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Mortality among rescue and recovery workers and community members exposed to the September 11, 2001 World Trade Center terrorist attacks, 2003–2014

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ABSTRACT

Background: Multiple chronic health conditions have been associated with exposure to the September 11, 2001 World Trade Center (WTC) terrorist attacks (9/11). We assessed whether excess deaths occurred during 2003–2014 among persons directly exposed to 9/11, and examined associations of 9/11-related exposures with mortality risk.

Materials and methods: Deaths occurring in 2003–2014 among members of the World Trade Center Health Registry, a cohort of rescue/recovery workers and lower Manhattan community members who were exposed to 9/11, were identified via linkage to the National Death Index. Participants' overall levels of 9/11-related exposure were categorized as high, intermediate, or low. We calculated standardized mortality ratios (SMR) using New York City reference rates from 2003 to 2012. Proportional hazards were used to assess associations of 9/11-related exposures with mortality, accounting for age, sex, race/ethnicity and other potential confounders.

Results: We identified 877 deaths among 29,280 rescue/recovery workers (3.0%) and 1694 deaths among 39,643 community members (4.3%) during 308,340 and 416,448 person-years of observation, respectively. The SMR for all causes of death was 0.69 [95% confidence interval (CI) 0.65–0.74] for rescue/recovery workers and 0.86 (95% CI 0.82–0.90) for community members. SMRs for diseases of the cardiovascular and respiratory systems were significantly lower than expected in both groups. SMRs for several other causes of death were significantly elevated, including suicide among rescue recovery workers (SMR 1.82, 95% CI 1.35–2.39), and brain malignancies (SMR 2.25, 95% CI 1.48–3.28) and non-Hodgkin's lymphoma (SMR 1.79, 95% CI 1.24–2.50) among community members. Compared to low exposure, both intermediate [adjusted hazard ratio (AHR) 1.36, 95% CI 1.10–1.67] and high (AHR 1.41, 95% CI 1.06–1.88) levels of 9/11-related exposure were significantly associated with all-cause mortality among rescue/recovery workers (p-value for trend 0.01). For community members, intermediate (AHR 1.13, 95% CI 1.01–1.27), but not high (AHR 1.14, 95% CI 0.94–1.39) exposure was significantly associated with all-cause mortality (p-value for trend 0.03). AHRs for associations of overall 9/11-related exposure with heart disease- and cancer-related mortality were similar in magnitude to those for all-cause mortality, but with 95% CIs crossing the null value.

Conclusions: Overall mortality was not elevated. Among specific causes of death that were significantly elevated, suicide among rescue/recovery workers is a plausible long-term consequence of 9/11 exposure, and is potentially preventable. Elevated mortality due to other causes, including non-Hodgkin's lymphoma and brain cancer, and small but statistically significant associations of 9/11-related exposures with all-cause mortality hazard warrant additional surveillance.

Abbreviations: CI, 95% confidence interval; AHR, Adjusted hazard ratio; COPD, Chronic obstructive pulmonary disease; ICD-10, International Classification of Disease codes, 10th revision; LTAS, Life Table Analysis System; MN, Malignant neoplasm; NDI, National Death Index; NIOSH, National Institute for Occupational Safety and Health; NYC, New York City; ref, Reference group; SMR, Standardized mortality ratios; the Registry, World Trade Center Health Registry; WTC, World Trade Center

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1. Introduction

During the September 11, 2001 World Trade Center (WTC) terrorist attacks (9/11) and the months-long recovery period that followed, hundreds of thousands of New York City (NYC) metropolitan area first responders, construction and clean-up workers, and community members experienced an array of potentially toxic environmental exposures (Murphy, 2009; Claudio, 2001). The detonation of two jet planes and resulting collapse of the WTC towers created a vast cloud of particulate matter and fumes that engulfed many survivors. Subsequent fires and the re-suspension of dust during rescue, recovery, and clean-up efforts prolonged the opportunities for 9/11-related environmental exposures (Claudio, 2001; Landrigan et al., 2004; Lioy et al., 2002; Clark et al., 2003).

Several chronic illnesses have since been linked to 9/11-related exposures (Landrigan et al., 2004; Brackbill et al., 2009; Cleven et al., 2017; Farfel et al., 2008; Wisnivesky et al., 2011). A number of these conditions, including asthma and other lower respiratory diseases, could potentially cause or contribute to premature mortality. Preliminary findings suggest that 9/11-related exposures may be linked to an elevated risk of cardiovascular disease, another potential cause of excess mortality (Jordan et al., 2011a, 2013). Although not definitively linked to 9/11 exposure, cancer, and therefore cancer-related mortality, is also of concern in this population because the dust that blanketed lower Manhattan during and after the attacks contained several known carcinogens (Lioy et al., 2002). Excess cases of incident thyroid and prostate cancers have been reported in three WTC-exposed cohorts (Zeig-Owens et al., 2011; Li et al., 2012; Solan et al., 2013). A subsequent study using three additional years of follow-up data found excess incident skin melanomas in both rescue/recovery workers and community participants, and excess incident non-Hodgkin's lymphoma cases among community participants (Li et al., 2016a).

Despite the biologic plausibility of increased mortality due to 9/11-related health conditions, neither of the two studies published to date of mortality among 9/11-exposed persons identified excess deaths during the decade following the attacks (Jordan et al., 2011b; Stein et al., 2016). These findings were based on comparisons of mortality rates from the WTC Health Registry (the Registry) and the WTC Health Program cohorts to rates in the general New York City and United States populations, respectively. An analysis conducted within the Registry cohort found that higher levels of 9/11-related exposure were associated with increased all-cause and cardiovascular mortality during 2003–2009 among community enrollees, in comparison to lower exposure (Jordan et al., 2011b). However, similar internal analyses of the Registry and Health Program cohorts did not consistently identify associations between 9/11-related exposures and mortality among rescue/recovery workers (Jordan et al., 2011b; Stein et al. 2016).

