SPECIAL FOCUS

Epidemiology of Respiratory Health Outcomes Among World Trade Center Disaster Workers: Review of the Literature 10 Years After the September 11, 2001 Terrorist Attacks

Christine C. Ekenga, PhD, MPH; George Friedman-Jiménez, MD

ABSTRACT

Tens of thousands of workers participated in rescue, recovery, and cleanup activities at the World Trade Center (WTC) site in lower Manhattan after the terrorist attacks on September 11, 2001 (9/11). The collapse of the WTC resulted in the release of a variety of airborne toxicants. To date, respiratory symptoms and diseases have been among the most examined health outcomes in studies of WTC disaster workers. A systematic review of the literature on respiratory health outcomes was undertaken to describe the available information on new onset of respiratory symptoms and diseases among WTC disaster workers after September 11, 2001. Independent risk factors for respiratory health outcomes included being caught in the dust and debris cloud, early arrival at the WTC site, longer duration of work, and delaying mask and respirator use. Methodological challenges in epidemiologic studies of WTC disaster workers involved study design, exposure misclassification, and limited information on potential confounders and effect modifiers. In the 10 years after 9/11, epidemiologic studies of WTC disaster workers have been essential in investigating the respiratory health consequences of WTC exposure. Longitudinal studies along with continued medical surveillance will be vital in understanding the long-term respiratory burden associated with occupational WTC exposure.

(*Disaster Med Public Health Preparedness*. 2011;5:S189-S196)

Key Words: September 11 terrorist attacks, epidemiology, occupational diseases, respiratory tract diseases, disasters

More than 90 000 disaster workers and volunteers participated in rescue, recovery, and cleanup activities at the site of the World Trade Center (WTC) towers in lower Manhattan in the aftermath of the September 11, 2001 (9/11) terrorist attacks. Firefighters, police officers, construction workers, remediation workers, and sanitation workers were among the many groups of workers who responded to the disaster. By the time cleanup and recovery activities at Ground Zero ended on May 30, 2002, workers had sifted through approximately 1.8 million tons of debris from the collapse of the 2 towers.

The collapse of the WTC resulted in the release of a variety of environmental toxicants. Among the many components from the collapsed buildings were pulverized concrete, including respirable silica dust, metal compounds, asbestos, polycyclic aromatic hydrocarbons, dioxins, and volatile organic compounds.[1-3] WTC disaster workers also were susceptible to inhalation hazards resulting from dust resuspension during cleanup efforts. Particulate material at the WTC contained gypsum and calcium carbonate, known to irritate the airways and eyes.[4]

In the first 10 years after the WTC disaster, epidemiologic studies of disaster workers have been vital in understanding the health effects of exposures to these toxicants. To date, respiratory symptoms and diseases have been among the most examined health outcomes in studies of WTC disaster workers. Epidemiologic studies have reported on the new onset and worsening of lower and upper respiratory symptoms, "WTC cough," and new-onset respiratory diseases such as asthma, reactive airways dysfunction syndrome (RADS), and parenchymal lung diseases.

This article summarizes the literature on respiratory health outcomes among WTC disaster workers, with 3 main goals: to review the existing evidence on risk factors for new-onset respiratory health outcomes among WTC disaster responders, to identify the methodological challenges associated with the study of disaster-related respiratory health outcomes, and to propose recommendations for future research.

EPIDEMIOLOGIC STUDIES

Early surveillance identified disaster workers as a high-risk population group among WTC-exposed persons. Studies of WTC disaster workers documented signifi-

cant associations between WTC exposures, increased incidence of new-onset respiratory symptoms and diseases, and significant reductions in forced expiratory volume in 1 second (FEV_1) and forced vital capacity (FVC). WTC responder programs, established to monitor health outcomes for up to 20 years post-9/11, have provided valuable insights into the mid-term (≥5 years after 9/11) respiratory health impact of WTC disaster work.

Studies of Early Respiratory Health Outcomes (<5 Years) After 9/11

The public health research response to the WTC disaster began soon after the collapse of the towers. Early studies of WTC disaster workers were characterized by surveillance of injuries and illnesses in the weeks after the disaster.[5-7] On September 14, 2001, the Centers for Disease Control and Prevention (CDC) began injury and illness surveillance at both temporary medical facilities and local emergency departments throughout New York City.[5] A review of medical records between September 11, 2001 and October 11, 2001 revealed that respiratory illnesses, comprising 16% of all of the reported injuries and illnesses, were the second leading cause of visits to medical facilities among workers who performed rescue and recovery work in the first month after the WTC disaster.[5]

The Fire Department of New York (FDNY) along with the National Institute for Occupational Safety and Health (NIOSH) established the FDNY WTC Medical Monitoring and Treatment Program in October 2001.[8] Injuries and illnesses among FDNY rescue workers during the 11 months postdisaster were reported by FDNY physicians. Approximately 90% of the 10 116 FDNY rescue workers who were evaluated in the first 48 hours after the attacks reported an acute cough accompanied by nasal congestion, chest tightness, or a burning sensation in the chest. The incidence of new respiratory illness among FDNY rescue workers did not begin to decrease until February 2002.[6]

