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A 15-year follow-up study of mortality in a pooled cohort of World Trade Center rescue and recovery workers

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ABSTRACT

Introduction: Hazardous exposures from the World Trade Center (WTC) terrorist attacks have been linked to increased incidence of adverse health conditions, often associated with increased mortality. We assessed mortality in a pooled cohort of WTC rescue/recovery workers over 15 years of follow-up.

Materials and methods: We analyzed mortality through 2016 in a pooled and deduplicated cohort of WTC rescue/recovery workers from three WTC-exposed cohorts (N = 60,631): the Fire Department of the City of New York (FDNY); the WTC Health Registry (WTCHR); and the General Responder Cohort (GRC). Standardized mortality ratios (SMRs) were estimated to assess mortality vs. the US and NY state populations. Multivariable Cox proportional hazards models were used to examine associations of WTC exposures (date of first arrival, working on the WTC debris pile) with mortality risk.

Results: There were 1912 deaths over 697,943.33 person-years of follow-up. The SMR for all-cause mortality was significantly lower-than-expected, both when using US (SMR 0.43, 95% confidence interval [CI] 0.42–0.45) and NYS (SMR 0.51, 95% CI 0.49–0.53) as reference populations. SMRs were not elevated for any of the 28 major causes of death. Arriving at the WTC site on 9/11-9/17/2001 vs. 9/18/2001-6/30/2002 was associated with 30–50% higher risk of all-cause, heart disease and smoking-related mortality in non-FDNY/non-GRC members. Conversely, arriving on 9/11/2001 vs. 9/18/2001-6/30/2002 was associated with 40% lower all-cause and smoking-related mortality risk in FDNY members. Working on vs. off the WTC pile was associated with an increased risk of all-cause mortality in non-FDNY/non-GRC members (adjusted hazard ratio [aHR] 1.25, 95% CI 1.04–1.50), and cancer-specific mortality in GRC members (aHR 1.39, 95% CI 1.05–1.84), but lower mortality risks were found in FDNY members.

Conclusions: We did not observe excess mortality among WTC rescue/recovery workers compared with general populations. However, significantly increased mortality risks among some sub-groups with high WTC exposure warrant further investigation.

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1. Introduction

It has been more than 20 years since the September 11, 2001 (9/11) terrorist attacks on the World Trade Center (WTC) in New York City (NYC). Numerous studies of the WTC rescue and recovery workers and volunteers (hereafter, responders) and/or exposed community members have reported short- and medium-term health risks, associated with the hazardous WTC exposures, many of which persist years after exposure (Wisnivesky et al., 2011; Jordan et al., 2015; Cleven et al., 2021). These include poor respiratory health, increased gastroesophageal reflux symptoms, sarcoidosis, post-traumatic stress disorder (PTSD), depression, and associated increase in smoking and alcohol use (Herbert et al., 2006; Perlman et al., 2011; Ekenga and Friedman-Jimenez, 2011). There is also a growing body of research suggesting the long-term effects of WTC exposure, including health outcomes such as cardiovascular diseases (Remch et al., 2018; Cohen et al., 2019; Sloan et al., 2021), cancer (Shapiro et al., 2020; Webber et al., 2021; Goldfarb et al., 2021a; Li et al., 2022) and pulmonary conditions (Li et al., 2019; Jordan et al., 2019; Cleven et al., 2021).

During the nearly ten-month rescue, recovery and clean-up efforts, responders were potentially highly exposed to environmental contaminants in the WTC dust and toxic substances present at the site (Lioy et al., 2002; Landrigan et al., 2004; Woskie et al., 2011; Lippmann et al., 2015) and to psychological trauma (Perrin et al., 2007; Berninger et al., 2010; Pietrzak et al., 2012). Previous studies reported that 45% of firefighters who were present during the collapse (Feldman et al., 2004), 65% of heavily exposed police officers (Buyantseva et al., 2007), and 54% of WTC workers and volunteers who were not affiliated with fire and rescue or law enforcement and present on 9/11 (Antao et al., 2011) did not use any respirator or mask. Consequently, responders, particularly those involved in the immediate response in the days after the attacks and working on the pile of rubble from the collapse of WTC buildings (Brackbill et al., 2021), may be at increased risk for adverse health outcomes associated with 9/11 and WTC exposure, which might ultimately lead to premature mortality.

Findings from previous mortality studies using cohorts of responders have been inconsistent. In an early mortality assessment among the responders who enrolled in the WTC Health Registry (WTCHR), all-cause and cause-specific mortality were lower than expected compared to the NYC population during the first six years of follow-up after enrollment (Jordan et al., 2011). A follow-up study of the same cohort with an additional five years of observation found a 40% elevation in all-cause mortality risk in responders who experienced high vs. low WTC exposure (defined based on self-reported arrival date, duration, and location of work related to the WTC rescue/recovery effort), though all-cause mortality remained lower than expected compared with the NYC population (Jordan et al., 2018). Additionally, neither study of mortality in the WTC general responder cohort (GRC), nor of the Fire Department of the City of New York (FDNY) firefighters and emergency medical service providers (EMS), reported excess all-cause or cause-specific mortality compared to the U.S. general population (Stein et al., 2016; Colbeth et al., 2020). Furthermore, mortality was not statistically significantly associated with levels of WTC exposure (defined differently in each cohort) in these two cohorts (Stein et al., 2016; Colbeth et al., 2020).