It is possible that these studies were performed too early to detect excess mortality related to 9/11; many 9/11-related conditions have long median survival times, and healthy worker and volunteer effects are likely to be strongest during the early years of observation of these cohorts (Pearce et al. 2007). The statistical power of the Registry's previous mortality study was also constrained by the limitation of the analytic sample to participants who resided in New York City at enrollment. Therefore, we built upon the earlier Registry study by gathering mortality data on the full cohort and extending the observation period for an additional five years. We sought to determine whether excess deaths have occurred since the Registry's inception, and to assess whether a clear relationship between 9/11-related exposures and mortality risk has emerged.

2. Materials and methods

We used data from the Registry, a longitudinal cohort study of rescue/recovery workers and lower Manhattan area community members (area workers, residents, students, and passers-by on 9/11) who were exposed to the 9/11 attacks in New York City or participated in rescue and recovery efforts. The Registry invited potentially-exposed persons identified through government agencies and lower Manhattan employers (list-identified enrollees) or through a broad-based, multilingual outreach campaign (self-identified enrollees) to be screened for eligibility, and ultimately enrolled 71,431 voluntary participants. During September 2003 through November 2004, enrollees completed telephone-administered (95%) or in-person (5%) interviews regarding 9/11 exposures, socio-demographic information, and physical and mental health conditions and symptoms. Additional information on the Registry's methods has been published previously (Farfel et al., 2008). The US Centers for Disease Control and Prevention and New York City Department of Health and Mental Hygiene institutional review boards approved the Registry's protocol.

2.1. Study sample

For the current study, we excluded enrollees who withdrew from the Registry as of 1/12/2017 (N = 1033); had been enrolled posthumously by proxies (n = 161); provided insufficient data to enable linkage to mortality records (n = 282); or did not provide age (n = 99). We also excluded participants whose only 9/11-related exposures were on the Staten Island landfill or barges (n = 934), due to insufficient information regarding the types and amount of exposures experienced, leaving an analytic sample of 68,923.

2.2. Ascertainment of deaths

We identified deaths among enrollees through a data linkage to the National Death Index (NDI), a centralized repository of US vital records, from January 1, 2003 through December 31, 2014. The record linkage was conducted by the NDI, and Registry staff manually reviewed potential matches as described previously (Jordan et al., 2011b). International Classification of Disease codes, 10th revision (ICD-10), for the underlying cause of death were obtained from the NDI records.

2.3. Definitions

Enrollees who performed rescue/recovery work, including volunteers, were considered rescue/recovery participants. Within rescue/recovery participants, those who were firefighters, emergency medical personnel, police officers (NYC or Port Authority), New York State troopers, or federal law enforcement officers were considered traditional rescue/recovery workers, as they were likely to have had some training in disaster response; other rescue/recovery workers and volunteers were considered non-traditional. Enrollees who had not performed any rescue/recovery work were categorized as community participants. Consistent with our previous mortality study (Jordan et al., 2011b), we used responses to questions about 9/11-related exposures from the 2003–2004 enrollment questionnaire to determine whether an enrollee had been exposed to the massive cloud of dust and debris resulting from the collapse of multiple buildings on 9/11, and to categorize the level of other rescue-recovery-related and community-related exposures as high, intermediate, or low (see Text box 1).

We obtained socio-demographic information and history of chronic illnesses from the enrollment questionnaire. Enrollees who reported clinician-diagnosed coronary artery disease, angina, heart attack, or any other heart disease before 9/11 were considered to have pre-9/11 heart disease, and those who reported clinician-diagnosed cancer (excluding non-melanoma skin cancer) before 9/11 were considered to have pre-9/11 cancer. Enrollees who reported clinician-diagnosed heart disease, cancer, stroke, emphysema, or diabetes before 9/11 were categorized as having pre-9/11 chronic disease.

Text box 1:
Definitions of overall levels of exposure to the World Trade Center disaster and its aftermath.

WTC-related rescue/recovery exposures:

- High: present in Manhattan south of Chambers Street between the time of the first plane impact and noon on 9/11 (encompassing the WTC towers' collapse) and (a) worked on the dust and debris pile on 9/11 or (b) worked for > 90 days starting before 9/18/2001
- Low: began work after 9/17/2001, did not work on pile, worked < 30 days, and was not present south of Chambers Street between the first plane impact and noon on 9/11
- Intermediate: rescue/recovery enrollees whose level of exposure fell between high and low

WTC-related community (residential, office, school, or transit) exposures:

- High: reported ≥ two injuries related to 9/11 and
  - o For area residents, also did not evacuate home
  - o For area students/school staff, also were present at school on 9/11
- Low: reported no injuries related to 9/11 and
  - o For area residents, also evacuated home
  - o For area students/school staff, also were not present at school on 9/11
- Intermediate: exposure level fell between high and low

2.4. Statistical analysis

The observation period began at the date of Registry enrollment and ended at December 31, 2014 or the date of death, whichever came first. We calculated standardized mortality ratios (SMR) accounting for age, sex, race, and calendar period of death using the National Institute for Occupational Safety and Health's Life Table Analysis System (LTAS). Because most participants (76%) resided in the New York City metropolitan area at enrollment, we used general New York City population mortality rates from 2003 to 2012 as the primary reference. We also conducted a secondary analysis using US population comparison rates from 2003 to 2011. Underlying cause of death was categorized per LTAS's 119-cause rate file (Schubauer-Berigan et al., 2011). [We refer to the LTAS category called "Intentional self-harm (minor cause 116) as "suicide" in this manuscript.] SMR calculations included person-time for enrollees who were aged 15 years or older during the observation period. Those who turned 15 during the study period began contributing person-time at their 15th birthday.

To assess relations of the intensity of 9/11-related exposures with mortality, we conducted multivariable Cox proportional hazards models. We assessed the statistical significance of trends in the hazard ratios for exposure by including each exposure as an ordinal variable in a multivariable model and testing whether its coefficient was significantly different from zero. SAS software version 9.4 was used for the proportional hazards models.

3. Results

3.1. Characteristics of the study sample

Rescue/recovery participants were primarily aged 25–44 at enrollment, 78% male, and 71% non-Hispanic white (Table 1). The majority of rescue/recovery workers (72.1%) were non-traditional (data not shown in tables). Community enrollees were also primarily middle-aged, but were predominantly female (53%), and somewhat more diverse in race/ethnicity. A higher proportion of rescue/recovery participants than community members were recruited via building and employer lists (36% vs. 24%). Community participants tended to have higher educational attainment than rescue/recovery participants. In both groups, the majority had never smoked. Nine percent of rescue/recovery participants and 11% of community members reported a history of chronic disease before 9/11.

