Health and Environmental Consequences of the World Trade Center Disaster

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The attack on the World Trade Center (WTC) created an acute environmental disaster of enormous magnitude. This study characterizes the environmental exposures resulting from destruction of the WTC and assesses their effects on health. Methods include ambient air sampling; analyses of outdoor and indoor settled dust; high-altitude imaging and modeling of the atmospheric plume; inhalation studies of WTC dust in mice; and clinical examinations, community surveys, and prospective epidemiologic studies of exposed populations. WTC dust was found to consist predominantly (95%) of coarse particles and contained pulverized cement, glass fibers, asbestos, lead, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polychlorinated furans and dioxins. Airborne particulate levels were highest immediately after the attack and declined thereafter. Particulate levels decreased sharply with distance from the WTC. Dust pH was highly alkaline (pH 9.0–11.0). Mice exposed to WTC dust showed only moderate pulmonary inflammation but marked bronchial hyperreactivity. Evaluation of 10,116 firefighters showed exposure-related increases in cough and bronchial hyperreactivity. Evaluation of 183 cleanup workers showed new-onset cough (33%), wheeze (18%), and phlegm production (24%). Increased frequency of new-onset cough, wheeze, and shortness of breath were also observed in community residents. Follow-up of 182 pregnant women who were either inside or near the WTC on 11 September showed a 2-fold increase in small-for-gestational-age (SGA) infants. In summary, environmental exposures after the WTC disaster were associated with significant adverse effects on health. The high alkalinity of WTC dust produced bronchial hyperreactivity, persistent cough, and increased risk of asthma. Plausible causes of the observed increase in SGA infants include maternal exposures to PAH and particulates. Future risk of mesothelioma may be increased, particularly among workers and volunteers exposed occupationally to asbestos. Continuing follow-up of all exposed populations is required to document the long-term consequences of the disaster. *Key words:* air pollution, airway hyperresponsiveness, asbestos, occupational lung disease, $PM_{2.5}$, PM_{10}, small for gestational age (SGA). ***Environ Health Perspect*** **112:731–739 (2004). doi:10.1289/ehp.6702 available via *http://dx.doi.org/* [Online 18 February 2004]**

The destruction of the World Trade Center (WTC) on 11 September 2001 caused the largest acute environmental disaster that ever has befallen New York City (Claudio 2001; Landrigan 2001). The combustion of more than 90,000 L of jet fuel at temperatures above 1,000°C released a dense and intensely toxic atmospheric plume containing soot, metals, volatile organic compounds (VOCs), and hydrochloric acid. The collapse of the towers pulverized cement, glass, and building contents and generated thousands of tons of particulate matter (PM) composed of cement dust, glass fibers, asbestos, lead, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organochlorine pesticides, and polychlorinated furans and dioxins (Clark et al. 2003; Lioy et al. 2002; McGee et al. 2003). These materials dispersed over lower Manhattan, Brooklyn, and for miles beyond. They entered nearby office, school, and residential buildings. Much remained at the site to form Ground Zero, a six-story pile of smoking rubble that burned intermittently for more than 3 months.

Populations at greatest risk of exposure included firefighters, police, paramedics, other first responders [Prezant et al. 2002; Centers for Disease Control and Prevention (CDC) 2002], and construction workers and volunteers who worked initially in rescue and recovery and then for many months cleared rubble at Ground Zero. Others at potentially elevated risk included workers who cleaned WTC dust from nearby buildings, women who were pregnant on 11 September and succeeding weeks in lower Manhattan and adjacent areas of Brooklyn, and community residents, especially the 3,000 children who resided within 1 km of the towers and the 5,500 who attended school there.

Previous studies have documented the acute traumatic consequences of the attacks on the WTC, most notably the occurrence of

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2,726 deaths, including 343 deaths among firefighters and 60 among police officers (CDC 2002). Early clinical and epidemiologic assessments documented a high prevalence of respiratory symptoms, particularly, persistent cough in firefighters and rescue workers exposed to WTC dust (CDC 2002; Prezant et al. 2002). The prevalence of those symptoms was related to intensity and duration of smoke and dust exposure. Studies of the mental health consequences of the disaster have documented a high prevalence of posttraumatic stress disorder (PTSD) (Galea et al. 2002b; Fairbrother et al. 2003) and other psychological sequelae, including increased rates of drug and alcohol abuse (Boscarino et al. 2002; Galea et al. 2002a; Stuber et al. 2002; Vlahov et al. 2002a, 2002b).

In this report we summarize a comprehensive assessment of the impacts on human health and the environment of the chemical contaminants generated by destruction of the WTC. The work was undertaken by a consortium of six research centers supported by the National Institute of Environmental Health Sciences (NIEHS) in collaboration with the New York City Department of Health, the U.S. Environmental Protection Agency (EPA), and the CDC.

Environmental Exposure Assessment

Four distinct phases can be distinguished in the sources and patterns of environmental contamination that followed the attack on the WTC. We have been able to construct a chronology of this contamination from the environmental sampling data (Table 1).

Settled dust. To evaluate the composition of material deposited in lower Manhattan immediately after destruction of the WTC, samples of settled dust were collected at sites in lower Manhattan (Lioy et al. 2002; McGee et al. 2003). In the inorganic fraction of these samples, metals, radionuclides, ionic species, and asbestos were identified. In the organic fraction, PAHs, PCBs, polychlorinated dibenzodioxins and dibenzofurans, pesticides, phthalate esters, brominated diphenyl ethers, and other hydrocarbons were found (Lioy et al. 2002; Offenberg et al. 2003).

Each sample of settled dust had a highly alkaline pH (9.0–11.0). Asbestos levels ranged from 0.8% to 3.0% of mass; PAHs comprised > 0.1% of total mass; and lead content ranged from 101 to 625 ppm. Morphologically, most of the dust was fibrous and contained mineral wool, glass fibers, asbestos, wood, paper, and cotton fibers (Figure 1). Coarse cement particles were also a major component (Figure 2).

To assess the composition of settled dust by size, samples were mechanically sieved and then separated aerodynamically into three fractions (Lioy et al. 2002; McGee et al. 2003). More than 95% of the mass consisted of PM > 10 µm in diameter. The largest mass concentration consisted of PM > 53 µm in diameter, and there were proportionately more particles in this large size range in outdoor than in indoor samples. PM ≤ 2.5 µm in aerodynamic diameter ($PM_{2.5}$) comprised 0.88–1.98% of total mass. Alkalinity decreased with decreasing particle size, and $PM_{2.5}$ had a more nearly neutral pH (Lioy et al. 2002; McGee et al. 2003). This finding is consistent with the dominant presence of highly alkaline, coarse cement particles in the large size fraction. There was no geographical variation in particle size distribution in the settled dust samples, nor was a relationship found in indoor samples between particle size distribution and height above the ground.