The inconsistent findings in previous mortality studies of responders may be related to the type of responders who were evaluated, inconsistent definitions of WTC exposure, relatively small sample sizes, and/or insufficient follow-up time in the different cohorts (Boffetta et al., 2016). Therefore, the present study used the combined and deduplicated cohort of WTC rescue and recovery workers (hereafter, the combined cohort) (Brackbill et al., 2021), with 15-years of follow-up to examine whether excess mortality has emerged compared to the general population. Levels of WTC exposure and their associations with mortality risk were also evaluated.

2. Materials and methods

2.1. Data source and study cohort

This is a longitudinal cohort study. We used data from the combined cohort, which includes workers and volunteers from three WTC-exposed cohorts based in NYC who were involved in rescue, response, recovery, clean-up and related activities after the 9/11 attacks (Brackbill et al., 2021). The sources of the combined cohort included the FDNY cohort (n = 16,221), GRC (n = 33,427), and WTCHR (n = 29,372) (Brackbill et al., 2021). The FDNY cohort consists of FDNY Responders (i.e., active or retired WTC-exposed firefighters and EMS workers) who have received routine monitoring, treatment, and medical examinations since September 11, 2001 via FDNY's WTC medical monitoring and treatment program (WTC-MMTP), an extension of the pre-existing occupational health service (Yip et al., 2016). The GRC cohort consists of WTC General Responders of the WTC Worker Monitoring Program (also a WTC-MMTP) that was established at the Icahn School of Medicine at Mount Sinai in July 2002 to provide comprehensive medical monitoring examinations. GRC members include police officers from New York City Police Department (NYPD), construction and communications workers, other workers, and volunteers who engaged in WTC rescue, recovery, and cleanup efforts (Savitz et al., 2008; Dasaro et al., 2017). The WTCHR was established in July 2002 as a collaborative effort between the NYC Department of Health and Mental Hygiene and the Agency for Toxic Substances and Disease Registry (ATSDR) to track and evaluate short- and long-term physical and mental health of people directly exposed to the WTC disaster (Farfel et al., 2008; Azofeifa et al., 2021) through periodical surveys. The WTCHR is not a WTC-MMTP and provides neither clinical treatments nor medical examinations. The 29,372 workers (e.g., firefighters, police, construction workers, etc. and volunteers) who were enrolled into WTCHR in 2003–2004 were involved in WTC rescue, recovery and/or cleanup efforts (Farfel et al., 2008). Following the Zagroga Act that was signed into law in January 2011, the Center for Disease Control and Prevention (CDC) WTC Health Program was created in July 2011, the three cohorts have been supported by the CDC WTC Health Program since then. The processes of pooling and deduplication of the three individual cohorts into one combined cohort of 69,102 responders has been described in detail elsewhere (Brackbill et al., 2021). In brief, the membership and deduplication of individuals in the combined cohort was categorized using the following hierarchical criteria: (a) member of FDNY regardless of membership in GRC or WTCHR (FDNY members); (b) member of GRC regardless of enrollment in the WTCHR, but not a member of FDNY (GRC members); (c) remaining member of the WTCHR, not in the GRC nor the FDNY (non-FDNY/non-GRC members) (Brackbill et al., 2021). Each cohort developed and administered its own questionnaire to capture data on sociodemographic factors and level of WTC exposures at enrollment.

The study sample for this analysis was restricted to those in the combined cohort who were aged 18 years or older on 9/11 and for whom we had race and ethnicity information. To mitigate potential selection bias, we excluded those who were enrolled after 2010, or who died or reached their 85th birthday during the first year after enrollment.

This study was approved by the Institutional Review Boards (IRB) of the Albert Einstein College of Medicine, New York City Department of Health and Mental Hygiene, and New York State Department of Health. The IRBs of Icahn School of Medicine at Mount Sinai and Stony Brook University granted exemptions.

2.2. Ascertainment of deaths

Vital status was ascertained via linkage with the CDC National Death Index (NDI). Linkages were performed independently by an individual cohort steward, then merged into the combined cohort for analysis. All deaths that occurred between enrollment date and 12/31/2016 were

identified. Underlying causes of death, defined based on the International Classification of Disease codes, 10th revision (ICD-10) provided by the NDI, were categorized into 28 major categories according to the 119-cause rate file from NIOSH life table analysis software (LTAS.NET) (Schubauer-Berigan et al., 2011). Heart-related (major category #16), cancer-related (major categories #2 through #10), and tobacco smoking-related (US HHS 2014) mortality were of specific interest in this analysis. Tobacco smoking-related mortality consists of: (1) cancers (lung; lip, pharynx and oral cavity; esophagus; stomach; pancreas; larynx; cervix uteri; kidney and renal pelvis; bladder; liver; colon and rectum; and acute myeloid leukemia); (2) cardiovascular diseases (coronary heart disease, rheumatic or pulmonary heart disease, and other forms of heart disease); (3) cerebrovascular and other vascular diseases; (4) metabolic diseases (diabetes mellitus); and (5) respiratory diseases (peumonia, influenza, tuberculosis, chronic obstructive pulmonary disease) (US HHS 2014).

