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Effect of World Trade Center Health Program on mortality among 9/11 responders

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ABSTRACT

Purpose: The World Trade Center Health Program (WTCHP) plays a critical role in medical monitoring and treatment to those exposed to the terrorist attacks of September 11, 2001 (9/11). We investigated the association of WTCHP membership with mortality risk among 9/11 responders while controlling for comorbidities using inverse probability weighting.

Methods: We prospectively analyzed 28,430 9/11 responders, followed from the time of their enrollment into the WTCHP or the WTC Health Registry, through 2020. NDI linkage provided death data. Non-cancer comorbidities were self-reported physician-diagnosis and cancer was identified through cancer registry linkage. We estimated the adjusted hazard ratio (aHR) with 95 % confidence interval (CI) for the association between WTCHP membership and all-cause and cause-specific mortality using Cox proportional hazards models and cause-specific hazard regression models, respectively.

Results: A total of 1657 deaths were identified over 444,425 person-years of follow-up. Compared to non-members, WTCHP members had a lower risk of all-cause mortality (aHR=0.87; 95 % CI=0.77–0.98) and smoking-related mortality (aHR=0.83; 0.69–0.99) after adjusting for demographics, WTC exposure, and weights of comorbidities. With the membership-sex interaction included, reduced risk of all-cause mortality remained statistically significant among males only (aHR=0.85; 0.75–0.96). Cancer- and heart-related mortality risk were not significantly different between WTCHP members and non-members.

Conclusions: This study found that WTCHP membership may reduce risks of all-cause and smoking-related mortality among 9/11 responders, even after accounting for underlying medical conditions, underscoring the importance of comprehensive health monitoring and treatment services for disaster-relief workers.

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Introduction

The World Trade Center (WTC) Health Program (WTCHP) is a long-term, federally funded health program that provides medical monitoring and treatment for specific WTC exposure-related medical conditions included in the aerodigestive, cancer, and mental health categories to enrolled members directly affected by the September 11, 2001 terrorist attacks on the WTC in New York City (NYC) [1, 2]. In 2020, a total of 76,543 responders were enrolled in the WTCHP, of which 43,503 had at least one certified WTC-related health condition [1].

Studies of 9/11 responders by different entities, including the Fire Department of the City of New York (FDNY), the General Responder Cohort (GRC) at the Icahn School of Medicine at Mount Sinai, and the WTC Health Registry (WTCHR) at the New York City Department of Health and Mental Hygiene, have reported similar long-term health effects associated with a high level of WTC exposure. This includes increased risk of respiratory diseases, gastroesophageal acid reflux (GERD), cancer (e.g., prostate cancer), cardiovascular conditions, and mental health disorders (e.g., post-traumatic stress disorder (PTSD), and depression) among 9/11 responders [3–10].

Collaborative studies using a de-duplicated combined cohort of 69,100 9/11 responders from FDNY, GRC, and WTCHR [11] have suggested the potential benefit of longer cancer survival [12] and lower all-cause mortality risk among those who were members of the WTCHP at FDNY or GRC compared to 9/11 responders who were not members of FDNY or GRC [13]. However, these prior studies [12, 13] were unable to adjust for comorbidities because the data on comorbidities were not collected using consistent questions or methods across the three cohorts, preventing the data from being harmonized for analysis. As a result, it remains unclear whether the observed mortality benefits are attributable to WTCHP membership itself or to unmeasured differences in baseline health status.

In this study, we addressed this gap by comparing mortality risk between WTCHP members and non-members, using additional data from the WTCHR. The WTCHR, one of the three contributing cohorts to the combined cohort of 9/11 responders, offers a unique advantage in having consistently collected comorbidity information across periodic follow-up surveys. This cohort also includes a comparison group of 9/11 responders who were not members of FDNY or GRC cohorts, allowing for comparisons in mortality risk over time, and enhancing internal validity and interpretability.

Materials and methods

Data source and study population

A combined cohort of 69,100 WTC rescue, recovery and cleanup workers or volunteers (hereafter, 9/11 responders) was established from three existing WTC-exposed cohorts: the FDNY (n = 16,221), the GRC at the Icahn School of Medicine at Mount Sinai (n = 33,427), and the WTCHR in the NYC Department of Health and Mental Hygiene (n = 29,372). Acting as an honest broker, the New York State (NYS) Cancer Registry applied a specified pooling algorithm to identify and remove duplicate individuals, thereby creating a combined cohort for analysis [11].