To measure the elemental concentration of dust particles, X-ray fluorescence and inductively coupled plasma–mass spectrometry (ICP-MS) analyses were employed. Additionally, selected samples of PM > 2.5 µm were sent to the National Institute of Standards and Technology (NIST; Gaithersburg, MD) for neutron activation analysis. Results showed that chlorine was detectable only in the $PM_{2.5}$ fraction, whereas antimony, aluminum, titanium, and magnesium were present principally in the PM_{10-53} fraction, and iron, zinc, and calcium were most highly abundant in the $PM_{2.5-10}$ and PM_{10-53} fractions. A possible explanation for this distribution is that Cl in particulates was generated by high-temperature combustion of plastics and thus was concentrated in the smaller size fractions, whereas elements associated with the larger particles generated by collapse of the buildings, such as Fe, Zn, and Ca, predominated in the larger fractions.

Organic pollutants were analyzed in 14 samples of settled dust separated according to particle size, including one indoor sample (Lioy et al. 2002; Offenberg et al. 2003). PCBs comprised less than 0.001% of total mass. Organochlorine pesticides, including chlordanes, hexachlorobenzene, heptachlor, 4,4′-dichlorodiphenyldichloroethylene (DDE), 2,4′-dichlorodiphenyltrichloroethane (DDT), and mirex, were found at low concentrations. PAHs were found in greatest concentrations in the relatively larger particles (PM_{10-53}), although concentrations greater than those typically found in urban air were found also in $PM_{2.5}$. An estimated 100–1,000 tons of PAHs were spread over a localized area of lower Manhattan within 0.5 km of Ground Zero (Lioy et al. 2002; Offenberg et al. 2003).

Airborne PM. Collection of airborne $PM_{2.5}$ samples was initiated at a site in lower Manhattan on 14 September 2001. Levels of daily $PM_{2.5}$ and of hourly airborne carbon

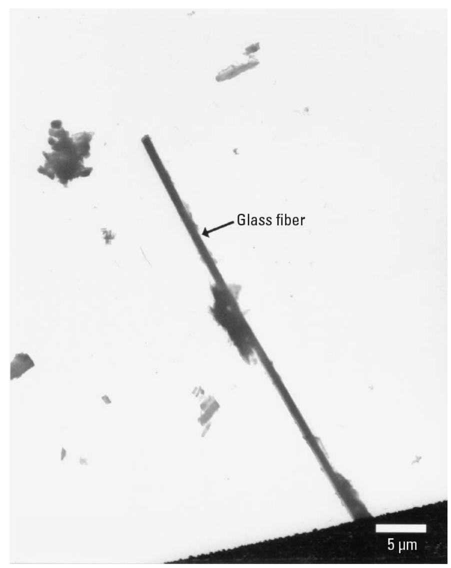

Figure 1. A glass fiber in a dust sample collected near the WTC, New York City, 12 September 2001. The figure is reproduced from Lioy et al. (2002) with permission from *Environmental Health Perspectives*.

Table 1. Sequence of environmental exposures after the attack on the WTC, September through December 2001.

Time period	Predominant sources of pollution	Airborne pollutants
First 12 hr after collapse (11 September 2001)	Burning jet fuel Fires Collapse of the Twin Towers	Combustion products: gaseous and particulate Evaporating gases from the collapse of towers Coarse particles
Days 1 and 2	Burning jet fuel Resuspension of settled dust/smoke	Combustion products: gaseous and particulate Gases evaporating from piles Resuspended coarse particles
Days 3–13	Smoldering fires Resuspension of settled dust/smoke	Combustion products: gaseous and particulate Coarse particle resuspension Diesel exhaust
Day 14 through 20 December 2001	Smoldering fires with occasional flareups Removal of debris by trucks and other heavy equipment	Combustion products: gases and particulates Diesel exhaust

Data from Lioy et al. (2002).

soot levels were measured at the New York University (NYU) Downtown Hospital (located 0.3 km east of Ground Zero) and at a site adjacent to the NYU Medical Center at First Avenue and 26th Street (0.7 km from Ground Zero). Collection of air samples at these locations continued until the last fire was extinguished on 20 December (Thurston and Chen 2002; Thurston et al. 2003; U.S. EPA 2004).

Levels of $PM_{2.5}$ very highly elevated above normal urban background were detected in the first days after 11 September (Figure 3). The sampling sites were not located directly in the path of the WTC plume, and thus actual levels may have been still higher.

$PM_{2.5}$ levels peaked in the night hours when winds were calm and thermal inversions allowed pollution to accumulate to higher levels than during the day (Figure 4). Levels decreased on rainy days when fires and wind-blown dust were diminished. Levels declined as the fires were extinguished, and they came to approach background ambient levels by mid-October.

Demolition and removal of debris began at Ground Zero in mid-October after the fires had decreased in intensity. Coarse dust generated by demolition was detectable in ambient air until December, when pollution from the site diminished greatly.

Trace elements. Concentrations of lead and Cl in $PM_{2.5}$ were intermittently elevated above background at sites near the WTC until mid-October, with occasional small peaks through October and into November. Ca levels, by contrast, were highest in October and November, possibly reflecting release of Ca-containing dust during demolition work at the site.

Dioxin and other chlorinated compounds. The extensive use of polyvinyl chloride (PVC) plastics within the WTC made possible the generation of dioxins during the fires. U.S. EPA monitoring data indicate that dioxin toxic equivalent (TEQ) levels in air samples near Ground Zero were several orders of magnitude above those typical of urban areas in the United States (U.S. EPA 2002). From 23 September through late November, dioxin levels in lower Manhattan ranged from 10 to > 150 pg TEQ/m^3. Dioxin concentrations several blocks from Ground Zero ranged from 1 to 10 pg, levels above typical urban background but considerably lower than those measured closer to Ground Zero. Dioxin levels declined rapidly during the autumn, and the U.S. EPA data suggest that by December 2001 they had decreased to typical urban background.

Asbestos. Asbestos, primarily chrysotile, was used for fire insulation in the construction of the North Tower of WTC up to the 40th floor (Nicholson et al. 1971; Reitze et al. 1972). Because of its known carcinogenic potential (Nicholson and Landrigan 1996), asbestos became a major health concern after 11 September. More than 10,000 ambient air samples from lower Manhattan were tested for asbestos by the U.S. EPA using phase-contrast light microscopy (PCM) to identify fibers > 5 µm in length; more than 8,000 of these samples were also examined by transmission electronic microscopy (TEM) to identify fibers of ≥ 0.5 µm in length (Columbia University 2003; U.S. EPA 2004).