Prezant et al were the first investigators to document WTC cough and bronchial hyperreactivity, syndromes among FDNY firefighters that occurred after short-term exposures to WTC irritants.[8] They defined WTC cough as a persistent cough that was accompanied by respiratory symptoms so severe that FDNY physicians had to place workers complaining of the cough on medical leave for at least 4 consecutive weeks. By March 2002, 332 of 10 993 firefighters evaluated had been diagnosed as having WTC cough. WTC cough also was significantly related to an early arrival at Ground Zero.[8] After adjusting for age, smoking status, and the presence of airflow obstruction, researchers found a significant association between early arrival at the WTC site and bronchial hyperreactivity. In longitudinal studies of FDNY rescue workers up to 4 years after 9/11, FEV_1 reduction, airway obstruction, persistent respiratory symptoms, and persistent bronchial hyperreactivity and RADS were significantly associated with early arrival and longer duration of work at the WTC site.[9-11]

Early studies of health outcomes among WTC disaster workers identified strong relations between WTC exposures, such as a presence in the building collapse dust cloud and early arrival at Ground Zero, and respiratory symptoms and diseases. The date of arrival at the WTC site was used as a surrogate for WTC exposure in studies of police first responders. Approximately 78% of 240 police officers from the New York Police Department's Emergency Service Unit reported new or worsening respiratory symptoms between September 11, 2001, and February 2002.[12] Although spirometric abnormalities were observed in only 29% of these police officers, early date of arrival at the WTC site was significantly associated with abnormal spirometry. In a longitudinal study of 426 New York City police officers with no previous respiratory condition, work at Ground Zero was significantly associated with persistent cough, persistent shortness of breath, and persistent wheeze up to 19 months after the WTC disaster.[13]

Similar associations between WTC exposures and new-onset respiratory symptoms were observed among ironworkers.[14] Skloot et al evaluated a total of 96 male ironworkers between October 2001 and February 2002 at the Mount Sinai-Irvin J. Selikoff Center for Occupational and Environmental Medicine. Among these ironworkers, being present at the WTC site in lower Manhattan on 9/11 was significantly associated with new-onset cough, dyspnea, and wheezing, after adjusting for the number of days worked at the WTC site, use of a respirator with a canister, and history of smoking. This study was one of the first to use oscillometric data to examine lung function among WTC disaster workers. More than half of the nonasthmatic ironworkers examined had elevated respiratory resistance, and oscillometric results indicated that use of a respirator with a canister was protective of large airways dysfunction.[14]

In addition to first responders and ironworkers, cleanup and recovery workers also were exposed to potential respiratory toxicants during their disaster work. Tao et al conducted a cross-sectional study of 1327 cleanup workers from local labor unions and the New York City Department of Sanitation.[15] The survey, which was self-administered approximately 20 months after the WTC disaster, included a modified version of the American Thoracic Society-Division of Lung Diseases-78 respiratory health questionnaire along with questions about WTC exposure, smoking history, and respirator use. Cleanup and recovery workers at the WTC site were 3 times more likely than workers who had never worked at the WTC site to report lower respiratory symptoms, after adjusting for confounders. Even among nontraditional responders such as cleanup workers, respiratory symptoms associated with WTC exposures were present almost 2 years after 9/11.

In 2002, NIOSH funded a medical screening program for WTC responders at 5 New York City metropolitan medical centers: Bellevue Hospital Center, City University of New York at Queens, Mount Sinai School of Medicine, State University of New York at Stony Brook, and University of Medicine and Den-

tistry of New Jersey. Five years after the WTC disaster, the WTC Responder Health Consortium published a study on a diverse group of disaster workers, including first responders, recovery and cleanup workers, and volunteers, who had participated in medical monitoring and received physical screening evaluations along with interviewer-administered exposure and medical questionnaires.[16] For this study, a total of 9443 participating and responders were consented and examined between June 2002 and April 2004. Among workers who reported no history of respiratory illness or symptoms before the WTC disaster, 32% reported developing new lower respiratory symptoms and 44% reported developing new upper respiratory symptoms in the months before the physical examination. Being engulfed in the building collapse dust cloud and having an early date of arrival at Ground Zero were significantly associated with new or worsening respiratory symptoms. Early date of arrival at the WTC site also was significantly associated with low FVC.

The spectrum of new-onset respiratory diseases reported among WTC disaster workers after 9/11 included new diagnoses of asthma,[17] interstitial lung diseases,[18] acute eosinophilic pneumonia,[19] and parenchymal lung diseases such as bronchiolitis obliterans with organizing pneumonia[20] and sarcoidosis.[21-23] New diagnoses of asthma were studied among a group of 25 748 disaster workers who enrolled in the WTC Health Registry and completed wave 1 interviews in 2003–2004. The 3-year incidence of newly diagnosed asthma after 9/11 among workers enrolled in the WTC Health Registry was 3.6%, 12 times higher than the expected incidence of 0.1%/y in the general adult population. Delays in the use of protective respiratory equipment such as masks and respirators were associated with an increased risk of asthma among workers who arrived at the WTC site on 9/11.[17]