2.3. WTC exposure

We used two WTC exposure indicators (hereafter, WTC exposures) that were self-reported on questionnaires at the time of enrollment and common to the three cohorts. First was date of first arrival to the WTC rescue/recovery effort (on September 11, on September 12, between September 13 and 17, between September 18, 2001, to June 30, 2002, or unknown), which is a proxy for the level of environmental toxic contaminants that was in the ambient air following the WTC attacks. Previous studies have shown that the levels of particulate matter in the ambient air peaked in the initial 5–6 h post collapse of the WTC buildings and then dissipated over the next days and months (Lioy and Georgopoulos, 2006). Therefore, early arrival is presumably an indication of greater exposure. Second was whether tasks were performed on the debris pile from the collapsed towers (yes, no, or unknown). The term "pile" refers to the former location of the Twin Towers of the WTC complex (Woskie et al., 2011) or the mound of rubble from the collapse of the WTC buildings (Pulliam et al., 2006); and the most common activities on the pile were search, rescue and recovery, security and debris removal (Woskie et al., 2011). Thus, performing tasks on pile is also an indicator of greater exposure to the environmental toxic contaminants that resulted from the WTC attacks.

2.4. Statistical analyses

Using standardized mortality ratios (SMRs), we compared the observed deaths in the study cohort to the expected deaths based on reference population rates for all causes combined and for each of the 28 NIOSH major causes of death (Schubauer-Berigan et al., 2011). All SMRs were computed accounting for age, sex, race/ethnicity, and calendar period using the NIOSH Life Table Analysis System (LTAS) (Schubauer-Berigan et al., 2011). Follow-time started one year after enrollment. Although a majority of WTC workers resided in New York State (NYS), we used reference rates from both the U.S. and NYS to allow for comparability with other previous mortality studies.

Using Cox proportional hazards modeling (Storer et al., 2008), we estimated hazards ratios (HR) with 95% confidence intervals (CIs) for the associations between WTC exposure classifications and risk of all-cause mortality. "First arrival date" on the WTC effort and "work on the pile" were evaluated separately in models adjusted for sex, race/-ethnicity and smoking status at enrollment. We also examined the associations of WTC exposure with cause-specific mortality, using a proportional hazards regression model for the sub-distribution of a competing risk proposed by Fine and Gray (1999). We selected this method for our primary analysis because this was a prediction study that had a low overall mortality rate (Van Der Pas et al., 2018). As a sensitivity analysis, we calculated cause-specific HRs to compare with sub-distribution HRs. Age was used as the time scale with follow-up duration determined as age one year after study enrollment date to age at death or censoring (age 85 years or age on December 31, 2016), whichever came earlier. Age as the time scale, rather than time-on-study, was used to minimize bias with respect to age and to allow for non-linear associations between age and mortality (Korn et al., 1997).

Given that there are potential differences among the cohort membership groups (e.g., differences in job-related, pre-employment screening and training) (Perrin et al., 2007; Woskie et al., 2011; Yip et al., 2016), we assessed whether the associations between WTC exposure and mortality differed by membership group (FDNY, GRC and non-FDNY/non-GRC) by including a cross-product term between WTC exposures and cohort membership in the multivariable models; the Wald test was used to determine statistical significance of between-group differences.

We assessed the proportional hazard (PH) assumption with Schoenfeld residuals methods (Schoenfeld, 1982). Age on 9/11 violated the PH assumption, therefore, we controlled for age on 9/11 (10-year intervals) with stratified Cox models (Kleinbaum and Klein, 2012).

Internal analyses were performed using SAS® version 9.4 (SAS Institute, Cary, NC). All statistical tests are two-sided, and statistical significance was indicated if the 95% CI did not contain the null value of 1 or if a *P* value was less than 0.05.

3. Results

3.1. Study cohort description

We excluded a total of 8471 WTC workers from the combined cohort: 186 whose age was under 18 years or unknown on 9/11, 14 who were aged 85 years or older during the first year of enrollment, 1795 with unknown race/ethnicity, 6394 who enrolled after 2010, 79 who died within the first year of enrollment, one with an unknown cause of death, and two duplicates who were not identified during the original pooling process.

The final analytic sample of 60,631 WTC workers (87.7% of the combined cohort) included 15,887 FDNY members, 25,657 GRC members, and 19,087 non-FDNY/non-GRC members. The cohort was predominantly male (84.2%), non-Hispanic White (71.3%) and never smokers at enrollment (59.5%) (Table 1). The median age on 9/11 was 39.0 years (inter-quartile range, IQR: 13.0). As shown in Table 2, the distribution of WTC exposures (date of first arrival at the WTC effort and on the WTC pile) varied by cohort membership. FDNY members compared (*cf.*) to GRC and non-FDNY/non-GRC members had a higher proportion arriving at the WTC effort on 9/11 (58.4% *cf.* 35.8% and 18.2%, respectively) and working on the pile (81.9% *cf.* 25.9% and 21.0%).