Twenty-two of the air samples analyzed by the U.S. EPA were found to contain asbestos

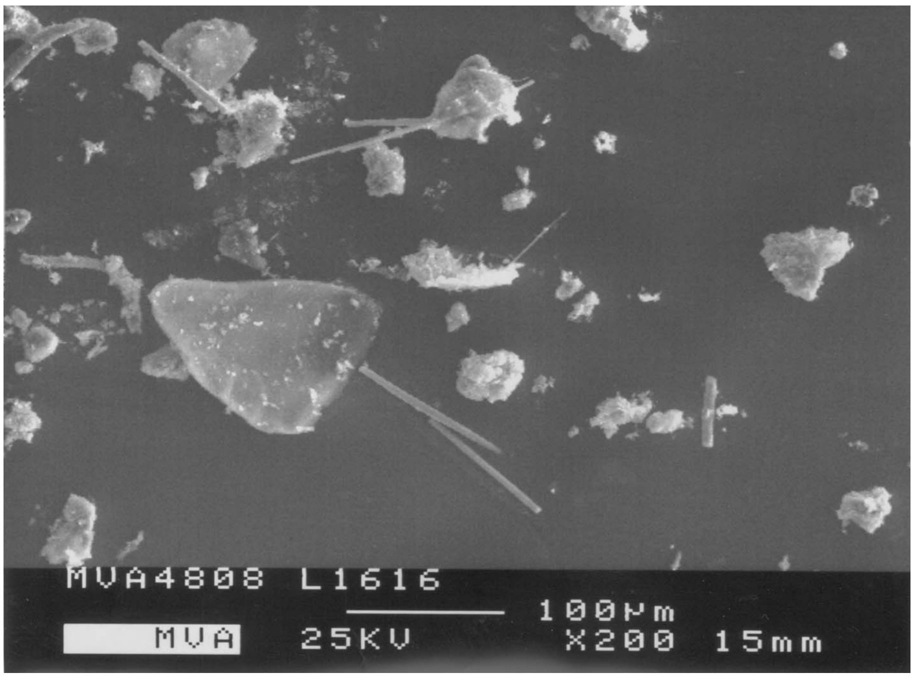

Figure 2. Photomicrograph of settled dust from the WTC containing cement particles and glass fibers, collected 12 September 2001.

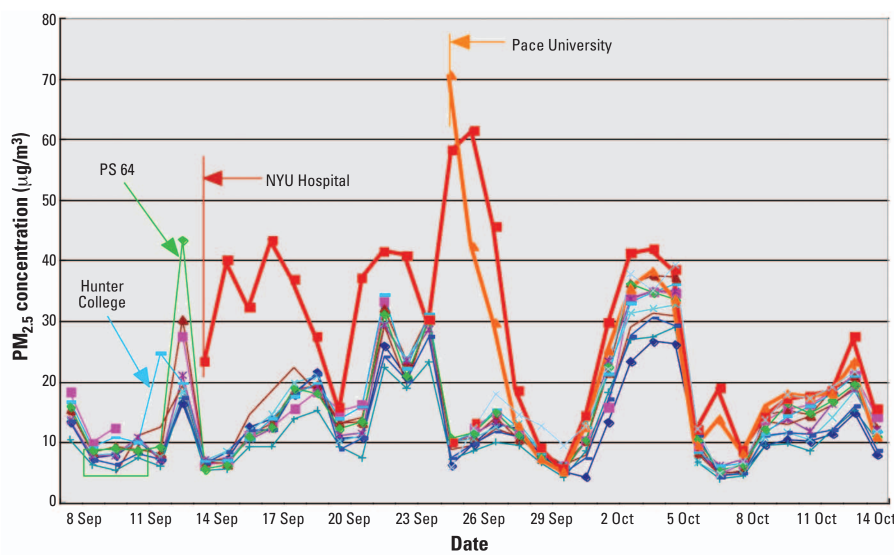

Figure 3. Airborne $PM_{2.5}$ mass concentrations at NYU Downtown Hospital (five blocks east of Ground Zero) and other sites in Manhattan, September through mid-October 2001. PS, public school. Data from Thurston et al. (2003).

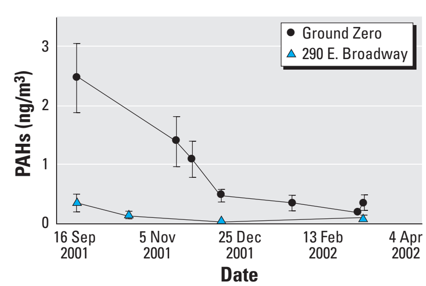

Figure 4. Mean airborne concentration of seven PAHs at Ground Zero and at 290 E. Broadway, Manhattan, September 2001 through April 2002.

at levels above the clearance standard of 70 fibers/mm^2 established under the Asbestos Hazard Emergency Response Act (U.S. EPA 1986). This standard uses the TEM measurement technique. Most of the elevated asbestos levels in air were observed in the earliest days after 11 September.

There were no 8-hr time-weighted average asbestos exposures to workers above the Occupational Safety and Health Administration standard (U.S. Department of Labor 2003), which uses the PCM measurement technique of 0.1 fiber/cm^3, although workers undoubtedly had short-term peak exposures when they disturbed asbestos-containing rubble at Ground Zero.

Asbestos was detected in settled dust samples within apartments and other buildings (Lioy et al. 2002). Because some residents had prolonged exposures to uncleaned apartments, these indoor exposures may have added significantly to ambient exposures.

Airborne PAHs. To characterize PAHs in $PM_{2.5}$ from the WTC, the National Exposure Research Laboratory (NERL) of the U.S. EPA collected air samples with 47-mm Teflon filters at and near Ground Zero from late September 2001 through May 2002. Samples were collected from three Ground Zero fenceline locations and at 290 E. Broadway (about 0.7 km from Ground Zero). Researchers at the University of North Carolina at Chapel Hill and the NERL used an assay developed to measure the larger (five- and six-ring) PAH molecules to determine the content of PAHs in these samples.

The PAHs in those samples consisted of a complex mixture including benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, benzo(*a*)pyrene, benzo(*e*)pyrene, ideno(1,2,3-*c,d*)pyrene, dibenzo(*a,h*)anthracene, and benzo(*g,h,i*)perylene. All except benzo(*e*)pyrene are known or suspected carcinogens and typically are produced by incomplete combustion of organic material. Levels at Ground Zero were highest immediately after the attack and declined over subsequent weeks (Figure 4). The consistently greater abundance of PAHs at Ground Zero than farther away indicates that burning debris at the site was a major source of airborne PAH pollution in lower Manhattan (Lioy et al. 2002; Offenberg et al. 2003). The unique pattern of PAHs found in these samples further confirmed that the WTC was the source.