3.2. Deaths occurring during 2003–2014

We identified 877 deaths among the 29,280 rescue/recovery participants (3.0%) during a total of 308,340 person-years of observation, and 1694 deaths among 39,643 community participants (4.3%) during 416,448 person-years of follow-up.

Four deaths occurred among children enrolled in the Registry. Two were reported in our previous study; a death at the age of 5 years due to a neoplasm, and one at the age of 14 due to a congenital defect. The other two were deaths at the age of 15 due to a neoplasm, and at the age of 17 due to suicide.

3.3. Standardized mortality ratios

All-cause SMRs for both rescue/recovery and community participants were significantly lower than expected in comparison to the general New York City population (SMR 0.69 95% CI 0.65–0.74, and SMR 0.86, 95% CI 0.82–0.90, respectively; Table 2). SMRs for many of the major cause-of-death categories, including diabetes mellitus, diseases of the heart, diseases of the circulatory system, and diseases of the respiratory system, were significantly lower than expected. However, malignant neoplasms of other and unspecified sites (includes melanoma, brain and other nervous system, and eye neoplasms) were elevated for both rescue/recovery (SMR 1.43, 95% CI 1.09–1.83) and community participants (SMR 1.45, 95% CI 1.16–1.79). Among community enrollees, cancer due to all causes (SMR 1.14, 95% CI 1.06–1.24), neoplasms of the lymphatic and hematopoietic tissues (SMR 1.35, 95% CI 1.05–1.72) and diseases of the nervous system and sense organs (SMR 1.84, 95% CI 1.38–2.41) were also significantly elevated.

We also examined SMRs for 119 more detailed (minor) causes of death which are sub-categories of the major causes. All statistically significant results are shown in Table 3. Multiple causes, including several related to the circulatory and respiratory systems, were significantly lower than expected.

Three minor causes of death, malignant melanoma (n = 12, SMR 2.71, 95% CI 1.40–4.74), motor vehicle accidents as the driver (n = 8, SMR 4.21, 95% CI 1.82–8.30), and suicide (n = 51, SMR 1.82, 95% CI 1.35–2.39) were elevated among rescue/recovery workers. The deaths due to malignant melanoma all occurred among white men, at a median age at death of 60 years. Of the rescue/recovery participant deaths attributed to suicide, most were due to handgun or other firearm discharge (n = 30); occurred among persons aged 45–64 (n = 31); and

Table 1
Characteristics of participants at study enrollment (2003–2004) and number of deaths.

Characteristic	Rescue/recovery participants			Community participants		
	N[a]	%	Deaths (n)[a]	N[a]	%	Deaths (n)[a]
Total	29,280		877	39,643		1694
Person-years of follow-up	308,340			416,448		
Age on 9/11/2001 (years)						
< 25	1741	6.0	10	5703	14.4	18
25–44	17694	60.4	293	18451	46.5	206
45–64	9339	31.9	490	13659	34.5	816
65+	503	1.7	84	1814	4.6	653
Sex						
Male	22858	78.1	753	18517	46.7	829
Female	6422	21.9	124	21126	53.3	865
Race/ethnicity						
Non-Hispanic white	20767	70.9	636	22515	56.8	939
Non-Hispanic black	2610	8.9	95	5673	14.3	270
Hispanic	4039	13.8	95	5305	13.4	190
Other	1864	6.4	51	6150	15.5	295
Study recruitment source						
list-identified	10545	36.0	363	9492	23.9	491
self-identified	18735	64.0	514	30151	76.1	1203
Education						
Less than college	8521	29.5	327	9964	25.5	671
Some college	9001	31.1	281	7301	18.7	333
College or more	11402	39.4	259	21770	55.8	651
Total household income						
< $50,000	7357	27.6	286	13081	38.0	835
$50–74,999	6657	25.0	179	5971	17.4	201
> $75,000	12627	47.4	321	15364	44.6	371
Smoking status						
Never	16233	56.0	327	22341	59.4	716
Former	7775	26.8	303	9664	25.7	608
Current	4978	17.2	239	5630	15.0	339
History of chronic illness before 9/11						
Yes	2652	9.2	641	4510	11.6	641
No	26189	90.8	215	34442	88.4	215
9/11-related rescue/recovery exposure[b]						
Low	4524	15.6	129	.	.	.
Intermediate	21267	73.3	649	.	.	.
High	3209	11.1	87	.	.	.
9/11-related community exposure level[b]						
Low	.	.	.	19875	50.8	602
Intermediate	.	.	.	16215	41.4	913
High	.	.	.	3060	7.8	143

[a] May not sum to total/100% due to missing data.
[b] See text box for definition of exposure level.

occurred among men (n = 47). The majority of these deaths (76.5%) occurred among non-traditional rescue/recovery workers. There were significantly fewer deaths than expected due to chronic obstructive pulmonary disease (COPD) and to malignant neoplasms of the trachea, bronchus, and lung.

There were also several elevated minor-cause SMRs among community participants, including malignant neoplasms of the pancreas (n = 50, SMR 1.37, 95% CI 1.02–1.80). Within this group, 50% were male, 50% were aged 45–64 at enrollment, 66% were white, 64% were current or former smokers, and 90% were self-identified as eligible for the Registry. Also elevated among community participants were malignant neoplasms of the brain and other nervous system (SMR 2.25, 95% CI 1.48–3.28); 1 of these cases was a temporal lobe neoplasm, and the other 26 were unspecified. Deaths due to malignant neoplasms of the eye (n = 2, SMR 10.88, 95% CI 1.32–39.31), specifically the ciliary body, were also elevated, as was non-Hodgkin's lymphoma (SMR 1.79, 95% CI 1.24–2.50). Most (59%) of the 34 non-Hodgkin's lymphoma-related deaths occurred among participants who were aged 45–64 at enrollment; 62% were male, 62% white, and 85% were self-identified. Finally, other nervous system diseases (SMR 1.96, 95% CI 1.47–2.57) were also elevated among community participants. Of these 52 deaths, 24 were attributed to Alzheimer's, 9 to unspecified motor neuron disease, 7 to Parkinson's, and the remainder to other causes.