3.2. External comparisons

There were 1912 deaths over the 697,943.33 person-years of follow up in the study sample. Cancer was the most common cause of death (n = 698). As shown in Table 3, the SMRs for all-cause mortality from 2002 to 2016 were significantly lower than expected, both when using the U. S. as the referent group (SMR 0.43, 95% CI 0.42–0.45) and when using NYS as the referent group (SMR 0.51, 95% CI 0.49–0.53). There were no significantly elevated SMRs for any of the 28 major causes of death, evaluated separately.

When using the U.S. as the referent group (Table 3), all but four of the major causes of death had an SMR that was statistically significantly lower than expected, ranging from 0.22 (95% CI 0.12–0.37) for tuberculosis and HIV-related disease (n = 14), 0.50 (95% CI 0.41–0.60) for violence (n = 108), to 0.70 (95% CI 0.48–0.97) for malignant neoplasm (MN) of male genital organs (n = 35). Similar SMRs were also observed for the major causes of death when using NYS as the reference population.

Table 1
Characteristic of study population and number of deaths (N = 60,631).

	N	Percent	Death (N)
Total	60,631	100.0	1912
Person-years of follow-up	697,943.33		
Socio-demographics			
Age on 9/11/2001			
Mean age (SD)	39.6 (9.8)		
Median age (IQR)	39.0 (13.0)		
18-29	8941	14.8	70
30-39	22,884	37.7	344
40-49	19,255	31.8	656
50-59	7643	12.6	573
60-69	1696	2.8	228
70–80	212	0.4	41
Sex			
Male	51,068	84.2	1715
Female	9563	15.8	197
Race/Ethnicity			
Non-Hispanic White	43,206	71.3	1403
Non-Hispanic Black	5955	9.8	245
Non-Hispanic, other race	1355	2.2	34
Hispanic	10,115	16.7	230
Smoking status at enrollment			
Current	9590	15.8	511
Former	14,126	23.3	596
Never	36,052	59.5	771
Missing	863	1.4	34
WTC Exposures			
Date of first arrival at WTC rescue and recovery effort			
9/11/2001	21,941	36.2	570
9/12/2001	11,155	18.4	381
Any day during 9/13 - 9/17/2001	11,630	19.2	424
During 9/18-12/31/2001	9270	15.3	319
During 1/1/2002 - 6/30/2002	2434	4.0	84
Missing	4201	6.9	134
Performed tasks on pile			
Yes	23,658	39.0	658
No	36,028	59.4	1199
Missing	945	1.6	55

3.3. Within cohort comparisons

Table 4 presents adjusted hazard ratios (aHR) for associations of arrival date at WTC site with all-cause and cause-specific mortality risk, adjusting for sex, race/ethnicity and smoking status at enrollment. Among FDNY members, those who arrived at the WTC effort on 9/11/2001 (*cf*. arrived between 9/18/2001-6/30/2002) had a 40% lower risk of all-cause mortality (aHR 0.60, 95% CI 0.41–0.88) and 45% lower risk of smoking-related mortality (aHR 0.55, 95% CI 0.33–0.94). Conversely, among non-FDNY/non-GRC members, those who arrived before 9/18/2001 (*cf*. arrived between 9/18/2001-6/30/2002) had a 32–40% higher risk of all-cause mortality, and 30–43% higher risk of smoking-related mortality. Additionally, non-FDNY/non-GRC members who arrived between 9/13–9/17/2001 had a 50% (aHR 1.50, 95% CI 1.01–2.23) elevated risk of heart disease-related mortality, compared with non-FDNY/non-GRC members who arrived between 9/18/2001-6/30/2002. Arrival date at the WTC effort was not associated with mortality risk in GRC members.

Table 5 shows the aHRs for associations of working on the WTC debris pile with overall and cause-specific mortality risk. Among FDNY members, the risk of all-cause mortality was 43% (aHR 0.57, 95% CI 0.45–0.73) lower in those who ever worked on the WTC pile compared with those who did not. Similar patterns of 37%–42% lower risks of cause-specific mortality were observed among FDNY members who worked on the pile. In contrast, working on the pile was associated with increased risk of all-cause mortality in non-FDNY/non-GRC members (aHR 1.25, 95% CI 1.04–1.50) and cancer-specific mortality in GRC members (aHR 1.39, 95% CI 1.05–1.84).

The cause-specific HRs from the sensitivity analysis were similar to the sub-distribution HRs depicted in Tables 4 and 5 (data not shown).