De la Hoz et al reported on the incidence of airway disease among WTC Medical Monitoring and Treatment Program participants between 2003 and 2005.[24,25] Workers who arrived at the WTC site within the first 48 hours after the attacks were more likely than those who arrived later to develop lower airway disease.[24] A total of 136 workers were further evaluated for atopy using radioallergosorbent and skin prick testing.[25] Multivariate analyses revealed that atopy was significantly associated with WTC-related upper airway diagnoses, suggesting an irritant-induced mechanism for lower airway diseases and an atopic mechanism for upper airway diseases.[25]

Mid-Term Studies of Respiratory Health Outcomes (≥5 Years) After 9/11

Immediately after the disaster, public health agencies including the CDC, the New York State Department of Health, and the New York City Department of Health and Mental Hygiene established research, medical monitoring, and treatment programs for workers exposed to the WTC disaster (Table). Several WTC monitoring programs, including the FDNY WTC Medical Monitoring and Treatment Program, the New York State Department of Health WTC Medical Monitoring Program, and the WTC Health Registry, have reported declines in measures of pulmonary function, persistence of respiratory symptoms, and newly diagnosed respiratory diseases among WTC disaster workers ≥5 years after 9/11.

TABLE

World Trade Center Responder Monitoring Programs				
Responder Monitoring Program	Occupational Groups	Disaster Worker Sample Size	Exposure Measures	Respiratory Outcome Measures |1rh|
FDNY, World Trade Center Medical Monitoring and Treatment Program	FDNY firefighters and EMS employees	>15 000	Date of arrival at WTC site, duration of WTC disaster work, dust cloud exposure, mask/respirator use	Respiratory health questionnaire, physical examination, pulmonary function tests
New York State Department of Health WTC Medical Monitoring and Treatment Program	New York State employees, New York State National Guard personnel	1677	Dust cloud exposure, semiquantitative dust exposure metric, semiquantitative smoke exposure metric	Respiratory health questionnaire, physical examination, pulmonary function tests
WTC Medical Monitoring and Treatment Program (Responder Health Consortium)	Cleaning/maintenance, construction, firefighters, law enforcement, public agency, technical and utilities, transportation, volunteers	>32 892	Date of arrival at WTC site, duration of WTC disaster work, dust cloud exposure, location of WTC disaster work, mask/respirator use	Respiratory health questionnaire, physical examination, pulmonary function tests
WTC Health Registry	Construction/utilities/ remediation, EMS/ medical/medical examiner, fire and rescue, law enforcement, public agency, sanitation, volunteers	30 665	Date of arrival at WTC site, duration of WTC disaster work, dust cloud exposure, location of WTC disaster work, mask/respirator use	Respiratory health questionnaire

EMS=emergency medical services; FDNY=Fire Department of New York; WTC=World Trade Center.

FDNY WTC Medical Monitoring and Treatment Program studies have provided strong clinical evidence for persistent symptoms and accelerated declines in pulmonary function among FDNY rescue workers. Aldrich and colleagues examined the lung function of 12 781 WTC FDNY firefighters and emergency medical services workers who were hired before September 25, 2001, and had undergone spirometry at least once before September 11, 2001.[26] In the first year after the disaster, significant relations were noted between WTC exposures and FEV_1 decline. By 2008, however, the relationships between FEV_1 value and the date of arrival or the duration of work at the WTC site were not significant. Although associations between FEV_1, as a measure of pulmonary function, and date of arrival or duration of work, as measures of WTC exposure, were no longer significant, exposed individuals experienced little recovery in FEV_1 7 years after 9/11.[26,27]

Skloot et al conducted a longitudinal study of pulmonary function among WTC Medical Monitoring and Treatment Program participants who completed both baseline and follow-up examinations up to 6 years after the disaster.[28] More than one-third of the 3160 study participants had abnormal spirometry on at least 1 examination, with low FVC as the most common abnormality. The mean change in spirometry between examinations of these WTC disaster workers was not greater than the mean change expected in the general population; however, the 24% prevalence of spirometric abnormalities among participating workers who underwent a second examination was higher than the prevalence of abnormalities expected in the general population.[28]

The New York State Department of Health WTC Medical Monitoring Program was established to follow the development of health outcomes among a cohort of WTC-exposed and WTC-unexposed state employees. New York State employees and New York State National Guard personnel who responded to the WTC disaster between September 11, 2001, and December 23, 2001, were offered medical monitoring and evaluation through the New York State Department of Health WTC Medical Monitoring Program.[29] Medical evaluations included clinical laboratory tests, physical examinations, and pulmonary function tests. The monitoring program recruited 578 New York State employees who responded to the WTC disaster (WTC-exposed) and a control group of 702 New York State employees who did not respond to the WTC disaster (WTC-unexposed).[30] Study participants completed 4 annual waves of health and exposure surveys between 2003 and 2006.

Five years after 9/11, WTC-exposed New York State employees were significantly more likely than WTC-unexposed employees to report new or worsening respiratory symptoms.[31] Among WTC-exposed workers, exposure was characterized using a semiquantitative exposure assessment method for WTC-related dust and WTC-related smoke.[32] After controlling for confounders such as sex, smoking history, and obesity, new-onset asthma after 9/11 was not found to be significantly associated with WTC exposures in this cohort of New York State employees.[31] With only 3 new-onset asthma cases expected in a 5-year follow-up of the 578 WTC-exposed workers, under the null hypothesis of no excess, this study was substantially underpowered to test the hypothesis of new-onset asthma.