In the secondary analysis using the general United States population from 2003 to 2009 as a reference (Appendix A), the all-cause SMRs for rescue/recovery (SMR 0.43, 95% CI 0.41–0.46) and community (SMR 0.52, 95% CI 0.50–0.55) participants were significantly lower than expected, and substantially lower than the SMRs found using New York City comparison rates. There were no elevated SMRs for major cause-of-death categories using United States comparison rates.

3.4. Associations of 9/11-related exposures with mortality

We examined factors associated with all-cause, heart disease-related, and cancer-related mortality separately among rescue/recovery and community participants (Tables 4a, 4b). Among rescue/recovery participants, those with intermediate or high levels of 9/11-related exposure had an elevated hazard of all-cause mortality compared to those with low exposure [adjusted hazard ratio (AHR) 1.36, 95% CI 1.10–1.67 and AHR 1.41, 95% CI 1.06–1.88, respectively; p-value for trend 0.01]. AHRs for the association of higher levels of 9/11-related exposures with heart disease- and cancer-related mortality were also elevated, although the CIs crossed the null value, and trends were not statistically significant (p-value for trend 0.21 for heart disease, 0.30 for cancer).

For community enrollees, an intermediate level of 9/11-related exposure was significantly associated with all-cause mortality compared to low exposure (AHR 1.13, 95% CI 1.01–1.27), although the association of high exposure and all-cause mortality did not reach statistical significance (AHR 1.14, 95% CI 0.94–1.39). The test for trend was statistically significant (p = 0.03). Hazard ratios for the relations of 9/11-associated exposures with heart disease- and cancer-related mortality were not statistically significant (p-value for trend 0.21 for heart disease, 0.79 for cancer).

We also examined associations of 9/11-related exposure levels with specific causes of death for which at least 10 deaths had occurred and SMRs were significantly elevated: pancreatic malignancies, brain malignancies, non-Hodgkin's lymphoma, and other nervous system disease among community participants, and malignant melanoma and suicide among rescue/recovery participants (Table 5). In unadjusted proportional hazards analyses, the only significant association was between higher levels of rescue/recovery exposure and death due to suicide [HR 4.57, 95% CI 1.11–18.89 for intermediate exposure (n = 42 deaths) and HR 5.42, 95% CI 1.09–26.86 for high exposure (n = 6 deaths), compared to low exposure (n = 2 deaths)]. The small number of suicides in the high and low exposure strata prevented multivariable analyses.

4. Discussion

We did not find evidence of excess all-cause mortality during 2003–2014 in this large cohort of 9/11-exposed rescue/recovery workers and lower Manhattan community members, based on comparisons to general NYC mortality rates. However, internal analyses did identify significant associations between higher levels of 9/11-related

Table 2
Observed deaths and standardized mortality ratios (SMR) for major causes of death among participants in the World Trade Center Health Registry, 2003–2014, compared to New York City reference rates[a].

Cause of death (NIOSH major category)[b]	Rescue/recovery participants					Community participants[c]				
	Observed	Expected	SMR	95% CI		Observed	Expected	SMR	95% CI	
All	877	1268.6	0.69**	0.65	0.74	1694	1966.5	0.86**	0.82	0.9
Tuberculosis and HIV related disease (01)	8	69.9	0.11**	0.05	0.23	21	68.9	0.30**	0.19	0.47
All cancers	322	341.9	0.94	0.84	1.05	620	541.6	1.14**	1.06	1.24
MN of buccal cavity + pharynx (02)	5	8.4	0.59	0.19	1.39	9	9.9	0.91	0.42	1.72
MN of digestive organs + peritoneum (03)	94	112.5	0.84	0.68	1.02	165	161.7	1.02	0.87	1.19
MN of respiratory system (04)	71	88.2	0.80	0.63	1.02	135	129.7	1.04	0.87	1.23
MN of breast (05)	11	14.7	0.75	0.37	1.34	69	49.8	1.39*	1.08	1.75
MN of female genital organs (06)	7	10.4	0.67	0.27	1.39	43	36.7	1.17	0.85	1.58
MN of male genital organs (07)	14	15.6	0.90	0.49	1.51	28	25.9	1.08	0.72	1.56
MN of urinary organs (08)	17	15.1	1.13	0.66	1.80	20	20.6	0.97	0.59	1.50
MN of other and unspecified sites (09)	61	42.8	1.43*	1.09	1.83	85	58.6	1.45**	1.16	1.79
Neoplasms of lymphatic + hematopoietic tissues (10)	42	34.3	1.23	0.88	1.66	66	48.8	1.35*	1.05	1.72
Benign and unspecified neoplasms (11)	5	4.1	1.23	0.40	2.86	11	6.4	1.73	0.86	3.09
Diseases of the blood + blood forming organs (12)	2	4.2	0.47	0.06	1.71	6	7.0	0.86	0.32	1.87
Diabetes mellitus (13)	18	42.0	0.43**	0.25	0.68	49	69.9	0.70*	0.52	0.93
Mental psychoneurotic + personality disorders (14)	20	33.1	0.60*	0.37	0.93	43	40.8	1.05	0.76	1.42
Diseases of the nervous system + sense organs (15)	15	16.0	0.94	0.53	1.55	54	29.3	1.84**	1.38	2.41
Diseases of the heart (16)	188	337.8	0.56**	0.48	0.64	408	615.3	0.66**	0.60	0.73
Other diseases of the circulatory system (17)	44	66.6	0.66**	0.48	0.89	101	120.0	0.84	0.69	1.02
Diseases of the respiratory system (18)	32	71.0	0.45**	0.31	0.64	118	137.1	0.86	0.71	1.03
Diseases of the digestive system (19)	41	55.5	0.74	0.53	1.00	52	66.7	0.78	0.58	1.02
Diseases of the skin and subcutaneous tissue (20)	2	1.6	1.28	0.16	4.63	4	3.1	1.29	0.35	3.30
Disease of the musculoskeletal + connective tissue systems (21)	1	5.1	0.20	0.00	1.09	9	9.0	1.00	0.46	1.90
Diseases of the genitourinary system (22)	8	14.3	0.56	0.24	1.10	20	30.3	0.66	0.40	1.02
Symptoms and ill-defined conditions (23)	1	12.4	0.08**	0.00	0.45	1	13.7	0.07**	0.00	0.41
Transportation injuries (24)	23	16.3	1.42	0.90	2.12	10	17.3	0.58	0.28	1.06
Falls (25)	7	10.4	0.67	0.27	1.39	20	13.4	1.50	0.91	2.31
Other injury (26)	46	64.4	0.71*	0.52	0.95	34	56.8	0.60**	0.41	0.84
Violence (27)	56	46.1	1.22	0.92	1.58	27	43.3	0.62*	0.41	0.91
Other causes (residual and blank codes; 28)	38	56.0	0.68*	0.48	0.93	86	76.6	1.12	0.90	1.39