We limited the present study to the sub-set from the established combined cohort of 9/11 responders who were originally submitted by the WTCHR (n = 29,372). We selected this group for analysis because it is the only group for which comorbidity data were collected during each WTCHR survey wave consistently. This subset not only includes validated information on cohort membership status (FDNY/GRC vs. non-FDNY/non-GRC), but also the membership enrollment date, obtained through linkage across the three cohorts conducted by the NYS Cancer Registry. We excluded the rest of the combined cohort due to the lack of consistent comorbidity data.

We further restricted the sample of 29,372 to those aged 18 years or older on 9/11 and who had complete information on covariates. To minimize selection bias, those who died or turned 85 years or older within the first year of enrollment were excluded (n = 49). We further excluded responders who were under 18 years old on 9/11 (n = 150), those with unknown smoking status (n = 268), unknown race/ethnicity (n = 417) status, and those who were proxy respondents for incapacitated individuals (n = 58). The final analytic sample included 28,430 9/11 responders who were involved in rescue, recovery and clean-up efforts.

WTCHP membership status

Cohort membership status was previously validated in the combined cohort, which is the exposure of interest in this study. For this study, WTCHR enrollees who overlapped with the FDNY or GRC cohorts at any time through 2016 were classified as WTCHP members (n = 9467), while those who did not overlap with the FDNY or GRC cohorts during this same period were classified as WTCHP non-members. This classification approach was used because both the FDNY and GRC cohorts are part of the WTCHP, which provides medical monitoring and treatment to enrolled members. In contrast, the WTCHR does not offer medical examinations or clinical treatment to its members.

Ascertainment of deaths

Vital status through December 31, 2020, was ascertained via linkage with the National Death Index (NDI) maintained by the Centers for Disease Control and Prevention (CDC). The NDI provided the underlying causes of death using the International Classification of Disease, 10th version (ICD-10), which we classified into smoking-, cancer-, and heart-related mortality. We used the 119-cause rate file from NIOSH life table analysis software (LTAS.NET) [14] to define cancer-specific death if the underlying cause of death was under major categories #2 through #10, and heart-related death if the underlying cause of death was under major category #16. We defined smoking-related mortality if the underlying cause of death included any of the following: (a) 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); (b) 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 (c) respiratory diseases (pneumonia, influenza, tuberculosis, chronic obstructive pulmonary disease) [15].

Covariates

Comorbidities

Comorbidity data were derived from WTCHR surveys and cancer registry linkage. Comorbidities consisted of the following conditions: aerodigestive disorder, mental health, cancer, and cardiovascular diseases. Aerodigestive conditions included asthma, reactive airways dysfunction syndrome (RADS), pulmonary fibrosis (PF), emphysema, chronic obstructive pulmonary disease (COPD), GERD, chronic bronchitis, and other lung diseases. Due to small case counts, RADS, PF, emphysema, and COPD were grouped into a single category under aerodigestive conditions. Mental health conditions included post-traumatic stress disorder (PTSD) and depression. Cardiovascular conditions included angina, stroke, heart attack, and other cardiovascular conditions. Cancer diagnosis was defined as any primary invasive malignant tumor, including in situ bladder cancers diagnosed through 2015; and identified through linkages with 10 state cancer registries in the U.S.

The information on health conditions other than cancer was based on self-reported clinician diagnoses. During the WTCHR baseline survey in 2003–2004 and three subsequent follow-up surveys during 2006–2016, participants were asked, “Have you ever been told by a doctor or other

health professional that you had any of these conditions:", and "What year were you first told by a doctor or other health professional that you had this condition?". We used the responses to these questions to determine comorbidity status.

For each comorbidity, individuals were classified into 4 categories: (a) diagnosed post-9/11, (b) diagnosed pre-9/11, c) no diagnosis, and d) unknown/missing diagnosis. For conditions reported across multiple survey waves, we used the first report of year of diagnosis to determine whether the condition was diagnosed before or after 9/11/2001. The unknown or missing diagnosis was defined as a reported medical condition with either an unknown year of diagnosis or a missing response to the medical condition question.

Other covariates

Data on WTC exposure and baseline demographics were obtained from the established combined cohort of the 9/11 responders [11]. Covariates included gender, race/ethnicity, smoking status, and WTC exposure. These data were obtained from the cohort in which the participant first enrolled (FDNY, GRC, or WTCHR) [11]. The WTC exposure variables included: a) date of first arrival to the WTC rescue and recovery effort (categorized as: on September 11, on September 12, between September 13 and 17, between September 18, 2001, and June 30, 2002, or unknown), and b) whether performed tasks on the WTC debris piles from the collapsed towers (categorized as: yes, no, or unknown).