Mauer and Cummings also measured respiratory function among New York State responders using an impulse oscillometry system technique.[33] A total of 99 exposed and 149 unexposed study participants were evaluated between June and October 2007. Impulse oscillometry results indicated a significant difference in respiratory function between those who used a respirator with a canister and those who did not use a respirator with a canister.[33] This finding was in agreement with the associations between the lack of protective respirator use and airways dysfunction observed in earlier studies of WTC ironworkers.

The WTC Health Registry was established by the New York City Department of Health and Mental Hygiene and CDC's Agency for Toxic Substances and Disease Registry to document and evaluate the long-term health consequences of the 9/11 terrorist attacks.[34] Study results of the WTC Health Registry's 2006-2008 follow-up survey indicated that incidence of self-reported newly diagnosed asthma after 9/11 peaked approximately 16 months after the terrorist attacks.[35] Five to seven years after the WTC disaster, however, newly diagnosed asthma among disaster workers remained significantly associated with WTC exposures.[35] These results differed from study results of new-onset asthma among workers reported by the New York State Department of Health WTC Medical Monitoring Program, which found no significant association. The differences between the 2 studies may have been due to differences in statistical power, exposure metrics, and study populations. The WTC Health Registry included a large, heterogeneous group of disaster workers who may have experienced a wider gradient of WTC exposures than responders in the New York State Department of Health WTC Medical Monitoring Program.

Among WTC disaster workers who experienced new-onset respiratory conditions after 9/11, mid-term studies have reported persistent respiratory symptoms and little to no recovery in pulmonary function. Longitudinal studies of WTC disaster workers suggest that the incidence of new-onset respiratory symptoms and diseases and the decline in pulmonary function stabilized within 3 years of exposure to the WTC disaster.

METHODOLOGICAL CHALLENGES

The unforeseen nature of the WTC disaster and the subsequent disaster-related exposures and respiratory health outcomes presented noteworthy epidemiologic challenges. Several methodological issues have arisen in studies of respiratory health outcomes among disaster workers, including study design, potential for selection bias, exposure assessment, and outcome ascertainment.

Study Design

To date, the majority of epidemiologic studies of respiratory health outcomes among WTC disaster workers has used a cross-sectional study design. Although appropriate for the assessment of acute health effects, cross-sectional studies present several limitations to studying the relationship between WTC exposures and respiratory health outcomes. In studies of respiratory symptoms, for example, the period prevalence of new-onset symptoms after 9/11 is often reported.[9,16,35,36] The interpretation of prevalence data are subject to prevalence-incidence bias because prevalence measures reflect both the incidence and the duration of respiratory symptoms.[37] In comparing prevalence of symptoms among high-exposed and low-exposed subjects, if average duration of symptoms among the high-exposed group differs from that among the low-exposed group, the prevalence ratio may give a biased estimate of the incidence ratio. Alternatively, the presentation of symptoms could be mitigated by therapeutic treatments.

Selection Bias

Selection bias can result when the relationship between exposure and disease among study participants is different from the relationship between exposure and disease among nonparticipants.[38] As is the case with many voluntary studies, symptomatic and high-exposed workers may be more inclined than asymptomatic, low-exposed workers to participate in WTC disaster studies.[39,40] In an examination of participation rates in the WTC Health Registry, Murphy and colleagues estimated that approximately 34% of the eligible exposed disaster workers enrolled in the Registry.[39] Exposure information and symptom outcomes among workers who did not enroll in the Registry were unknown, and there were few data available to examine other enrollment characteristics such as demographic and socioeconomic factors. Studies of WTC disaster workers have been vulnerable to low response rates and differential participation by exposure and symptom status.[15,31] Notable exceptions have been epidemiologic studies of FDNY employees that have reported participation rates as high as 85%.[11]

Selective participation is also a concern with WTC medical monitoring programs.[16,29,40] Disaster workers who participate in these treatment programs are often recruited for follow-up epidemiologic studies. To the extent that potential participants may not have adequate access to medical care outside WTC treatment programs, those who are uninsured or underinsured may be more likely to participate, and those who are adequately insured may be more underrepresented in the study group. Studies of workers in medical monitoring programs have several strengths, including standardized examinations for pulmonary function, respiratory symptoms, and diseases.[11,14,33,41] Despite the collection of detailed histories from each study participant, there are determinants of participation that are unknown or are not collected during baseline assessments.