4. Discussion

This is the largest study of mortality among responders to date, comprising almost 700,000 person-years of observation. In the combined cohort, all-cause and cause-specific mortality were significantly lower than expected compared to the US or NYS general populations, which is consistent with previous studies in the individual cohorts (Stein et al., 2016; Jordan et al., 2018; Colbeth et al., 2020). When WTC exposure level was evaluated based on arrival date and working on the debris pile, there was some evidence of increased mortality risk in both non-FDNY/non-GRC and GRC members. Specifically, non-FDNY/non-GRC members who arrived before 9/18/2001, compared with those who arrived later, had significantly increased risk

Table 2
World Trade Center exposures and causes of mortality by the Cohort membership (N = 60,631).

	Cohort members, Col %				Death, N			
	ALL	FDNY	GRC	nonFDNY/nonGRC	ALL	FDNY	GRC	nonFDNY/nonGRC
Total, N	60,631	15,887	25,657	19,087	1912	440	682	790
WTC Exposures								
Date of first arrival at WTC site								
9/11/2001	21,941	58.41	35.77	18.25	570	207	216	147
9/12/2001	11,155	16.78	19.22	18.64	381	77	140	164
Any day during 9/13 - 9/17/2001	11,630	14.52	19.72	22.33	424	84	145	195
During 9/18/2001 - 6/31/2002	11,704	4.27	13.27	39.93	319	21	89	209
Missing	4201	6.01	12.02	0.85				
Performed tasks on pile								
Yes	23,658	81.87	25.88	21.02	658	313	183	162
No	36,028	13.28	74.08	78.13	1199	80	498	621
Missing	945	4.85	0.05	0.85				
Cause of mortality								
Heart disease					378	94	106	178
All cancers					698	152	261	285
Tobacco smoking-related[a]					982	223	333	426
Cancer					*425*	*93*	*161*	*171*
Cardiovascular disease & diabetes					*494*	*114*	*145*	*235*
Respiratory diseases					*63*	*16*	*27*	*20*

[a] Tobacco smoking-related mortality consists of: (1) cancers (lung; lip, pharynx and oral cavity; esophagus; stomach; pancreas; larynx; cervix uteri; kidney & renal pelvis; bladder; liver; colon and rectum; and acute myeloid leukemia); (2) cardiovascular diseases (coronary heart disease, rheumatic or pulmonary heart disease, other forms of heart disease, cerebrovascular and other vascular diseases), and metabolic diseases (diabetes mellitus); and (3) respiratory diseases (pneumonia, influenza, tuberculosis, chronic obstructive pulmonary disease) (US HHS 2014).

Table 3
Observed deaths and standardized mortality ratios (SMR) for major causes of death among WTC rescue and recovery workers, compared to US or New York State reference population, 2002–2016 (N = 60,631).

Cause of death (NIOSH major category)	Obs.	Compared to US reference population			Compared to NYS reference population		
		SMR	95% CI		SMR	95% CI	
All	1912	0.43**	0.42	0.45	0.51**	0.49	0.53
Tuberculosis and HIV related disease (01)	14	0.22**	0.12	0.37	0.15**	0.08	0.25
All cancers	698	0.60**	0.55	0.64	0.65**	0.61	0.70
MN of buccal cavity & pharynx (02)	12	0.40**	0.21	0.70	0.46**	0.24	0.80
MN of digestive organs & peritoneum (03)	228	0.64**	0.56	0.73	0.68**	0.60	0.78
MN of respiratory system (04)	150	0.44**	0.37	0.51	0.50**	0.43	0.59
MN of breast (05)	22	0.67	0.42	1.01	0.71	0.44	1.07
MN of female genital organs (06)	11	0.54*	0.27	0.96	0.50*	0.25	0.90
MN of male genital organs (07)	35	0.70*	0.48	0.97	0.77	0.54	1.07
MN of urinary organs (08)	30	0.50**	0.34	0.72	0.57**	0.39	0.82
MN of other and unspecified sites (09)	112	0.64**	0.52	0.76	0.73**	0.60	0.87
Neoplasms of lymphatic & hematopoietic tissues (10)	98	0.96	0.78	1.18	0.96	0.78	1.17
Benign and unspecified neoplasms (11)	12	0.82	0.42	1.43	0.89	0.46	1.55
Diseases of the blood & blood forming organs (12)	<10	0.42**	0.18	0.82	0.51	0.22	1.00
Diabetes mellitus (13)	43	0.27**	0.20	0.37	0.36**	0.26	0.48
Mental psychoneurotic & personality disorders (14)	39	0.45**	0.32	0.61	0.49**	0.35	0.68
Diseases of the nervous system & sense organs (15)	30	0.25**	0.17	0.36	0.39**	0.26	0.55
Diseases of the heart (16)	378	0.39**	0.35	0.43	0.41**	0.37	0.46
Other diseases of the circulatory system (17)	93	0.34**	0.28	0.42	0.44**	0.36	0.55
Diseases of the respiratory system (18)	100	0.35**	0.29	0.43	0.42**	0.34	0.52
Diseases of the digestive system (19)	81	0.32**	0.25	0.40	0.44**	0.35	0.55
Diseases of the skin and subcutaneous tissue (20)	<10	0.44	0.09	1.29	0.49	0.10	1.44
Disease of the musculoskeletal & connective tissue systems (21)	<10	0.28**	0.09	0.66	0.35**	0.11	0.81
Diseases of the genitourinary system (22)	20	0.25**	0.15	0.38	0.37**	0.22	0.57
	22	0.39**	0.24	0.59	0.41**	0.25	0.61
Symptoms and ill-defined conditions (23)	52	0.38**	0.29	0.50	0.72*	0.54	0.94
Transportation injuries (24)	21	0.59*	0.37	0.90	0.66	0.41	1.01
Falls (25)	110	0.47**	0.39	0.57	0.58**	0.48	0.70
Other injury (26)	108	0.50**	0.41	0.60	0.74**	0.61	0.89
Violence (27)	97	0.61**	0.50	0.75	0.90	0.73	1.10
Suicide	11	0.19**	0.10	0.34	0.31**	0.15	0.55
Assault & Homicide	75	0.37**	0.29	0.47	0.43**	0.34	0.54
Other causes (residual and blank codes; 28)							

