 and 2; the results suggest that some groups had recent or continual exposures to these compounds. Because of the variety of sources potentially contributing to the low levels measured, including fires, solvents in the debris, indoor air, drinking water, vehicular fuels, and exhausts, it is difficult to ascribe a specific source. Only six exposed firefighters had volatile organic concentrations above proposed reference ranges (Ashley et al. 1994).

Study limitations. Sanderson (1997) outlined the limitations of our knowledge about public health consequences of fires and the difficulties in epidemiologic studies after these incidents. Our study has several limitations. First, biomonitoring measurements were made at only one time point. Several repeat measurements starting soon after the initial fire and spanning at least 2 weeks would have improved our exposure assessment. This design would have been especially useful for chemicals with short half-lives to determine whether exposure differences were persistent or transient. Second, although the control group was composed of FDNY firefighters, comparability may be limited because most had been assigned office duty because of orthopedic injury and therefore may have lacked recent fire-related exposures. Last, current technology does not allow for biomonitoring of asbestos, fiberglass, silicates, and other inorganic particulates. Thus, this study cannot provide any information about exposure to or potential health effects from these materials.

Conclusions

Biomonitoring of firefighters' blood and urine is an effective exposure assessment tool that can be used to further understand exposures and evaluate the effectiveness of worker protection strategies. Known products of combustion, such as PAH metabolites, were present in greater amounts in exposed firefighters than controls. Unanticipated increases in urinary antimony, serum heptachlorodibenzodioxin, and heptachlorodibenzofuran were also evident. Comparison of exposed and control groups indicated that levels in exposed firefighters, although statistically elevated, were generally low compared with reference values in the general population or workplace threshold levels (when available). Firefighter exposures during the WTC disaster were unique and extreme; our findings should not be generalized to other populations working or living near WTC.

Appendix 1. 110 Chemicals Measured in the WTC Firefighters

Polyaromatic hydrocarbon metabolites in urine (14)

1-Hydroxybenzo[*a*]anthracene
1-Hydroxybenzo[*c*]phenanthrene
1-Hydroxyphenanthrene
1-Hydroxypyrene
2-Hydroxybenzo[*c*]phenanthrene
2-Hydroxyfluorene
2-Hydroxyphenanthrene
3-Hydroxybenzo[*a*]anthracene
3-Hydroxybenzo[*c*]phenanthrene
3-Hydroxychrysene
3-Hydroxyfluoranthrene
3-Hydroxyfluorene
3-Hydroxyphenanthrene
6-Hydroxychrysene

Volatile organics in blood (29)

Dibromochloromethane
Dibromomethane
Bromodichloromethane
Bromoform
Carbon tetrachloride
1,1-Dichloroethane
1,2-Dichloroethane
1,1,1-Trichloroethane
1,1,2-Trichloroethane
1,1,2,2-Tetrachloroethane
Hexachloroethane
trans-1,2-Dichloroethylene
cis-1,2-Dichloroethylene
1,1-Dichloroethylene

Trichloroethylene
Tetrachloroethylene
1,2-Dichloropropane
Chlorobenzene
1,2-Dichlorobenzene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
Benzene
Ethylbenzene
meta/para-Xylene
ortho-Xylene
Styrene
Toluene
2,5-Dimethylfuran
Methyl *tert* butyl ether

Coplanar polychlorinated biphenyls in serum (3)

3,3,4,4',5,5'-Hexachlorobiphenyl
3,3,4,4',5-Pentachlorobiphenyl
3,4,4',5-Tetrachlorobiphenyl

Polychlorinated biphenyls in serum (31; International Union for Pure and Applied Chemistry nomenclature)

PCB-101
PCB-105
PCB-110
PCB-118
PCB-128
PCB-138–158
PCB-146

PCB-149
PCB-151
PCB-153
PCB-156
PCB-157
PCB-167
PCB-170
PCB-74
PCB-99
PCB-172
PCB-177
PCB-178
PCB-180
PCB-183
PCB-187
PCB-189
PCB-196–203
PCB-201
PCB-28
PCB-44
PCB-49
PCB-52
PCB-66
PCB-87

Chlorinated dibenzodioxins and dibenzofurans in serum (15)

1,2,3,4,5,6,7,8-Octachlorodibenzodioxin
1,2,3,4,5,6,7,8-Octachlorodibenzofuran
1,2,3,4,6,7,8-Heptachlorodibenzodioxin
1,2,3,4,6,7,8-Heptachlorodibenzofuran
1,2,3,6,7,8-Hexachlorodibenzodioxin

1,2,3,7,8,9-Hexachlorodibenzodioxin
1,2,3,4,7,8-Hexachlorodibenzofuran
1,2,3,7,8,9-Hexachlorodibenzofuran
2,3,4,6,7,8-Hexachlorodibenzofuran
1,2,3,6,7,8-Pentachlorodibenzofuran
1,2,3,7,8-Pentachlorodibenzodioxin
1,2,3,7,8-Pentachlorodibenzofuran
2,3,4,7,8-Pentachlorodibenzofuran
2,3,7,8-Tetrachlorodibenzodioxin
2,3,7,8-Tetrachlorodibenzofuran

Metals in urine (13)

Total mercury
Antimony
Barium
Beryllium
Cadmium
Cesium
Cobalt
Lead
Molybdenum
Platinum
Thallium
Tungsten
Uranium

Metals in blood (4)

Cadmium
Inorganic mercury
Total mercury
Lead

Blood cyanide

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