Exposure Assessment

The collapse of the WTC towers exposed first responders, recovery workers, and cleanup workers to extraordinary amounts of dust, airborne particulates, and gases released from building fires. Analyses of the components of the settled dust collected from the vicinity of the WTC site indicated that WTC dust was composed of respiratory irritants such as highly alkaline particulate matter and glass fibers.[4,42] Exposure assessments for epidemiologic studies of respiratory health outcomes have been limited substantially by the absence of environmental monitoring data in the days immediately after the WTC disaster. The air-monitoring station near the WTC site was destroyed on 9/11, and air sampling by NIOSH did not begin until September 18, 2001.[43]

The limited availability of environmental monitoring data has led to the use of crude, qualitative exposure assessments in epidemiologic studies of WTC disaster workers. Many epidemiologic studies of WTC disaster have relied on questionnaires to obtain information about exposures. Epidemiologic studies conducted in the years after the disaster used measures of WTC exposure such as the arrival date at the WTC site, the cumulative number of days worked at the WTC site, work location at the WTC site, job categories, and occupational group categories (Table).[8,16,17,29,35] These WTC exposures were self-reported and may have been subject to exposure misclassification. Exposure metrics also have been limited because of their inability to account for the complexity of airborne contaminants at the site and the variability of exposure patterns during the 9 months of rescue, recovery, and cleanup activities.

Several efforts have been made to incorporate objective measures of WTC exposures into epidemiologic studies of disaster workers. Herdt-Losavio et al developed a semiquantitative exposure assessment method for New York State workers who responded to the WTC disaster.[32] An exposure algorithm for smoke and dust was developed using 2 data sources: a mailed questionnaire and Environmental Protection Agency air-monitoring data. The major limitation of this method, however, was the use of ambient air-monitoring data to assess individual-level exposures.

In one of the few studies of exposure monitoring among WTC disaster workers during cleanup activities, Geyh and colleagues conducted personal monitoring of 69 truck drivers for total dust, PM_{10}, $PM_{2.5}$, and volatile organic compounds.[44] Study results indicated that total dust concentrations were higher among drivers who were in the middle of the pile compared with drivers who were at the perimeter of the WTC site. To date, this study by Geyh et al is the only disaster worker study that has used personal air-monitoring data in WTC exposure assessment.

Ascertainment of Respiratory Health Outcomes

In many of the WTC disaster worker studies, respiratory health outcomes are self-reported by study participants.[16,29,34,35] WTC

disaster workers who participated in responder studies may have been more likely than study nonparticipants to report respiratory health outcomes if participation was motivated by poor health status. Several studies have tried to minimize the impact of outcome reporting bias by using reference groups from within the study cohort. Nevertheless, reporting bias could have a significant impact on measures of association if outcomes reporting behavior differed by exposure category. Verification through physical examinations and the review of medical records have been among the best methods to validate new-onset respiratory health outcomes among WTC disaster workers.[26,28] However, reliable, sensitive, and specific diagnostic tests may not be available for some diseases such as asthma, so self-report of physician diagnoses may be the best available outcome measure.

Disease misclassification is another potential source of bias in studies of WTC disaster workers. An example has been the debate about the diagnosis of RADS. Before 9/11, dust had never been documented as a cause of RADS, and Brooks and colleagues's definition of RADS was limited to an irritant gas, fume, or vapor exposure.[45,46] Pulmonologists disagree on the association between WTC dust and debris exposure and RADS.[46] Some have argued that the high prevalence of RADS among WTC disaster workers may be a reflection of heightened awareness among physicians who treat WTC-exposed workers. An alternative explanation has been that other subtypes of irritant-induced asthma may be misclassified as RADS by physicians who treat WTC-exposed workers. A limitation of epidemiologic studies has been the absence of detailed exposure and medical histories that could clarify the relation between WTC exposures and RADS in WTC disaster workers.

Chronic bronchitis is another disease that is difficult to diagnose properly because of its overlap with other conditions such as chronic obstructive pulmonary disease (COPD), emphysema, and asthma.[47] The lack of a common and precise definition of chronic bronchitis can lead to bias in epidemiologic studies of chronic bronchitis. If the definition is too strict, then chronic bronchitis is underdiagnosed, and true outcomes are underestimated. If a definition of chronic bronchitis that includes COPD and emphysema is used, then cases of chronic bronchitis in a study population could be overestimated, resulting in biased study results.

Assessment of Potential Confounders and Effect Modifiers

The assessment of confounding in observational studies relies on identifying and obtaining proper measurements of potential confounders. Several WTC cohort studies have prospectively collected data on factors that could confound the relations between WTC exposures and new-onset respiratory health outcomes.[31,34] Psychological stress, for example, has been identified as a contributor to a range of chronic diseases, including respiratory diseases,[48] and many studies of WTC disaster workers acknowledge the potential impact of psychological stress on

health outcomes.[29,35,49-51] A longitudinal study by Niles et al examined comorbid trends in WTC cough and posttraumatic stress disorder (PTSD) symptoms among FDNY firefighters up to 4 years after 9/11. After adjusting for WTC exposures, PTSD symptoms present among firefighters at baseline examinations were associated with both diagnosis and symptomatology of WTC cough at follow-up examination. Similar associations among FDNY firefighters were observed between diagnosis and symptomatology of WTC cough at baseline and PTSD symptoms at follow-up.[51] In addition to psychological stress, observed associations may be explained by other unmeasured factors such as health-seeking behaviors or previous occupational exposures. Many WTC disaster workers continue to work in occupations that involve exposures to smoke, particulates, and metal dusts and fumes. Controlling for work histories has been difficult, and residual confounding may occur in studies of WTC disaster workers because of inadequately measured occupational factors.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

WTC responder monitoring programs have been established to conduct longitudinal follow-up studies of health outcomes among disaster workers. Future research on respiratory health outcomes among disaster workers includes the following key questions.