Statistical analysis

We compared the characteristics of the study sample by WTCHP membership status using the chi-squared test. We also assessed the magnitude of balance in the distribution of comorbidities between WTCHP members and non-members, using the standardized mean differences [16] with values below 0.10 indicating acceptable balance, before and after the weighting. We then used Cox proportional hazards regression to estimate hazard ratios (HRs) and 95 % confidence intervals (CIs) for the association between WTCHP membership status and all-cause mortality. For analysis of cause-specific mortality, we used cause-specific hazard regression models to account for competing risks [17].

In all Cox models, age was used as the time scale, rather than time-on-study, to minimize bias with respect to age and to allow for non-linear associations between age and mortality [18]. Follow-up time started one year after the earlier enrollment date to either WTCHP or WTCHR (to minimize selection bias) until age at death or censoring (age 85 years or age on December 31, 2020), whichever came earlier. To account for the time-dependent nature of WTCHP membership status, given that some participants initially enrolled in the WTCHR and later joined FDNY or GRC over follow-up (n = 4315), we structured the data using the counting process format [19]. This approach allows for WTCHP membership status to change over follow-up by splitting an individual's observation into two risk intervals when transitioning from non-member to member. We examined associations between WTCHP membership and mortality in unadjusted models and in models adjusted for the covariates. In Model 1, we adjusted for baseline characteristics, including gender, race/ethnicity, smoking status, date of first arrival at WTC site, and working on the WTC piles, all treated as fixed effects. In Model 2, we adjusted for the same covariates as fixed effects in Model 1, and we applied stabilized inverse probability weights (IPW) to address the imbalance in comorbidities between WTCHP members and non-members. IPW was used to adjust for commodities due to the large number of medical conditions that needed to be accounted for. To compute the IPW, we fitted a logistic regression model in which WTCHP membership status was predicted by the set of 10 comorbidities. We then used the model's predicted probabilities to calculate stabilized IPW [20].

We tested the proportional hazards assumptions with Schoenfeld residuals methods [21] and found no violations. However, we found evidence of multiplicative effect modification by gender for the association between WTCHP membership status and all-cause mortality. Therefore, in addition to the main models described above, we fitted models that included an interaction term between WTCHP membership status and gender. We also examined associations stratified by gender and found consistent results from the interaction term model. Therefore, we only present the gender-specific associations from the interaction term model.

Differential attrition bias is a concern in studies utilizing survey data across multiple time points. Among the analytic sample (N = 28,430), response rates declined across the three WTCHR follow-up surveys, with 71 % in 2006–07, 66 % in 2011–2012, and 56 % in 2015–2016. WTCHP members consistently had higher response rate than non-members over three follow-up surveys ($p < 0.001$). To address potential bias arising from attrition and incomplete self-reporting of comorbidities, given that not all enrollees participated in follow-up surveys between 2006 and 2016, we conducted two sensitivity analyses. One, we restricted comorbidity data to information collected at baseline survey (2003–2004); another, we limited the sample to enrollees who completed at least one of the three follow-up surveys.

We used SAS version 9.4 (SAS Institute, Cary, NC) to conduct data analysis. We also used R version 4.4.1 (The R Foundation for Statistical Computing, Vienna, Austria) to compute standardized difference for comorbidities distribution using the "tableone" package [16]. All statistical tests were two-sided, and p-values < 0.05 were considered statistically significant.

Results

We identified 424 deaths over 155,941 person-years among WTCHP members (n = 9467) and 1233 deaths over 288,484 person-years among non-members (n = 18,963). Compared to non-members, WTCHP members were more likely to be male, in the age groups of 30–39 and 40–49; non-Hispanic White, never smokers, and to have arrived earlier at the WTC site and performed tasks on the pile (Table 1). In addition, WTCHP members had a statistically significantly higher proportion of post-9/11 comorbidities compared to non-WTCHP members (Table 2). However, non-members had significantly higher pre-9/11 diagnoses of certain conditions, including asthma, depression, and cardiovascular conditions. Prior to weighting, standardized differences between WTCHP members and non-members exceeded 20 % for seven of the ten conditions (the exceptions were cancer and two cardiovascular conditions); there were no imbalances observed after weighting.