Source identification. Multi-element analyses by ICP-MS of airborne samples collected at Ground Zero were used to generate chemical profiles that could identify specific sources of emission (Chillrud et al., unpublished data; McGee et al. 2003). These studies relied on factor analyses.

The principal emission sources identified included *a*) torch-cutting and heating of steel products (e.g., structural beams); *b*) combustion of building materials and contents; *c*) resuspension of earth crustal materials; and *d*) combustion of fossil fuels in engines with catalytic converters. A quantitative source apportionment analysis of ambient $PM_{2.5}$ samples collected in lower Manhattan five blocks from Ground Zero indicated that airborne emissions from several of these same sources had spread to the surrounding community. Levels of WTC pollutants in the nearby community declined rapidly after September, and emissions from other conventional sources (e.g., oil heating combustion) came to predominate as the fires subsided.

Mapping the WTC plume. To better characterize the spatial distribution of the material released to the atmosphere by the destruction of the WTC, researchers at the Lamont-Doherty Earth Observatory, the U.S. Geological Survey (USGS), NASA (National Aeronautics and Space Administration), the U.S. EPA, and Analytical Imaging and Geophysics, LLC (Boulder, CO, USA) used images of lower Manhattan acquired on 16, 18, and 23 September 2001 by NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). The resulting data had sufficiently clear resolution (1.7 m) to quantify the structure of the plume within street canyons in lower Manhattan (Chillrud et al., unpublished data; Clark et al. 2003).

The AVIRIS images indicate that the plume moved southeast from Ground Zero on the afternoon of 11 September across lower Manhattan and over areas of Brooklyn. The optical opacity of the plume appeared to diminish significantly from the fifth to the seventh days and to the twelfth day postcollapse, probably reflecting overall weakening of the fires during that time. On 16 and 18 September, the plume moved southward. By 23 September the plume had become significantly weaker (McCurdy et al. 2000).

Pollution modeling and individualized exposure assessment. Preliminary estimates of the plume location and relative dilution models have been used to develop 8-hr average characterizations of plume spread over Manhattan and Brooklyn for the first 2 weeks after 11 September. For the days immediately after 11 September, this information includes SPOT (Satellite Pour l'Observation de la Terre) and LANDSAT satellite images, NASA space station photographs, and MODIS (Moderate Resolution Imaging Spectroradiometer) images (Figure 5).

To go beyond the AVIRIS data and comprehensively model individual exposures from the WTC plume, the high-altitude imagery is being integrated with information on the geographic location of individuals within the epidemiologic study populations and with health outcomes data. A nested/multiscale WTC plume location and relative dilution model being developed by the Environmental and Occupational Health Sciences Institute (EOHSI) will be used in this program to reconstruct individual exposure profiles for incorporation in the epidemiologic studies within the NIEHS program.

Health Risk Assessment

Overview. Health risk assessments by the NIEHS Centers began by identifying populations at high risk of exposure to WTC contaminants and then undertaking clinical and epidemiologic studies within these groups (Landrigan 2001). Future analyses will seek to relate health outcomes data to geocoded information on contaminant levels (McCurdy et al. 2000).

Firefighters. Firefighters were among the most heavily exposed populations. They also suffered the greatest loss of life of all occupational groups. In the first 24 hr after the attack on the WTC, 240 New York City firefighters sought emergency medical treatment; of these, 50 (20.8%) received treatment of acute respiratory symptoms caused by inhalation of airborne smoke and dust (Prezant et al. 2002; Spadafora 2002). Firefighters described walking through dense clouds of dust and smoke in the hours immediately after the attack, in which "the air was thick as soup" (CDC 2002).

Follow-up medical evaluation of 10,116 firefighters was conducted over the 6 months after the attack (Prezant et al. 2002). Persistent cough accompanied by other respiratory symptoms so severe as to require at least 4 weeks' leave of absence, termed "World Trade Center cough," was diagnosed in 332 firefighters (Chen and Thurston 2002; Scanlon 2002). Prevalence of WTC cough was related to intensity of smoke exposure, and occurred in 128 (8%) of 1,636 firefighters with a high level of exposure, in 187 (3%) of 6,958 with moderate exposure, and in 17 (1%) of 1,320 with low-level exposure (Figure 6). Among firefighters without WTC cough, bronchial hyperreactivity was present in 77 (23%) of those with a high level of exposure, and in 26 (8%) of those with moderate exposure (Prezant et al. 2002). One case of eosinophilic pneumonia was diagnosed in a firefighter (Beckett 2002; Rom et al. 2002). Induced sputum analysis of New York City firefighters showed increases in sputum PM levels as well as in neutrophil and eosinophil counts. Those abnormalities were positively correlated with levels of exposure to WTC dust and combustion products, as well as with levels of PAHs in the bodies of firefighters (Edelman et al. 2003).

Cleanup and recovery workers. Many hundreds of workers were involved in clearing rubble and transporting it off-site. To assess the occupational exposures and health status of these workers, many of whom were truck drivers, a team from the Bloomberg School of Public Health at Johns Hopkins University and the Mailman School of Public Health at Columbia University undertook area air monitoring, personal exposure assessment, and health studies.

Air monitoring was conducted in October 2001 and April 2002. It focused on PM, asbestos, and VOCs. Monitoring was conducted across both day and night shifts, 7 days/week. Personal monitoring was conducted for 69 truck drivers. A total of 458 personal and area air samples were collected.

In October 2001, the highest concentrations of total dust were found at the debris pile (median, 1,603 μg/m^3). Total dust levels on the pile in October were approximately five times higher than at the perimeter. By April 2002, total dust concentrations of the site had become significantly lower and were more uniformly distributed. In October 2001, median personal particulate exposure was 323.7 μg/m^3. By April 2002, median exposure had fallen to 137.7 μg/m^3. Airborne asbestos concentrations were found to be generally low. The fibers detected were mostly very short. Concentrations of VOCs were generally low.

To assess prevalence of respiratory symptoms and lung dysfunction, a cross-sectional clinical and epidemiologic study was initiated in December 2001. A convenience sampling strategy was used to recruit workers on-site. Inclusion criteria required that participants be at least 18 years of age, employed at the site, and willing to answer a respiratory health questionnaire. Informed consent was obtained from all participants. Chronic respiratory symptoms were assessed using an interviewer-administered questionnaire adapted from the American Thoracic Society questionnaire. Spirometric measurements were performed using American Thoracic Society guidelines (American Thoracic Society 1994) to characterize lung function and to identify individuals with lung function below the normal range. Two trained pulmonary function technicians certified by the National Institute for Occupational Safety and Health (NIOSH) conducted all spirometric assessments. Questionnaires and spirometry were administered to 183 rubble removal workers.