As monitoring programs continue to recruit for follow-up studies of health outcomes among WTC disaster workers, will participants differ from nonparticipants with regard to health status and health-related behaviors? Can studies of disaster workers effectively control for this potential selection bias? In the analysis phase of epidemiologic studies, bias from self-selected participation can be minimized through the use of internal reference groups only if good measures of relevant exposures are available. WTC responder programs can inform the study-design phase of future disaster research efforts by identifying the most effective strategies for recruiting and retaining representative samples of disaster workers.

How can future epidemiologic studies of disaster workers reduce misclassification of exposures and outcomes? Retrospective exposure assessments have been vital in characterizing the exposures associated with WTC disaster work, yet only 2 studies have included environmental monitoring data.[32,44] Although rarely done to a degree that is scientifically adequate, actual measurements of potentially relevant exposures soon after a disaster occurs would resolve many of the validity problems of studies attempting to reconstruct exposures retrospectively. In the absence of adequate postdisaster exposure measurements, retrospective assessments that integrate available environmental monitoring and subjective questionnaire data may be the most effective framework for studying exposures among disaster workers. Statistical modeling of individual exposures, job-exposure matrices, and exposure-validation substudies using personal exposure monitoring on small, epidemiologically appropriate samples of subjects can be

useful methods to reduce bias resulting from exposure misclassification. Because many epidemiologic studies continue to use self-reported questionnaires to assess respiratory symptoms and diseases, validation of outcome measures through clinical assessments, review of medical records, and objective diagnostic testing or, if possible, biomarker measurements will be essential in evaluating new-onset respiratory health outcomes.

What is the relationship between psychological distress and new-onset respiratory health outcomes among WTC disaster workers? After 9/11, WTC disaster workers were exposed to both respiratory irritants and psychological stressors. PTSD has been one of the most prevalent psychiatric disorders reported after the WTC disaster, and PTSD prevalence among disaster workers has been reported to be as high as 21.2%.[52,53] Prospective studies should examine the influence of trauma and psychological stress on the development and progression of respiratory health outcomes among WTC disaster workers.

Finally, what are the long-term respiratory health consequences associated with occupational exposure to the WTC disaster? Comprehensive surveillance should continue to document the progression and possible new onset of respiratory symptoms among WTC disaster workers in addition to their pulmonary responses to treatment and medications. Many WTC disaster worker studies have reported a high prevalence of coughing and shortness of breath, symptoms that are associated with COPD. Follow-up studies will be necessary to determine whether the new-onset respiratory symptoms observed among disaster workers will develop into chronic conditions such as COPD. Also, because COPD is a debilitating respiratory condition that has been shown to result in long-term disability, future studies should examine the new onset and course of COPD among WTC disaster workers, particularly among smokers and older workers.

The burden of respiratory symptoms and diseases among WTC disaster workers has been well documented in the decade after 9/11. Longitudinal studies will help clarify the relation between WTC exposures and new-onset respiratory health outcomes among WTC disaster workers. By identifying key risk factors for respiratory morbidity, epidemiologic studies of WTC disaster workers can guide treatment efforts and inform worker-safety efforts during future disaster response activities.

Author Affiliation: Dr Ekenga is with the Department of Environmental Medicine, New York University School of Medicine.

Correspondence: Address correspondence and reprint requests to Dr Christine C. Ekenga, Department of Environmental Medicine, NYU School of Medicine, 650 First Ave, New York, NY 10016 (e-mail: Christine.Ekenga@nyumc .org).

Author Disclosures: The author reports no conflicts of interest.