Abbreviations: World Trade Center (WTC), National Institute for Occupational Safety and Health (NIOSH), confidence interval (CI), malignant neoplasm (MN), observed number of deaths (Obs.).*P < 0.05. **P < 0.01.

of all-cause mortality, smoking-related mortality, and heart disease-related mortality. Working on the pile was also associated with increased risk of all-cause mortality in non-FDNY/non-GRC members and with increased risk of cancer-specific mortality in GRC members. In contrast, we observed that arrival on 9/11 and working on the pile were both associated with decreased mortality risk among FDNY members.

We did not observe excess deaths, overall or for any major cause of death, among responders in this study. We also did not find excess suicide deaths, though a previous study of responders reported excess suicide deaths especially among non-traditional responders (Jordan et al., 2018). The lower-than-expected mortality rate in this combined cohort might be due, at least in part, to a healthy worker effect resulting from the selection of the general population as a comparison group, healthy hire effect and/or healthy worker survivor effect (Kirkeleit et al., 2013). The SMRs might underestimate the true relative risks of WTC exposure, because the general population also includes individuals that are not healthy enough to be in the workforce. The underlying health differences between the comparison groups are likely exacerbated by the fact that there are stringent, pre-employment screenings and a level of fitness and health that must be met to be hired into some of the principal job categories (e.g., firefighters, police) that made up the majority of the combined cohort. We are currently conducting two separate studies using comparable occupational groups as reference populations, including non-WTC exposed firefighters and non-WTC exposed police officers, in an attempt to minimize the healthy worker effect and to help identify whether certain subgroups of responders are at increased mortality risk.

One way to account for the healthy worker effect is through internal comparison analyses. Yet, among FDNY members, a significant reduced risk of mortality was again found in association with higher WTC exposure (i.e., arrival on 9/11, working on the pile). These findings might also reflect a potential bias due to the healthy worker effect given that there are known differences between FDNY members who arrived on 9/11 compared with FDNY members who arrived later. For example, FDNY members arriving on 9/11, compared with those arriving later, were more likely to be firefighters than EMS (Yip et al., 2016). A recent study using the FDNY cohort found that firefighters had statistically significant lower mortality risk than EMS; both groups had similar health access and health care benefits, but the levels of fitness and health required for employment are higher for firefighters (Colbeth et al., 2020). Differences in the types of workers who arrived on 9/11, compared with those arriving at a later date, might also explain the non-significant association between early arrival and mortality risk in

Table 4
Adjusted hazard ratios (AHR) and 95% confidence intervals (CI) for association of date of first arrival at WTC site with mortality of selected specific causes and of all causes combined among WTC rescue and recovery workers.[a]