Abbreviations: National Institute for Occupational Safety and Health (NIOSH), 95% confidence interval (CI), malignant neoplasm (MN).

[a] New York City population mortality rates from 2003 to 2012 were used as the reference.

[b] Causes of death are from the NIOSH major cause of death categories and are listed with the associated NIOSH numbers in parentheses. International Classification of Diseases, 10th revision, codes for NIOSH categories are available in Robinson CF, Schnorr TM, Cassinelli RT, et al. Tenth revision US mortality rates for use with the NIOSH Life Table Analysis System. *J Occup Environ Med* 2006; 48: 662–67.

[c] Community participants include lower Manhattan area residents, area workers, school students and staff, and passers-by and commuters through lower Manhattan on September 11, 2001.

* $P < 0.05$.

** $P < 0.01$.

exposure and mortality among rescue/recovery workers, and a suggestion of such an association for community members as well.

A contrast between results of the SMR analyses, which relied on general population comparison groups, and results of the proportional hazards models, which used cohort members with low 9/11-related exposures as the comparison groups, was also found in our previous study of mortality in this cohort (Jordan et al., 2011b). SMRs have important limitations, particularly in a voluntary cohort that includes a high proportion of rescue/recovery workers. Rates of cardiovascular and respiratory deaths among Registry enrollees continue to be far lower than those observed in the general NYC and US populations, consistent with healthy worker and volunteer effects (Checkoway and Eisen, 1998; Lindsted et al., 1996), and thus indicative of inherent differences between the study and comparison populations that could potentially obscure a subtle association between 9/11 exposure and mortality, if one exists. Notably, all-cause SMRs in the current study were generally higher than those reported in our earlier study and by the WTC Health Program worker cohort, which followed participants through 2009 and 2011, respectively (Jordan et al., 2011b; Stein et al., 2016). This may be due to a diminution in the healthy worker and healthy volunteer effects over time; however, further study will be needed to determine whether this is a sustained trend, or simply fluctuation.

Because of the known weaknesses of mortality analyses that are based on external comparisons, we present these findings along with results of the more methodologically sound internal analyses (Pearce et al., 2007), which found that higher levels of rescue/recovery-related exposures were associated with increased all-cause mortality. There are differences between results of the internal analyses in the present study and those from our previous analysis, which found a small but statistically significant association of community-related exposures, but not rescue-recovery-related exposures, with all-cause mortality (Jordan et al., 2011b) Our current analysis used a larger study sample and included five additional years of follow-up, providing both greater statistical power and an enhanced ability to detect deaths due to conditions with long induction and survival times. That elevated mortality could be more closely associated with rescue/recovery than with community exposures is conceivable because 9/11-related physical health conditions tend to be more prevalent among exposed rescue/recovery workers than among exposed community members (Brackbill et al., 2009; Farfel et al., 2008; Li et al., 2016b; Li et al., 2011). Nonetheless, because the significant hazard ratios in the current study were modest in magnitude (in the range of 1.4), we cannot rule out uncontrolled confounding as a potential explanation for these associations. Furthermore, analyses conducted within the WTC Health Program responder cohort did not find a significant relationship between intensity or duration of 9/11-related rescue/recovery work and mortality (Stein et al., 2016). Taken together, findings to date, although suggestive of a relationship between 9/11-related exposures and mortality, are not conclusive.

Table 3
Observed deaths and standardized mortality ratios (SMR) for all minor causes of death with SMRs that were statistically different from expected among participants in the World Trade Center Health Registry, 2003–2014[a].

	Rescue/recovery participants					Community participants[c]				
Cause (NIOSH major, minor category)[b]	N	Expected	SMR	95% CI		N	Expected	SMR	95% CI	
Higher than expected										
MN pancreas (3,13)	22	24.1	0.91	0.57	1.38	50	36.5	1.37*	1.02	1.80
MN melanoma (9,29)	12	4.4	2.71**	1.40	4.74	10	5.1	1.96	0.94	3.61
MN brain & other nervous (9,33)	14	10.2	1.37	0.75	2.31	27	12.0	2.25**	1.48	3.28
MN eye (9,34)	1	0.2	6.08	0.15	33.87	2	0.2	10.88*	1.32	39.31
Non-Hodgkin's lymphoma (10,38)	11	14.1	0.78	0.39	1.39	34	19.0	1.79**	1.24	2.50
BN eye, brain, other nervous (11,41)	1	0.4	2.64	0.07	14.71	3	0.7	4.39	0.91	12.84
Other nervous system diseases (15, 52)	13	14.0	0.93	0.49	1.58	52	26.5	1.96**	1.47	2.57
Motor vehicle - driver (24, 92)	8	2.0	4.21**	1.82	8.30	0	1.6	0.00	0.00	2.25
Suicide (27, 116)	51	28.0	1.82**	1.35	2.39	21	24.5	0.86	0.53	1.31
Lower than expected										
HIV-related (1,3)	7	69.0	0.10**	0.04	0.21	21	67.8	0.31**	0.19	0.47
MN trachea, bronchus, lung (4,16)	64	82.6	0.77*	0.60	0.99	126	123.1	1.02	0.85	1.22
Alcoholism (14, 49)	9	18.0	0.50*	0.23	0.95	11	15.2	0.72	0.36	1.29
Hypertension w/heart disease (16, 54)	28	48.5	0.58**	0.38	0.83	46	73.7	0.62**	0.46	0.83
Ischemic heart disease (16, 55)	140	265.8	0.53**	0.44	0.62	310	501.2	0.62**	0.55	0.69
Hypertension w/o heart disease (17, 61)	5	15.3	0.33**	0.11	0.76	18	31.2	0.58*	0.34	0.91
Pneumonia (18, 65)	5	33.1	0.15**	0.05	0.35	52	69.7	0.75*	0.56	0.98
COPD (18, 66)	12	23.6	0.51*	0.26	0.89	43	45.3	0.95	0.69	1.28
Hernia & intestinal obstruction (19,73)	2	2.2	0.90	0.11	3.25	0	4.2	0.00*	0.00	0.88
Chronic & unspecified renal failure (22, 82)	6	8.2	0.73	0.27	1.60	6	15.2	0.39*	0.14	0.86
Motor vehicle - pedestrian (24, 94)	0	5.9	0.00**	0.00	0.62	4	7.0	0.58	0.16	1.47
Accidental poisoning (26, 112)	36	48.5	0.74	0.52	1.03	18	40.1	0.45**	0.27	0.71
Assault & homicide (27, 117)	5	16.7	0.30**	0.10	0.70	6	17.6	0.34**	0.13	0.74