REFERENCES

1. Lioy PJ, Georgopoulos P. The anatomy of the exposures that occurred around the World Trade Center site: 9/11 and beyond. *Ann N Y Acad Sci.* 2006; 1076:54-79.
2. Lorber M, Gibb H, Grant L, Pinto J, Pleil J, Cleverly D. Assessment of inhalation exposures and potential health risks to the general population that resulted from the collapse of the World Trade Center towers. *Risk Anal.* 2007;27(5):1203-1221.
3. Landrigan PJ, Lioy PJ, Thurston G, et al; NIEHS World Trade Center Working Group. Health and environmental consequences of the world trade center disaster. *Environ Health Perspect.* 2004;112(6):731-739.
4. McGee JK, Chen LC, Cohen MD, et al. Chemical analysis of World Trade Center fine particulate matter for use in toxicologic assessment. *Environ Health Perspect.* 2003;111(7):972-980.
5. Berríos-Torres SI, Greenko JA, Phillips M, Miller JR, Treadwell T, Ikeda RM. World Trade Center rescue worker injury and illness surveillance, New York, 2001. *Am J Prev Med.* 2003;25(2):79-87.
6. Centers for Disease Control and Prevention (CDC). Injuries and illnesses among New York City Fire Department rescue workers after responding to the World Trade Center attacks. *MMWR Morb Mortal Wkly Rep.* 2002;51(Spec No):1-5.
7. Centers for Disease Control and Prevention (CDC). Physical health status of World Trade Center rescue and recovery workers and volunteers - New York City, July 2002-August 2004. *MMWR Morb Mortal Wkly Rep.* 2004;53(35):807-812.
8. Prezant DJ, Weiden M, Banauch GI, et al. Cough and bronchial responsiveness in firefighters at the World Trade Center site. *N Engl J Med.* 2002;347(11):806-815.
9. Webber MP, Gustave J, Lee R, et al. Trends in respiratory symptoms of firefighters exposed to the world trade center disaster: 2001-2005. *Environ Health Perspect.* 2009;117(6):975-980.
10. Banauch GI, Alleyne D, Sanchez R, et al. Persistent hyperreactivity and reactive airway dysfunction in firefighters at the World Trade Center. *Am J Respir Crit Care Med.* 2003;168(1):54-62.
11. Banauch GI, Hall C, Weiden M, et al. Pulmonary function after exposure to the World Trade Center collapse in the New York City Fire Department. *Am J Respir Crit Care Med.* 2006;174(3):312-319.
12. Salzman SH, Moosavy FM, Miskoff JA, Friedmann P, Fried G, Rosen MJ. Early respiratory abnormalities in emergency services police officers at the World Trade Center site. *J Occup Environ Med.* 2004;46(2):113-122.
13. Buyantseva LV, Tulchinsky M, Kapalka GM, et al. Evolution of lower respiratory symptoms in New York police officers after 9/11: a prospective longitudinal study. *J Occup Environ Med.* 2007;49(3):310-317.
14. Skloot G, Goldman M, Fischler D, et al. Respiratory symptoms and physiologic assessment of ironworkers at the World Trade Center disaster site. *Chest.* 2004;125(4):1248-1255.
15. Tao XG, Massa J, Ashwell L, Davis K, Schwab M, Geyh A. The world trade center clean up and recovery worker cohort study: respiratory health amongst cleanup workers approximately 20 months after initial exposure at the disaster site. *J Occup Environ Med.* 2007;49(10):1063-1072.
16. Herbert R, Moline J, Skloot G, et al. The World Trade Center disaster and the health of workers: five-year assessment of a unique medical screening program. *Environ Health Perspect.* 2006;114(12):1853-1858.
17. Wheeler K, McKelvey W, Thorpe L, et al. Asthma diagnosed after 11 September 2001 among rescue and recovery workers: findings from the World Trade Center Health Registry. *Environ Health Perspect.* 2007;115(11): 1584-1590.
18. Wu MX, Gordon RE, Herbert R, et al. Case report: Lung disease in World Trade Center responders exposed to dust and smoke: carbon nanotubes found in the lungs of World Trade Center patients and dust samples. *Environ Health Perspect.* 2010;118(4):499-504.
19. Rom WN, Weiden M, Garcia R, et al. Acute eosinophilic pneumonia in a New York City firefighter exposed to World Trade Center dust. *Am J Respir Crit Care Med.* 2002;166(6):797-800.

20. Mann JM, Sha KK, Kline G, Breuer FU, Miller A. World Trade Center dyspnea: bronchiolitis obliterans with functional improvement: a case report. *Am J Ind Med*. 2005;48(3):225-229.

21. Bowers B, Hasni S, Gruber BL. Sarcoidosis in World Trade Center rescue workers presenting with rheumatologic manifestations. *J Clin Rheumatol*. 2010;16(1):26-27.

22. Izbicki G, Chavko R, Banauch GI, et al. World Trade Center "sarcoid-like" granulomatous pulmonary disease in New York City Fire Department rescue workers. *Chest*. 2007;131(5):1414-1423.

23. Crowley LE, Herbert R, Moline JM, et al. "Sarcoid like" granulomatous pulmonary disease in World Trade Center disaster responders. *Am J Ind Med*. 2011;54(3):175-184.

24. de la Hoz RE, Shohet MR, Chasan R, et al. Occupational toxicant inhalation injury: the World Trade Center (WTC) experience. *Int Arch Occup Environ Health*. 2008;81(4):479-485.

25. de la Hoz RE, Shohet MR, Wisnivesky JP, Bienenfeld LA, Afilaka AA, Herbert R. Atopy and upper and lower airway disease among former World Trade Center workers and volunteers. *J Occup Environ Med*. 2009;51 (9):992-995.

26. Aldrich TK, Gustave J, Hall CB, et al. Lung function in rescue workers at the World Trade Center after 7 years. *N Engl J Med*. 2010;362(14):1263-1272.

27. Weiden MD, Ferrier N, Nolan A, et al. Obstructive airways disease with air trapping among firefighters exposed to World Trade Center dust. *Chest*. 2010;137(3):566-574.

28. Skloot GS, Schechter CB, Herbert R, et al. Longitudinal assessment of spirometry in the World Trade Center medical monitoring program. *Chest*. 2009;135(2):492-498.

29. Mauer MP, Cummings KR, Carlson GA. Health effects in New York State personnel who responded to the World Trade Center disaster. *J Occup Environ Med*. 2007;49(11):1197-1205.

30. Mauer MP, Herdt-Losavio ML, Carlson GA. Asthma and lower respiratory symptoms in New York State employees who responded to the World Trade Center disaster. *Int Arch Occup Environ Health*. 2010;83(1):21-27.