Overall, WTCHP members had a lower risk of all-cause mortality (Model 1: aHR = 0.80, 95 % CI = 0.71–0.91) compared to non-members after adjusting for demographics, smoking status, and 9/11 exposure (Table 3). This association remained statistically significant after adjusting for comorbidities by IPW in Model 2 (aHR = 0.87, 95 % CI = 0.77–0.98). When we included an interaction term between membership and gender in the model, this association was statistically significant among men (Model 2: aHR = 0.85, 95 % CI = 0.75–0.96), but not among women (Model 2: aHR = 1.16, 95 % CI = 0.80–1.68).

In analyses of cause-specific mortality (Table 3), WTCHP members had a lower risk of smoking-related mortality compared to non-members, after adjusting for demographics, smoking status, and 9/11 exposure (Model 1: aHR = 0.78, 95 % CI = 0.64–0.99). This association remained statistically significant after adjusting for comorbidities by IPW in Model 2 (aHR = 0.83, 95 % CI = 0.69–0.99); and was not modified by gender (Model 2: p-value for interaction term=0.65). The association between WTCHP membership and heart-related mortality was statistically significant after adjusting the fixed-effect covariates only (Model 1: aHR= 0.76, 95 % CI= 0.58–0.99), but was no longer statistically significant after applying the IPW adjusting for comorbidities (Model 2: aHR= 0.87, 95 % CI= 0.67–1.13). WTCHP membership status was not associated with cancer-specific mortality. Results from

Table 1
Characteristics of the study sample by WTC Health Program (WTCHP) membership status (N = 28,430).

	Overall		WTCHP Membership Status			
			Yes		No	
Characteristics	No	%	No.	%	No.	%
Total	28,430	100	9467	33.3	18,963	66.7
Age on 9/11, years						
18–29	4120	14.5	1025	10.8	3095	16.3
30–39	9603	33.8	3721	39.3	5882	31.0
40–49	9306	32.7	3437	36.3	5869	31.0
50–59	4246	14.9	1114	11.8	3132	16.5
60–80	1155	4.1	170	1.8	985	5.2
Sex						
Male	22,237	78.2	8485	89.6	13,752	72.5
Female	6193	21.8	982	10.4	5211	27.5
Race/Ethnicity						
Non-Hispanic White	20,738	72.9	7231	76.4	13,507	71.2
Non-Hispanic Black	2845	10.0	743	7.8	2102	11.1
Non-Hispanic, others	886	3.1	179	1.9	707	3.7
Hispanic	3961	13.9	1314	13.9	2647	14.0
Smoking Status						
Current	4918	17.3	1526	16.1	3392	17.9
Former	7325	25.8	2231	23.6	5094	26.9
Never	16,187	56.9	5710	60.3	10,477	55.2
Date of first arrival at WTC rescue and recovery effort						
9/11/2001	8019	28.2	4561	48.2	3458	18.2
9/12/2001	5538	19.5	2003	21.2	3535	18.6
During 9/13–9/17/2001	5972	21.0	1740	18.4	4232	22.3
After 9/17/2001	8515	30.0	937	9.9	7578	40.0
Unknown	386	1.4	226	2.4	160	0.8
Performed tasks on WTC pile						
Yes	9353	32.9	5366	56.7	3987	21.0
No	18,895	66.5	4079	43.1	14,816	78.1
Unknown	182	0.6	22	0.2	160	0.8

the two sensitivity analyses were similar to the main findings presented in Table 3.

Discussion

This study provides new evidence on the association between WTCHP membership and mortality, by presenting the first analysis to account for differences in comorbidities between WTCHP members and non-members. We found WTCHP membership was independently associated with lower all-cause mortality through 2020 among 9/11 responders, with smoking-related deaths contributing substantially to this reduction. Furthermore, we observed that the association was mainly observed in men, with no significant mortality reduction seen in women. Our findings support the study hypothesis that WTCHP membership is associated with lower mortality risk and are consistent with previous research on all-cause and smoking-related mortality in the WTC population. Importantly, this study provides consistent evidence that the observed survival benefit persists even after accounting for underlying medical conditions, which were not considered in earlier analyses.

When we examined cause-specific mortality, WTCHP membership was found to be associated with reduced smoking-related mortality. Smoking is a well-established risk factor for numerous chronic conditions, including respiratory diseases, cardiovascular disease, and several types of cancer [22–25]. The observed lower smoking-related mortality may reflect differences in smoking histories between WTCHP members compared to non-members. For example, previous studies have shown that FDNY personnel (who make up a large proportion of WTCHP members) have lower smoking rates compared to both other firefighter populations and the general U.S. population [8]. However, because we

Table 2
Distribution of comorbidities by WTC Health Program (WTCHP) membership status (N = 28,430).