Among the 183 workers surveyed, a high proportion (32.8%) reported experiencing cough that began after the start of employment at the WTC site; 24.0% reported new onset of phlegm production; and 17.5% reported new onset of wheeze. Approximately half of all workers reported that they had experienced at least one new symptom since they had begun working at the WTC site. The average percentage of predicted values for forced expiratory volume in 1 sec (FEV_1) and forced vital capacity (FVC) were 96.3% and 98.8%, respectively, and the mean FEV_1:FVC ratio was 80.5%.

Community residents. To assess prevalence of new-onset respiratory symptoms after 11 September 2001 among previously healthy persons in lower Manhattan as well as in residents with preexisting asthma, a team from NYU Medical Center in collaboration with the New York State Department of Health and the New York Academy of Medicine conducted a clinical and epidemiologic survey (Reibman et al. 2003). Symptoms were assessed by questionnaire, and pulmonary

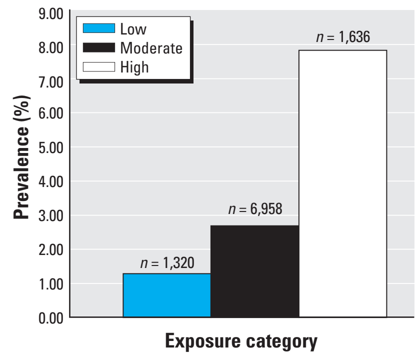

Figure 6. Prevalence of persistent cough in New York City firefighters exposed to smoke and dust from the WTC, September 2001 through March 2002. Data from Prezant et al. (2002).

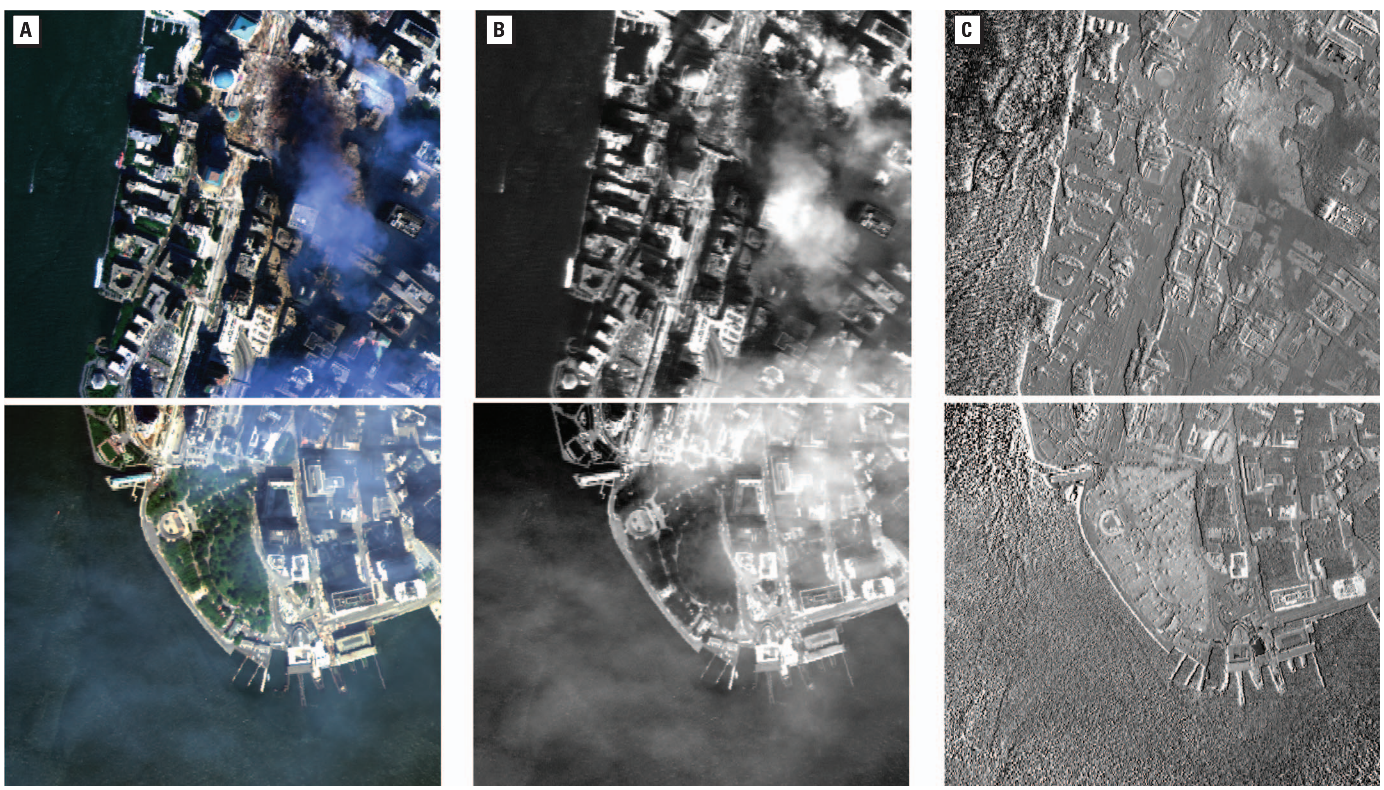

Figure 5. AVIRIS imagery of lower Manhattan acquired on 16 September 2001. (*A*) Visible color composite of the plume (RGB = 0.66/0.55/0.44 μm). (*B*) The short-wavelength visible blue band (0.44 μm) shows the extent of aerosol scattering as brighter areas. (*C*) The near-infrared band ratio (0.94 μm/0.86 μm) indicates the spatial extent of the plume.

function was evaluated in a subset of the study population by standard screening spirometry.

A total of 2,166 residents of lower Manhattan living within a 1.6-km radius of the WTC were enrolled in this survey and compared with 200 persons living 1.6–8.0 km distant. Spirometry was performed in 52 residents. Preliminary data indicate that previously healthy persons living near Ground Zero had a greater increase in prevalence of respiratory symptoms after 11 September than did more distant residents. These symptoms were predominantly cough, wheeze, and shortness of breath. Symptoms were not associated with abnormal screening spirometry.

Preexisting asthmatic residents in the exposed area also reported a higher prevalence of respiratory symptoms after 11 September. They also reported an increased use of asthma medication relative to controls.