	AHR (95% CI)			
	All-Cause Mortality (Death = 1912)	Heart Disease Mortality[b] (Death = 378)	Cancer-specific Mortality[b] (Death = 698)	Smoking-related Mortality[b] (Death = 982)
Sex				
Female	ref	ref	ref	ref
Male	1.77 (1.52–2.07)	2.48 (1.67–3.69)	1.32 (1.05–1.68)	1.92 (1.52–2.42)
Race/Ethnicity				
Non-Hispanic White	ref	ref	ref	ref
Non-Hispanic Black	1.28 (1.11–1.47)	1.75 (1.31–2.34)	0.92 (0.71–1.19)	1.33 (1.08–1.62)
Non-Hispanic, other race	0.85 (0.60–1.20)	1.16 (0.57–2.37)	0.88 (0.50–1.57)	1.08 (0.67–1.73)
Hispanic	0.95 (0.82–1.10)	0.97 (0.68–1.39)	0.92 (0.72–1.18)	0.93 (0.75–1.17)
Smoking status at enrollment				
Current	2.45 (2.19–2.75)	3.17 (2.46–4.07)	2.36 (1.95–2.86)	3.55 (3.01–4.19)
Former	1.24 (1.11–1.38)	1.34 (1.03–1.73)	1.21 (1.00–1.45)	1.52 (1.28–1.80)
Never	ref	ref	ref	ref
Missing	1.37 (0.91–2.05)	1.22 (0.54–2.78)	1.41 (0.74–2.67)	1.43 (0.83–2.46)
Date of first arrival at WTC rescue and recovery effort (ref: 9/18/2001 - 6/30/2002) by membership groups				
9/11/2001				
FDNY	0.60 (0.41–0.88)	0.50 (0.23–1.08)	0.87 (0.42–1.81)	0.53 (0.32–0.89)
GRC	1.09 (0.85–1.40)	1.91 (0.98–3.72)	1.06 (0.69–1.61)	1.17 (0.82–1.69)
Non-FDNY/non-GRC	1.32 (1.07–1.62)	1.37 (0.88–2.13)	1.03 (0.72–1.47)	1.39 (1.05–1.845)
9/12/2001				
FDNY	0.71 (0.47–1.08)	0.81 (0.36–1.83)	0.86 (0.39–1.92)	0.77 (0.45–1.34)
GRC	1.18 (0.90–1.54)	1.25 (0.59–2.65)	1.51 (0.98–2.32)	1.19 (0.81–1.75)
Non-FDNY/non-GRC	1.40 (1.14–1.72)	1.42 (0.91–2.20)	1.19 (0.84–1.68)	1.43 (1.09–1.89)
9/13 - 9/17/2001				
FDNY	0.86 (0.57–1.30)	0.61 (0.26–1.43)	1.40 (0.65–3.02)	0.68 (0.39–1.20)
GRC	1.13 (0.86–1.47)	1.37 (0.66–2.84)	1.23 (0.79–1.89)	1.11 (0.76–1.64)
Non-FDNY/non-GRC	1.34 (1.11–1.62)	1.50 (1.01–2.23)	1.13 (0.82–1.54)	1.31 (1.01–1.96)

Abbreviations: World Trade Center (WTC), confidence interval (CI), reference group (ref).
[a] All models included a cross-product term between date of first arrival and cohort membership groups. This cross-product term was statistically significant for all-cause, heart disease and smoking-related mortality, but not for cancer-specific mortality.
[b] Adjusted for competing event, using "eventcode" option.

GRC members. A majority of GRC members arriving on 9/11 were in protective services (primarily police officers as first responders), whereas those arriving later were more likely to be non-police responders such as construction and electrical workers (Woskie et al., 2011). As with firefighters, police officers have more rigorous pre-employment health and fitness requirements and different job training than other types of responders that might make them more resilient to the adverse effects of WTC exposure. In addition, the use of respirators and other personal protective equipment was relatively low among firefighters, police officers and other workers involved in the initial response on 9/11 (Feldman et al., 2004; Buyantseva et al., 2007; Antao et al., 2011), which was unlikely to play a role in our observed findings among FDNY members.

Clinical health services provided by WTC-MMTP might also have affected the mortality risk in FDNY and GRC members. The WTC-MMTP provides no out-of-pocket-cost comprehensive medical monitoring (e.g., examinations, screening tests and diagnostic procedures) and treatment to eligible rescue and recovery workers (for certified, WTC-related conditions). Several studies have evaluated the impact of WTC-MMTP monitoring and heath care on WTC-related health problems (Santiago-Colón et al., 2020; Azofeifa et al., 2021; Smith et al., 2021), and several benefits have been reported, including improved cancer survival in the combined cohort of responders (Goldfarb et al., 2021b, 2021c). A recent cancer survival study of those with a cancer diagnosis in the combined cohort of responders demonstrated that cancer patients among FDNY and GRC members had significant lower mortality (all-cause or cancer-specific) compared to NYS cancer patients; but there was no difference in mortality risk between the non-FDNY/non-GRC group (i.e., those who were not enrolled in the WTC-MMTP) and the NYS cancer patients (Goldfarb et al., 2021b). Despite the health benefits of WTC-MMTP, the observed higher cancer-specific mortality risk in GRC members who worked on the pile (*cf*. not on the pile) further supports the need for continued monitoring of mortality risk in the WTC-exposed population, as well as future mortality studies focusing on the effect of activities conducted on or adjacent to the debris pile at the WTC site (Woskie et al., 2011).

In the present study, higher WTC exposure was associated with increased all-cause, heart disease and smoking-related mortality risk among non-FDNY/non-GRC members, a subset of WTC responders who were not enrolled in the WTC Health Registry (Farfel et al., 2008). The increased risk in all-cause mortality among non-FDNY/non-GRC members with high WTC exposure is consistent with our previous mortality study of responders in the WTCHR cohort (Jordan et al., 2018), suggesting that non-FDNY/non-GRC members might be a particularly vulnerable population, as they are not traditional first responders like firefighters or police. While the WTCHR does not provide medical monitoring and treatment (Farfel et al., 2008; Azofeifa et al., 2021), it does conduct extensive outreach to encourage its enrollees to apply for medical care in WTC-MMTP (Welch et al., 2014; Petrsoric et al., 2018). A future study comparing non-FDNY/non-GRC members with the WTCHR workers who enrolled in the WTC-MMTP may further our understanding of factors associated with increased mortality risk and help identify target groups for mortality risk reduction.