Abbreviations: National Institute for Occupational Safety and Health (NIOSH), 95% confidence interval (CI), malignant neoplasm (MN), benign neoplasm (BN), chronic obstructive pulmonary disease (COPD).

[a] New York City population mortality rates from 2003 to 2012 were used as the reference.

[b] Causes of death are from the NIOSH major and minor cause of death categories and are listed with the associated NIOSH numbers in parentheses. International Classification of Diseases, 10th revision, codes for NIOSH categories are available in Robinson CF, Schnorr TM, Cassinelli RT, et al. Tenth revision US mortality rates for use with the NIOSH Life Table Analysis System. *J Occup Environ Med* 2006; 48: 662–67.

[c] Community participants include lower Manhattan area residents, area workers, school students and staff, and passers-by and commuters through lower Manhattan on September 11, 2001.

* $P < 0.05$.

** $P < 0.01$.

Among the specific causes of death for which significantly elevated SMRs were found, suicide among rescue/recovery workers (n = 51, SMR 1.82, 95% CI 1.35–2.39) is the most plausibly related to 9/11 exposure, as supported by the association of higher levels of 9/11-related rescue/recovery exposure and suicide in an unadjusted internal analysis. The majority of these deaths occurred among middle-aged men, with firearms as the most common method, similar to patterns seen in suicides in the general US population (Hu et al., 2008). Most (76.5%) occurred among non-traditional rescue/recovery workers, who may have been less likely than their traditional counterparts to have had pre-9/11 experience or training to prepare for the physical and psychological demands of such work (Perrin et al., 2007). However, the majority of rescue/recovery workers (72.1%) enrolled in the Registry were non-traditional as well, suggesting that factors other than type of rescue/recovery worker may be more important risks for suicide in this cohort. To date, no other published study has reported increased suicides among 9/11 survivors; additional follow-up and replication in other cohorts will be key to determining whether such a relationship exists. The other significantly elevated SMRs among rescue/recovery workers were for malignant melanoma and motor vehicle accidents as the driver, which were likely due to exposures incurred during routine work (sunlight, occupations that require driving), rather than as a consequence of 9/11. In particular, an association between firefighting and melanoma has been described (Bates, 2007).

Among community members in the Registry, SMRs for four specific types of cancer were significantly elevated: pancreatic, brain and other nervous system, eye cancers, and non-Hodgkin's lymphoma. Together, these elevations outweighed the significantly low SMRs found for other specific types of cancer, resulting in a slight elevation of the all-cancer SMR among community enrollees. A recent study of incident post-9/11 cancer among Registry enrollees did not find elevated rates of pancreatic, brain, or eye cancers (Li et al., 2016a), suggesting that associations in the current study may be due to chance, as increased incidence would be expected to precede or accompany increased mortality. However, non-Hodgkin's lymphoma in the Registry's cancer incidence study was significantly elevated among non-rescue/recovery enrollees (standardized incidence ratio 1.49, 95% CI 1.13–1.93), and, although the WTC Health Program mortality study did not report specifically on non-Hodgkin's lymphoma, the proportion of cancer deaths due to neoplasms of the lymphatic and hematopoietic tissue in that study was higher than the respective proportion in the general US population (Stein et al., 2016). There is some evidence implicating exposures to chemicals, including benzene [which was identified in WTC dust (National Institute for Occupational Safety and Health NIOSH, 2011), as risk factors for non-Hodgkin's lymphoma, providing some biologic plausibility for such an association (Smith et al., 2007). The Registry will continue to follow both incidence and mortality of each of these types of cancer.

The final elevated SMR among community members was for other nervous system diseases, the plurality of which were due to Alzheimer's disease at advanced ages. The basic demographics of Alzheimer's decedents in this study do not suggest an unusual pattern. Studies of cognitive function among 9/11-exposed persons may illuminate this subject. Although our study could not determine whether the nine deaths due to unspecified motor neuron disease were related to 9/11 exposure, recent observations of neuropathic symptoms and motor neuron disease among 9/11-exposed community members suggest a need for further study (Marmor et al., 2017; Stecker et al., 2016).

Table 4a
Adjusted hazard ratios for all-cause, heart disease-related, and cancer-related mortality among rescue/recovery participants.