Toxicologic studies. To complement the clinical and epidemiologic studies of workers, toxicologic examinations of WTC dust were performed (Gavett et al. 2003).

Methodology. Samples of $PM_{2.5}$ were obtained by size fractionation of bulk settled WTC dust. These samples were chemically characterized (McGee et al. 2003). Consistent with findings in the total bulk dust samples, these samples were found to contain Ca, sulfur, and Ca–carbon particles. Levels of Ca ranged from 22 to 33%, and sulfur (as sulfate) ranged from 37 to 43%. Only very low levels of transition and metallic elements were present. These samples were administered to mice by aspiration in doses of 10, 31.6, or 100 µg. The samples administered included WTC $PM_{2.5}$ from seven individual collection sites, a sample pooled from these seven locations (WTCX), and a sieved sample from an eighth location (WTC3). Comparison $PM_{2.5}$ samples were derived from Mount Saint Helen's dust, residual oil fly ash (ROFA), and NIST Standard Reference Material 1649a (urban PM from Washington, DC).

Results. Aspirated samples of WTCX $PM_{2.5}$ were found to induce a mild to moderate degree of pulmonary inflammation in rodents at a relatively high dose (100 µg) (Figure 7). This inflammatory response was not as great as that caused by ROFA or NIST 1649a (Gavett et al. 2003).

A 100-µg dose of WTC $PM_{2.5}$ was found to cause a striking degree of airway hyperresponsiveness to methacholine aerosol. This hyperresponsiveness was comparable with that produced by NIST 1649a and greater than that produced by ROFA (Figure 8). Although the pulmonary neutrophilic inflammation observed in exposed mice diminished 1–3 days after exposure, the hyperresponsiveness to methacholine did not diminish significantly in that time period.

Mice exposed to lower doses of pooled WTC $PM_{2.5}$ (10 µg and 31.6 µg) and mice exposed by nose-only inhalation manifested neither neutrophilic inflammation nor methacholine responsiveness. No variation in response was noted in relation to the geographical locations at which the dust samples had been collected.

Pregnant women and their offspring. Many pregnant women were either working in the WTC or working or residing in the communities of lower Manhattan on 11 September 2001. To assess pregnancy outcomes in these women and impacts on their infants, teams from the Mount Sinai School of Medicine and the Mailman School of Public Health of Columbia University established complementary prospective epidemiologic cohort studies.

Populations. The Mount Sinai population consisted of 187 pregnant women who were either in or near the WTC on 11 September (Berkowitz et al. 2003). Twelve were actually inside the towers, and an additional 122 (65%) were within 10 blocks. A comparison group (n = 2,367) consisted of all private patients not known to have been near the WTC who delivered at Mount Sinai Hospital during the same time period.

The racial/ethnic composition of the exposed group in the Mount Sinai study was 72.5% white, 11.0% African American, 6.6% Hispanic, 3.9% Asian, and 6.0% of mixed or other race/ethnicity. Participants were relatively old: 15.4% were younger than 30 years of age, 40.1% were 30–34 years of age, 33.0% were 35–39 years of age, and 11.5% were ≥ 40 years of age. The women in the Mount Sinai study were evenly distributed by trimester of pregnancy on 11 September. Of the 187 women originally recruited into the study, 3 miscarried and 2 were lost to follow-up, leaving 182 participants with live births. The last delivery occurred in June 2002. Deliveries took place at 47 hospitals in the New York City area. The Mount Sinai School of Medicine team is collaborating with EOHSI exposure modelers who are developing individualized exposure profiles for each woman based on their location (e.g., in an affected structure, in a downwind location) and the time spent in each location (indoors and outdoors) in the days and weeks after 11 September.

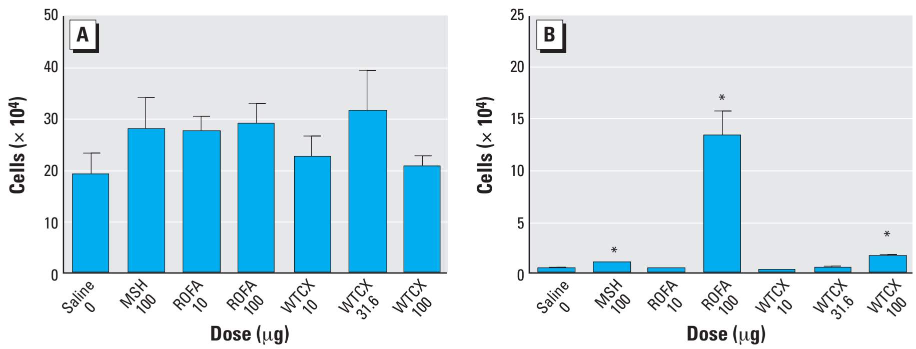

Figure 7. Number of cells recovered by bronchoalveolar lavage from mice 1 day after aspiration of PM samples in saline or saline vehicle alone. (*A*) Macrophages. (*B*) Neutrophils. MSH, Mount Saint Helen's dust.
*Significantly greater number of neutrophils than for saline control groups.

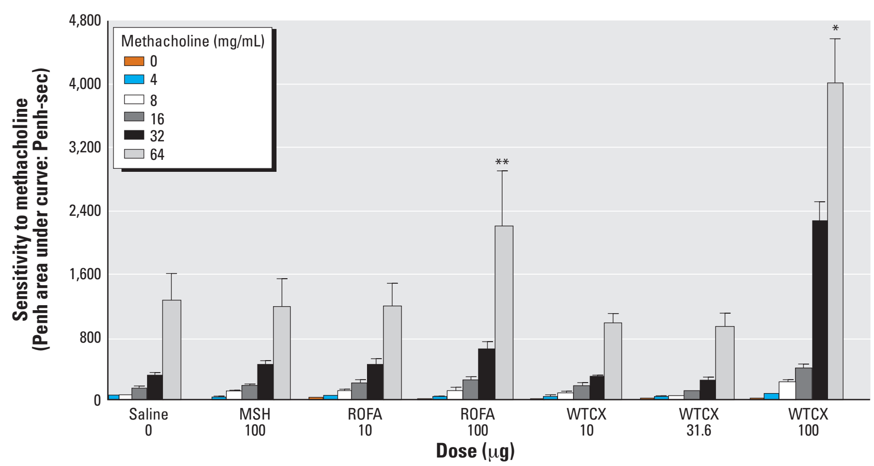

Figure 8. Airway responsiveness to methacholine aerosol in mice exposed to PM sample or saline vehicle and tested 1 day later. Penh (enhanced pause) is an indicator of airway resistance; changes in Penh have been demonstrated to correlate with changes in airway resistance during methacholine challenge.
*Significantly more responsive than all other groups. **Significantly more responsive than all except the WTCX 100-µg group.