There main strength of this mortality study was the maximum sample size (and thereby improved statistical power) which enabled the identification of a subgroup of cohort members that may need closer evaluation of their disease burden and health care access, to identify and strategize efforts to reduce mortality risk.

This study is also subject to some limitations. Most of responders voluntarily enrolled in various years. To lessen self-selection bias that might lead to overestimation of mortality, we excluded those who were enrolled after 2010, lagged the start of follow-up time by one year after

Table 5
Adjusted hazard ratios (AHR) and 95% confidence intervals (CI) for association of working on pile with mortality of selected specific causes and of all causes combined among WTC rescue and recovery workers.[a]

	AHR (95% CI)			
	All-Cause Mortality (Death = 1912)	Heart Disease Mortality[b] (Death = 378)	Cancer-specific Mortality[b] (Death = 698)	Smoking-related Mortality[b] (Death = 982)
Sex				
Female	ref	ref	ref	ref
Male	1.82 (1.56–2.12)	2.57 (1.75–3.80)	1.35 (1.07–1.71)	2.0 (1.6–2.5)
Race/Ethnicity				
Non-Hispanic White	ref	ref	ref	ref
Non-Hispanic Black	1.31 (1.14–1.51)	1.77 (1.33–2.36)	0.93 (0.71–1.20)	1.35 (1.11–1.65)
Non-Hispanic, other race	0.86 (0.60–1.22)	1.16 (0.57–2.35)	0.88 (0.49–1.56)	1.09 (0.68–1.75)
Hispanic	0.97 (0.83–1.12)	0.97 (0.69–1.38)	0.93 (0.72–1.18)	0.94 (0.76–1.17)
Smoking status at enrollment				
Current	2.47 (2.21–2.77)	3.15 (2.46–4.04)	2.36 (1.95–2.86)	3.58 (3.03–4.22)
Former	1.24 (1.11–1.39)	1.33 (1.03–1.72)	1.21 (1.01–1.46)	1.53 (1.30–1.81)
Never	ref	ref	ref	ref
Missing	1.42 (0.97–2.07)	1.15 (0.49–2.70)	1.66 (0.90–3.08)	1.77 (1.05–2.99)
Performed tasks on WTC pile (ref: not on pile) by membership groups				
FDNY	0.57 (0.45–0.73)	0.42 (0.25–0.69)	0.52 (0.35–0.78)	0.58 (0.41–0.83)
GRC	1.18 (0.99–1.40)	1.13 (0.73–1.76)	1.39 (1.05–1.84)	1.10 (0.85–1.43)
Non-FDNY/non-GRC	1.25 (1.04–1.50)	1.42 (0.98–2.05)	0.97 (0.68–1.37)	1.20 (0.93–1.55)

Abbreviations: World Trade Center (WTC), confidence interval (CI), reference group (ref).

[a] All models included a cross-product term between date of first arrival and cohort membership groups. This cross-product term between worked on pile and cohort membership in each of the multivariable models was statistically significant.

[b] Adjusted for competing event, using "eventcode" option.

enrollment and removed any deaths that occurred within the first year after enrollment from the analytic sample. Our observed internal comparison findings may also be potentially biased by unmeasured/unavailable confounding factors that are linked to WTC exposure and mortality risk, such as comorbidities or residual confounding due to imperfect measurement of covariates, such as pack-years of smoking. The lack of data on disease burden or morbidity in this combined cohort is due to the inconsistent approaches in collecting data on history of comorbidities across the three exposed cohorts. To mitigate the potential bias in mortality estimates, we may consider using data on self-rated health in future studies. Self-ratings of health have been well documented as a valid measure of health status (Jylhä, 2009) and a predictor of mortality (Idler and Benyamini, 1997; Benyamini, 2011).

5. Conclusion

Despite the limitations, our findings are reassuring in showing no excess mortality overall or from specific causes among responders. Nonetheless, there is some evidence of increased risk of mortality associated with WTC exposure among highly exposed responders, especially non-FDNY/non-GRC members who were not enrolled in the WTC-MMTP. These findings might suggest that to avoid excess mortality, future disaster responses, whenever possible, should favor the inclusion of responders pre-screened for health, fitness, and ability to participate in post-disaster health programs. Although we have not observed excess deaths among responders, compared to the U.S. or NYS populations, longer term follow-up of responders is warranted. Observed findings of an increased mortality risk in subgroups highlight the need for continued evaluation, monitoring and treatment of the WTC-exposed population to reduce disease burden over time, and ultimately to prevent premature deaths among this population.

Author contributions

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Human subjects review

This study was approved by the Institutional Review Boards (IRB) of the Albert Einstein College of Medicine, United States; New York City Department of Health and Mental Hygiene, New York State, United States; FDNY and New York State Department of Health, United States. IRBs of Icahn School of Medicine at Mount Sinai and Stony Brook University, United States, granted exemptions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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