	All-cause mortality[a]			Heart disease mortality[a]			Cancer-related mortality[a]		
Characteristic	AHR[b]	95% CI		AHR[b]	95% CI		AHR[b]	95% CI	
Age (continuous, years)	1.08	1.07	1.09	1.09	1.08	1.11	1.10	1.09	1.11
Sex (male vs. female)	1.59	1.30	1.95	2.43	1.43	4.12	1.31	0.96	1.78
Race/ethnicity									
Non-Hispanic white	ref			ref			ref		
Non-Hispanic black	1.16	0.92	1.45	1.26	0.78	2.05	0.86	0.57	1.30
Hispanic	0.91	0.73	1.14	0.99	0.61	1.60	0.79	0.54	1.17
Other	0.97	0.70	1.33	1.03	0.52	2.03	1.09	0.67	1.76
Education									
Less than college	1.40	1.18	1.66	1.38	0.95	2.01	1.37	1.04	1.81
Some college	1.36	1.14	1.62	1.31	0.89	1.93	1.26	0.95	1.67
College or more	ref			ref			ref		
Smoking status at study enrollment									
Never	ref			ref			ref		
Former	1.19	1.01	1.41	1.38	0.94	2.02	1.32	1.02	1.72
Current	2.41	2.03	2.87	4.17	2.86	6.09	2.26	1.68	3.05
History of chronic illness before 9/11	1.98	1.68	2.33	.	.	.			
Diabetes before 9/11	.	.	.	2.67	1.74	4.09	.	.	.
Heart disease before 9/11	.	.	.	2.68	1.81	3.97	.	.	.
Cancer before 9/11	.	.	.	.	.	.	2.32	1.52	3.54
9/11-related exposure[c]									
Low	ref			ref			ref		
Intermediate	1.36	1.10	1.67	1.40	0.89	2.20	1.35	0.99	1.85
High	1.41	1.06	1.88	1.44	0.76	2.74	1.14	0.70	1.87

Abbreviations: adjusted hazard ratio (AHR), 95% confidence interval (CI), reference group (ref).
[a] Includes participants with all data available (n = 28,210 for all-cause; 28,303 for heart disease; 28,544 for cancer).
[b] Adjusted for age, sex, race/ethnicity, education, smoking, and pre-9/11 chronic disease (for all cause), pre-9/11 cancer (for cancer deaths), or pre-9/11 diabetes and pre-9/11 heart disease (for heart deaths).
[c] See text box for definition of exposure levels. P-values for trend: all-cause mortality, 0.01; heart disease mortality, 0.21; cancer mortality, 0.30.

When interpreting results of this study, it is important to consider that all deaths occurring during 2003–2014 were included, regardless of the timing of onset of the illnesses that ultimately lead or contributed to these deaths. Thus it is likely that many of the deaths due to chronic illnesses with long median survival times, including those due to many types of cancer, resulted from disease processes that were first diagnosed before the 9/11 attacks. Additional years of follow-up may enable the Registry to examine whether there is a relationship between 9/

Table 4b
Adjusted hazard ratios for all-cause, heart disease-related, and cancer-related mortality among community participants.

	All-cause mortality[a]			Heart disease mortality[a]			Cancer-related mortality[a]		
Characteristic	AHR[b]	95% CI		AHR[b]	95% CI		AHR[b]	95% CI	
Age (continuous, years)	1.10	1.09	1.10	1.12	1.11	1.13	1.09	1.08	1.09
Sex (male vs. female)	1.25	1.13	1.38	1.48	1.20	1.83	1.05	0.89	1.24
Race/ethnicity									
Non-Hispanic white	ref			ref					
Non-Hispanic black	1.28	1.11	1.48	1.59	1.19	2.11	1.14	0.90	1.46
Hispanic	1.05	0.89	1.23	1.15	0.83	1.60	0.87	0.65	1.17
Other	0.83	0.72	0.97	0.67	0.49	0.92	0.95	0.74	1.22
Education									
Less than college	1.28	1.13	1.45	1.43	1.10	1.85	1.16	0.95	1.43
Some college	1.19	1.03	1.37	1.41	1.06	1.88	1.17	0.94	1.46
College or more	ref			ref					
Smoking status at study enrollment									
Never	ref			ref					
Former	1.28	1.14	1.43	1.15	0.92	1.45	1.55	1.28	1.87
Current	2.49	2.17	2.86	2.24	1.66	3.01	2.87	2.30	3.59
History of chronic illness before 9/11	1.69	1.52	1.89	.	.	.	.	.	.
Diabetes before 9/11	.	.	.	1.96	1.48	2.59	.	.	.
Heart disease before 9/11	.	.	.	2.08	1.64	2.64	.	.	.
Cancer before 9/11	.	.	.	.	.	.	2.57	2.00	3.29
9/11-related exposure[c]									
Low	ref			ref					
Intermediate	1.13	1.01	1.27	1.19	0.95	1.51	0.98	0.82	1.18
High	1.14	0.94	1.39	1.14	0.76	1.73	1.09	0.80	1.48

Abbreviations: adjusted hazard ratio (AHR), 95% confidence interval (CI), reference group (ref).
[a] Includes participants with all data available (n = 36,431 for all-cause; 36,533 for heart disease; 39,643 for cancer).
[b] Adjusted for age, sex, race/ethnicity, education, smoking, and pre-9/11 chronic disease (for all cause), pre-9/11 cancer (for cancer deaths), or pre-9/11 diabetes and pre-9/11 heart disease (for heart deaths).
[c] See text box for definition of exposure levels. P-values for trend: all-cause mortality, 0.03; heart disease mortality, 0.21; cancer mortality, 0.79.

Table 5
Unadjusted associations of 9/11-related exposure levels with specific causes of death for which SMRs were elevated.[a].

Cause (NIOSH major, minor category)[b]	Exposure level[c]	No. deaths	Hazard ratio	95% CI	
Rescue/recovery participants					
MN melanoma (9,29)					
	Low	3	ref		
	Intermediate	7	0.51	0.13	1.98
	High	2	1.12	0.19	6.70
Suicide (27, 116)					
	Low	2	ref		
	Intermediate	42	4.57	1.11	18.89
	High	6	5.42	1.09	26.86
Community participants					
MN pancreas (3,13)					
	Low	21	ref		
	Intermediate	23	0.78	0.43	1.41
	High	6	1.15	0.46	2.85
MN brain & other nervous (9,33)					
	Low	17	ref		
	Intermediate	8	0.34	0.15	0.78
	High	2	0.48	0.11	2.08
Non-Hodgkin's lymphoma (10,38)					
	Low	10	ref		
	Intermediate	18	1.27	0.59	2.75
	High	6	2.27	0.82	6.28
Other nervous system diseases (15, 52)					
	Low	20	ref		
	Intermediate	28	1.03	0.58	1.83
	High	3	0.56	0.17	1.91

Abbreviations: National Institute for Occupational Safety and Health (NIOSH), 95% confidence interval (CI), malignant neoplasm (MN), reference group (ref).