31. Mauer MP, Cummings KR, Hoen R. Long-term respiratory symptoms in World Trade Center responders. *Occup Med (Lond)*. 2010;60(2):145-151.

32. Herdt-Losavio ML, Mauer MP, Carlson GA. Development of an exposure assessment method for epidemiological studies of New York State personnel who responded to the World Trade Center disaster. *Ann Occup Hyg*. 2008;52(2):83-93.

33. Mauer MP, Cummings KR. Impulse oscillometry and respiratory symptoms in World Trade Center responders, 6 years post-9/11. *Lung*. 2010; 188(2):107-113.

34. Farfel M, DiGrande L, Brackbill R, et al. An overview of 9/11 experiences and respiratory and mental health conditions among World Trade Center Health Registry enrollees. *J Urban Health*. 2008;85(6):880-909.

35. Brackbill RM, Hadler JL, DiGrande L, et al. Asthma and posttraumatic stress symptoms 5 to 6 years following exposure to the World Trade Center terrorist attack. *JAMA*. 2009;302(5):502-516.

36. Herbstman JB, Frank R, Schwab M, et al. Respiratory effects of inhalation exposure among workers during the clean-up effort at the World Trade Center disaster site. *Environ Res*. 2005;99(1):85-92.

37. Greenland S, Rothman KJ. Measures of occurrence. In: Rothman KJ, Greenland S, Lash TL, eds. *Modern Epidemiology*. 3rd ed. New York: Lippincott Williams & Wilkins; 2008:47-48.

38. Rothman KJ, Greenland S, Lash TL. Validity in epidemiologic studies. In: Rothman KJ, Greenland S, Lash TL, eds. *Modern Epidemiology*. 3rd ed. New York: Lippincott Williams & Wilkins; 2008:134-135.

39. Murphy J, Brackbill RM, Thalji L, Dolan M, Pulliam P, Walker DJ. Measuring and maximizing coverage in the World Trade Center Health Registry. *Stat Med*. 2007;26(8):1688-1701.

40. Savitz DA, Oxman RT, Metzger KB, et al. Epidemiologic research on man-made disasters: strategies and implications of cohort definition for World Trade Center worker and volunteer surveillance program. *Mt Sinai J Med*. 2008;75(2):77-87.

41. Feldman DM, Baron SL, Bernard BP, et al. Symptoms, respirator use, and pulmonary function changes among New York City firefighters responding to the World Trade Center disaster. *Chest*. 2004;125(4):1256-1264.

42. Lioy PJ, Weisel CP, Millette JR, et al. Characterization of the dust/smoke aerosol that settled east of the World Trade Center (WTC) in lower Manhattan after the collapse of the WTC 11 September 2001. *Environ Health Perspect*. 2002;110(7):703-714.

43. Centers for Disease Control and Prevention (CDC). Occupational exposures to air contaminants at the World Trade Center disaster site–New York, September-October, 2001. *MMWR Morb Mortal Wkly Rep*. 2002; 51(21):453-456.

44. Geyh AS, Chillrud S, Williams DL, et al. Assessing truck driver exposure at the World Trade Center disaster site: personal and area monitoring for particulate matter and volatile organic compounds during October 2001 and April 2002. *J Occup Environ Hyg*. 2005;2(3):179-193.

45. Brooks SM, Weiss MA, Bernstein IL. Reactive airways dysfunction syndrome (RADS). Persistent asthma syndrome after high level irritant exposures. *Chest*. 1985;88(3):376-384.

46. Truncale T, Brooks SM, Prezant DJ, Banauch GI, Nemery B. World Trade Center dust and airway reactivity. *Am J Respir Crit Care Med*. 2004;169 (7):883-884, author reply 884-885.

47. Mannino DM. COPD: epidemiology, prevalence, morbidity and mortality, and disease heterogeneity. *Chest*. 2002;121(5)(Suppl):121S-126S.

48. Cohen S, Janicki-Deverts D, Miller GE. Psychological stress and disease. *JAMA*. 2007;298(14):1685-1687.

49. Stellman JM, Smith RP, Katz CL, et al. Enduring mental health morbidity and social function impairment in world trade center rescue, recovery, and cleanup workers: the psychological dimension of an environmental health disaster. *Environ Health Perspect*. 2008;116(9):1248-1253.

50. Bills CB, Dodson N, Stellman JM, et al. Stories behind the symptoms: a qualitative analysis of the narratives of 9/11 rescue and recovery workers. *Psychiatr Q*. 2009;80(3):173-189.

51. Niles JK, Webber MP, Gustave J, et al. Co-morbid trends in World Trade Center cough syndrome and probable PTSD in firefighters. *Chest*. 2011; (May):5. Epub ahead of print.

52. Perrin MA, DiGrande L, Wheeler K, Thorpe L, Farfel M, Brackbill R. Differences in PTSD prevalence and associated risk factors among World Trade Center disaster rescue and recovery workers. *Am J Psychiatry*. 2007;164 (9):1385-1394.

53. Berninger A, Webber MP, Cohen HW, et al. Trends of elevated PTSD risk in firefighters exposed to the World Trade Center disaster: 2001-2005. *Public Health Rep*. 2010;125(4):556-566.