The population in the Columbia study consisted of 329 women who were recruited when they arrived in labor at one of three hospitals in lower Manhattan (Beth Israel Medical Center, NYU Downtown Hospital, as well as its affiliated St. Vincent's Hospital and Medical Center, and its affiliated Elizabeth Seton Childbearing Center). Women were eligible to participate if they were between 18 and 39 years of age, were not having a multiple birth, had not smoked during pregnancy, did not report having had any of a list of specified health conditions, and provided a maternal (n = 211) and/or cord (n = 290) blood sample. Women's eligibility for participation in the exposed (n = 160) or control (n = 169) groups was based on the distance of their residence and work sites from the WTC and the number of hours they had spent at these locations during the 2 weeks after 11 September 2001. All women were enrolled between 13 December 2001 and 27 June 2002.

The 329 women in the final Columbia sample were 40% white, 34% Asian, 15% African American, and 10% "other" or not reported. Twenty-one percent also identified themselves as Hispanic. The languages of interviews were English, 76%; Mandarin, 21%, Spanish, 1.5%, and Cantonese, 1.2%. Over 80% of the women were married or cohabiting > 7 years. Average educational attainment was 13.9 years; 18.5% of the subjects did not have a high school diploma, and 42% had at least a college degree. Household incomes of ≤ $50,000 were reported by 55.7% of the women who reported incomes.

Continuing follow-up. The Mount Sinai team is currently following the infants. In addition to obtaining indices of growth, two assessments of early cognitive development have been performed: the Fagan Infantest and the Visual Expectation Paradigm (Canfield et al. 1997; Canfield and Kirkham 2001; Jacobson et al. 1992; Shepherd and Fagan 1987). To date, cognitive assessments at 9 months of age have been completed on 159 infants. Further follow-up assessments are planned to at least 3 years of age.

In the Columbia study, participants were reinterviewed by phone when infants reached 6 months of age. Information was sought regarding the diet of each child as well as breast-feeding patterns. All hospitalizations and their causes were recorded. Two hundred ninety-four women completed this interview. To assess cognitive and motor function, the Bayley Scales of Infant Development (Bayley and Gyurke 1993) is being administered at the 1-year follow-up visit. Each child's weight, height, and head circumference were measured. The mother was reinterviewed at this meeting to determine any changes in key variables, to obtain details about the mother's and infant's health and postnatal exposures, and to complete the list of the infant's hospitalizations through the first year of life.

Pregnancy outcomes. In the Mount Sinai cohort, no significant differences were found between the groups in mean gestational age or mean birth weight. There were no significant differences in frequency of preterm births (< 37 weeks of gestation) or in incidence of low birth weight (Table 2) (Berkowitz et al. 2003).

However, the Mount Sinai WTC cohort had a 2-fold increased risk of small-for-gestational-age (SGA) infants, defined as infants with a birth weight below the 10th percentile for gestational age in the nomogram of Brenner et al. (1976) (Table 2). This statistically significant difference was still evident after controlling for relevant covariates and potential confounders, including maternal age, parity, race/ethnicity, sex of the infant, and maternal smoking history. No significant difference in the frequency of SGA infants was observed according to the trimester of pregnancy on 11 September. No associations were evident between symptoms of posttraumatic stress, based on the PTSD Checklist (Schlenger et al. 2002), and frequency of preterm birth, low birth weight, or SGA infants.

In the Columbia study, there was no difference between the exposed and control groups in newborn birth weight (3,377 vs. 3,459 g), length, head circumference, or Apgar scores, but gestation duration was significantly shorter in the exposed group (274.3 vs. 275.9 days; $p = 0.045$). The study groups did not differ significantly in maternal age, height, prepregnancy weight, parity, or marital status, but the exposed group had 1 more year of education (14.4 vs. 13.4 years; $p < 0.05$).

Discussion

This report presents the most comprehensive summary to date of the environmental exposures resulting from the attack on the WTC and of their effects on human health. Our main focus was on chemical exposures. Our findings complement earlier reports describing the acute physical consequences of the disaster (CDC 2002; Prezant et al. 2002) and its psychological impacts (Boscarino et al. 2002; Fairbrother et al. 2003; Galea et al. 2002a, 2002b; Stuber et al. 2002; Vlahov et al. 2002a, 2002b).

Our assessments show that exposures to chemical contaminants were not uniform in New York after 11 September (Clark et al. 2003; Lioy et al. 2002; McGee et al. 2003; Offenberg et al. 2003). Instead, there were sharp gradients by time after the attack and by distance from Ground Zero (Table 1). In the first few hours, extremely heavy exposures to high levels of dust and smoke as well as to gaseous products of combustion predominated. This pattern continued for the next 2 days, when there occurred rapid decline of smoke and dust levels and continuing decline in levels of combustion products as jet fuel and flammable building contents were consumed. A large fraction of the outdoor dust was eliminated over the first weekend after the disaster by rain that fell on Friday, 14 September, and by the U.S. EPA's cleanup of the Wall Street area. Over the next several weeks, airborne particulate levels in lower Manhattan continued to decline but rose intermittently at night and when the air was still. Transient increases were noted also when the pile was disturbed and fires flared. Diesel exhaust became an important contaminant with the arrival on site of scores of cranes, heavy trucks, and other construction equipment. For weeks, an acrid cloud hung over lower Manhattan and areas of Brooklyn until the fires were finally extinguished on 20 December.

Asbestos was of great concern to the public in New York City and to government agencies after 11 September. Asbestos, principally chrysotile, was used in the early 1970s in construction of the WTC as fireproofing up to the 40th floor of the North Tower (Nicholson et al. 1971; Reitze et al. 1972). Asbestos was not used beyond that point because of the recognition of its hazard and its replacement in the remainder of the construction with non-asbestiform fireproofing materials. Although some of this asbestos had been removed over the preceding 30 years, hundreds of tons remained on 11 September 2001 and were blasted free. Ambient air samples showed that asbestos exposures were initially elevated but fell to within U.S. EPA standards after the first few days (U.S. EPA 2004). Asbestos was found in settled dust at Ground Zero in concentrations ranging from 0.8 to 3.0% (Lioy et al. 2002). Asbestos was found in dust in nearby apartments, sometimes at higher levels than in the outside environment (Lioy et al. 2002).

Airborne lead levels were elevated in the first days after 11 September, but never highly.

Table 2. Pregnancy outcomes in relation to the attack on the WTC, September 2001 through June 2002.