[a] Excludes causes to which fewer than 10 deaths were attributed.

[b] Causes of death are from the NIOSH major and minor cause of death categories and are listed with the associated NIOSH numbers in parentheses. International Classification of Diseases, 10th revision, codes for NIOSH categories are available in Robinson CF, Schnorr TM, Cassinelli RT, et al. Tenth revision US mortality rates for use with the NIOSH Life Table Analysis System. *J Occup Environ Med* 2006; 48: 662–67.

[c] See text box for definition of exposure levels.

11-related exposures and mortality due to post-9/11-onset illnesses. The Registry is also collaborating with other 9/11-exposed rescue/recovery worker cohorts to establish a combined worker cohort that will afford increased statistical power to explore such questions. These studies may further elucidate the relationship between 9/11-related exposures and heart disease, as there is some indication of an association of 9/11-related exposures with incident post-9/11cardiovascular illnesses, (Jordan et al., 2011a, 2013) but as yet no consistent association with cardiovascular mortality.

Our study has limitations in addition to those mentioned above. Detailed, objectively measured exposure data for Registry enrollees do not exist, for such exposures were not gathered systematically during the tumultuous period following 9/11. We therefore used self-reported exposure data that were gathered in 2002–2003, and thus vulnerable to recall decay, among other types of bias. Additionally, our ability to conduct detailed analyses of specific causes of death remains constrained by small numbers of deaths in most categories.

Nonetheless, these results are valuable because they are based on data from a large, relatively diverse closed cohort of 9/11-exposed rescue-recovery workers and community members, and used established, systematic methods to ascertain a well-defined outcome. Although we have not identified excess all-cause mortality among Registry enrollees to date, several minor causes of death were significantly elevated, and internal analyses offer some evidence that 9/11-related exposures may confer a modest increase in mortality risk. Together with studies of disease incidence, continued surveillance of mortality among Registry enrollees will be increasingly revealing with extended observation.

Appendix A

See Table A1

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Human subjects review

The US Centers for Disease Control and Prevention and New York City Department of Health and Mental Hygiene institutional review boards approved the Registry's protocol.

Conflicts of interests

None.

Table A1
Observed deaths and standardized mortality ratios (SMR) for major causes of death among participants in the World Trade Center Health Registry, 2003–2014, compared to US reference rates[a].

NIOSH category[b]		Rescue/recovery				Community[c]			
	Cause of death	n	SMR	95% CI		n	SMR	95% CI	
	All	877	0.43**	0.41	0.46	1694	0.52**	0.50	0.55
1	Tuberculosis and HIV related disease	8	0.22**	0.09	0.43	21	0.54**	0.33	0.82
2	MN of buccal cavity and pharynx	5	0.40*	0.13	0.93	9	0.62	0.28	1.18
3	MN of digestive organs and peritoneum	94	0.61***	0.49	0.74	165	0.74**	0.63	0.86
4	MN of respiratory system	71	0.40**	0.31	0.51	135	0.53**	0.45	0.63
5	MN of breast	11	0.51*	0.26	0.92	69	0.94	0.73	1.19
6	MN of female genital organs	7	0.54	0.22	1.11	43	0.94	0.68	1.26
7	MN of male genital organs	14	0.57*	0.31	0.95	28	0.68*	0.45	0.99
8	MN of urinary organs	17	0.64	0.37	1.03	20	0.55**	0.34	0.85
9	MN of other and unspecified sites	61	0.76*	0.58	0.97	85	0.78*	0.62	0.96
10	Neoplasms of lymphatic + hematopoietic tissue	42	0.85	0.62	1.15	66	0.89	0.69	1.13
11	Benign and unspecified neoplasms	5	0.71	0.23	1.67	11	0.95	0.47	1.70
12	Diseases of the blood and blood forming organs	2	0.23*	0.03	0.82	6	0.36**	0.13	0.78
13	Diabetes mellitus	18	0.25**	0.15	0.40	49	0.40**	0.30	0.53
14	Mental psychoneurotic + personality disorders	20	0.54**	0.33	0.83	43	0.51**	0.37	0.68
15	Diseases of the nervous system and sense organs	15	0.29**	0.16	0.48	54	0.47**	0.35	0.61
16	Diseases of the heart	188	0.40**	0.35	0.47	408	0.53**	0.48	0.58
17	Other diseases of the circulatory system	44	0.33**	0.24	0.45	101	0.37**	0.30	0.45
18	Diseases of the respiratory system	32	0.24**	0.17	0.34	118	0.48**	0.39	0.57
19	Diseases of the digestive system	41	0.39**	0.28	0.53	52	0.39**	0.29	0.51
20	Diseases of the skin and subcutaneous tissue	1	0.34	0.01	1.89	4	0.63	0.17	1.61
21	Dis of the musculoskeletal + connective systems	1	0.12**	0.00	0.64	9	0.49*	0.23	0.94
22	Diseases of the genitourinary system	7	0.18**	0.07	0.37	18	0.21**	0.12	0.33
23	Symptoms and ill-defined conditions	1	0.04**	0.00	0.22	1	0.03**	0.00	0.14
24	Transportation injuries	23	0.37**	0.24	0.56	10	0.16**	0.08	0.30
25	Falls	7	0.48*	0.19	0.99	20	0.92	0.56	1.42
26	Other injury	46	0.51**	0.38	0.68	34	0.37**	0.25	0.51
27	Violence	56	0.65**	0.49	0.84	27	0.33**	0.22	0.48
28	Other causes (residual and blank codes)	40	0.46**	0.33	0.62	88	0.62**	0.50	0.76

Abbreviations: National Institute for Occupational Safety and Health (NIOSH), 95% confidence interval (CI), malignant neoplasm (MN).

[a] US reference population, 2003–2009.

[b] ICD 10 codes for NIOSH categories are available in Robinson CF, Schnorr TM, Cassinelli RT, et al. Tenth revision US mortality rates for use with the NIOSH Life Table Analysis System. *J Occup Environ Med* 2006; 48: 662–67.

[c] Community participants include lower Manhattan area residents, area workers, school students and staff, and passers-by and commuters through lower Manhattan on September 11, 2001.

* $P < 0.05$.

** $P < 0.01$.

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