	WTC group	Control group	p-Value
No.	187	2,367	—
Mean gestational age (weeks)	39.1	39.0	0.55
Mean birth weight (g)	3,203	3,267	0.14
Frequency of preterm birth (%)	9.9	9.2	0.76
Frequency of low birth weight (%)	8.2	6.8	0.47
Frequency of SGA infants (%)	8.2	3.8	< 0.01

Data from Berkowitz et al. (2003).

There is little indication that ambient air lead exposures posed substantial health risks to the population of lower Manhattan (U.S. EPA 2004).

Airborne dioxin levels were elevated substantially above normal urban background levels in the initial days after 11 September. The U.S. EPA's initial risk analysis suggests that these elevations did not result in a significant elevation in cancer or noncancer risk (U.S. EPA 2003). Further follow-up of exposed populations will be required to evaluate the accuracy of that assessment.

Risks to health were determined by the timing, duration, and chemical composition of exposures as well as by proximity to Ground Zero. Firefighters, police, and other first responders sustained heaviest initial exposures. Studies of firefighters confirmed the presence of a positive relationship between intensity and duration of exposure and severity of pulmonary effects (Figure 6) (Prezant et al. 2002) as well as of PM levels in sputum. Prolonged exposures occurred among firefighters and other public safety personnel who remained at Ground Zero as well as among construction workers, volunteers, and workers removing rubble (Levin et al. 2002; Lippy 2002). Workers cleaning nearby buildings may also have sustained potentially serious exposures (Malievskaya et al. 2002).

Health data from the study of rubble removal workers confirm that these workers, many of whom worked at Ground Zero for many months, had sustained clinically significant exposures to airborne irritants, resulting in symptoms consistent with upper and lower airway inflammation (Levin et al. 2002). To extend these initial studies, the team at Mount Sinai has initiated the World Trade Center Worker and Volunteer Medical Screening Program. This program, supported by NIOSH, has already examined more than 10,000 workers. These workers will be followed prospectively to assess long-term and delayed effects.

Toxicologic studies have elucidated the pathophysiologic mechanisms underlying the clinical findings seen in worker populations (Gavett et al. 2003). High-dose exposures to fine airborne particulates ($PM_{2.5}$) from the WTC, such as occurred in the immediate aftermath of the collapse, were shown in mice to produce mild to moderate degrees of respiratory inflammation and a very striking degree of hyperresponsiveness of airways. A property of the dust that appears to have contributed to its intense respiratory irritability was its high alkalinity (Lioy et al. 2002; McGee et al. 2003). Larger particles composed principally of cement dust were especially alkaline (pH 9.0–11.0). These particles were of a size likely to be caught in the upper airways. Along with inhaled glass fibers, they were probably responsible for the intense irritation of the nasal passages as well as for the chronic debilitating cough observed in heavily exposed populations (Chen and Thurston 2002; Scanlon 2002; Thurston and Chen 2002).

Further experiments will be necessary to determine whether the pulmonary hyperresponsiveness observed in mice is persistent. Such research may provide insights also into the anticipated duration of the pulmonary effects in workers. Factors that may influence persistence in workers include level of exposure, use of respiratory protection, individual differences in sensitivity, and interspecies differences.

Airborne exposures in the residential and business communities of lower Manhattan beyond Ground Zero were much lower than those sustained by workers (U.S. EPA 2004). Daily average levels of fine particulate pollution in these communities were generally within U.S. EPA limits when averaged over a 24-hr period. Higher short-term peaks were, however, observed especially at night and could have contributed to reported health effects, especially in susceptible populations such as children, the elderly, and persons with respiratory or cardiac disease. Indoor exposures to resuspended dust may have added to total exposures (Lioy et al. 2002). Residents in these communities reported an increased frequency of new-onset pulmonary symptoms (Reibman et al. 2003) but had no abnormalities on pulmonary function testing. These findings are consistent with the observed gradient of exposures.

An increase in incidence of SGA was the major adverse health effect seen in infants born to women who were inside the towers or within approximately 10 blocks of the WTC on 11 September (Berkowitz et al. 2003). Incidence of SGA infants was 2-fold greater among the WTC mothers than in a demographically similar comparison population not known to have been in lower Manhattan on 11 September 2001 ($p < 0.01$).

SGA is an index of intrauterine growth restriction (IUGR). Biologically plausible causes of IUGR in these babies include exposures to fine PM and PAHs. Previous studies have found associations between particulate air pollution and IUGR (Bobak et al. 2001; Dejmek et al. 1999); other investigations have linked air pollution to preterm births (Ritz et al. 2000). High levels of PAH–DNA adducts in umbilical cord leukocytes have been associated with reduced birth size (Perera et al. 1998). Prenatal exposure to cigarette smoke, which contains PAHs among other toxins, is a well-established risk factor for IUGR. Maternal stress is another possible cause of the observed increase in SGA, but we were unable to detect any correlation between reported levels of stress and SGA incidence.

Important questions about possible future risks to health of persons exposed to contaminants from the WTC remain unanswered:

- Will pulmonary disease persist in workers exposed to dust, especially in those who sustained very heavy exposures in the first days after 11 September and those with prolonged exposures?
- Will an increased incidence of mesothelioma result from exposures to asbestos? All types of asbestos fibers have been shown in laboratory as well as clinical studies to be capable of causing mesothelioma (Nicholson and Landrigan 1996). Pathologic studies have found short chrysotile fibers, the predominant type of fiber in WTC dust, to be the predominant fiber in mesothelioma tissue (Dodson et al. 1991; LeBouffant et al. 1973; Suzuki and Yuen 2002). Mesothelioma has been reported in persons with relatively low-dose, nonoccupational exposure to asbestos (Anderson 1982; Camus et al. 1998; Magnani et al. 2001). The greatest future risk of mesothelioma would appear to exist among first responders who were enveloped in the cloud of dust, other workers employed directly at Ground Zero, and workers employed in cleaning asbestos-laden dust from contaminated buildings. The risk of mesothelioma to residents of lower Manhattan must be considered to be extremely low but may still be elevated above background.
- Will exposure to airborne dioxin in lower Manhattan in the days and weeks after 11 September increase risk of cancer, diabetes, or other chronic disease (Kogevinas 2001)?
- Will the increased frequency of SGA observed in babies born to women who were within or near the WTC on 11 September result in long-term adverse effects on growth or development (Berkowitz et al. 2003)?

Full elucidation of these and other questions concerning the long-term and delayed health effects of exposures resulting from the attack on the WTC will require continuing, prospective, multiyear clinical and epidemiologic follow-up and further refinement of exposure assessments. That work is under way.

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