Comorbidity*	WTCHP Membership Status				Standardized Difference†	
	Yes		No			
	No.	%	No.	%	Before weighting	After weighting
Aerodigestive Disorders						
Asthma						
Post-911 diagnosis	2111	22.3	1574	8.3	0.343	0.002
Pre-911 diagnosis	893	9.4	2289	12.1		
None	6355	67.1	14,989	79.0		
Unknown‡	108	1.1	111	0.6		
RADS, Emphysema/ COPD and/or PF					0.381	0.003
Post-911 diagnosis	1841	19.4	1072	5.7		
Pre-911 diagnosis	170	1.8	226	1.2		
None	7264	76.7	17,520	92.4		
Unknown‡	192	2.0	145	0.8		
Chronic bronchitis					0.248	0.005
Post-911 diagnosis	1476	15.6	1418	7.5		
Pre-911 diagnosis	398	4.2	714	3.8		
None	6260	66.1	12,733	67.1		
Unknown‡	1333	14.1	4098	21.6		
Other Lung disease					0.208	0.004
Post-911 diagnosis	450	4.8	305	1.6		
Pre-911 diagnosis	99	1.0	163	0.9		
None	6492	68.6	11,963	63.1		
Unknown‡	2426	25.6	6532	34.4		
Gastroesophageal reflux disease (GERD)					0.421	0.005
Post-911 diagnosis	3087	32.6	2326	12.3		
Pre-911 diagnosis	304	3.2	628	3.3		
None	3851	40.7	9658	50.9		
Unknown‡	2225	23.5	6351	33.5		
Mental Health Conditions						
Posttraumatic stress disorder (PTSD)					0.308	0.005
Post-911 diagnosis	1923	20.3	1730	9.1		
Pre-911 diagnosis	446	4.7	757	4.0		
None	5914	62.5	12,542	66.1		
Unknown‡	1184	12.5	3934	20.7		
Depression					0.230	0.007
Post-911 diagnosis	1830	19.3	2549	13.4		
Pre-911 diagnosis	551	5.8	1503	7.9		
None	5904	62.4	10,885	57.4		
Unknown‡	1182	12.5	4026	21.2		
Cancer§					0.055	0.005
Post-911 diagnosis	680	7.2	1019	5.4		
Pre-911 diagnosis	92	1.0	214	1.1		
None	8695	91.8	17,730	93.5		
Cardiovascular Disease						

(continued on next page)

Table 2 (*continued*)

Comorbidity*	WTCHP Membership Status				Standardized Difference†	
	Yes		No			
Cardiovascular conditions (angina, stroke, heart attack)					0.096	0.012
Post-911 diagnosis	637	6.7	1161	6.1		
Pre-911 diagnosis	133	1.4	428	2.3		
None	8575	90.6	17,172	90.6		
Unknown‡	122	1.3	202	1.1		
Other cardiovascular conditions					0.065	0.008
Post-911 diagnosis	485	5.1	752	4.0		
Pre-911 diagnosis	92	1.0	373	2.0		
None	8807	93.0	17,740	93.6		
Unknown‡	83	0.9	98	0.5		

Abbreviations: Reactive airway disease (RADS), Chronic obstructive pulmonary disease (COPD), Pulmonary fibrosis (PF).

* All, except for cancer, were self-reported clinician-diagnosed health conditions. The year of diagnosis was based on the diagnosis year that was first reported over the period from September 11, 2001 through 2015.

† This was used to quantify the magnitude of the difference between WTCHP and non-WTCHP groups. Standardized difference above 0.10 suggests group imbalance.

‡ Included missing or condition with unknown year of diagnosis.

§ Referred to all reportable cancers that were identified from 10 state cancer registries via linkages.

adjusted for smoking status at the time of WTCHR enrollment, the observed lower smoking-related mortality is unlikely to be fully explained by differences in smoking prevalence. Instead, the lower smoking-related mortality may reflect better healthcare access among WTCHP members, and the effectiveness of targeted interventions offered by the WTCHP. For example, the WTCHP has included smoking cessation support as part of its broader health monitoring and treatment services, which may have contributed to reduced tobacco use over time [26]. These findings suggest that the WTCHP may be improving long-term health outcomes not only through early detection and treatment, but also by facilitating behavior change through preventive care and health promotion.

We did not observe statistically significant differences in heart-related mortality or cancer-specific mortality between WTCHP members and non-members. The lack of association for heart-related mortality may be because cardiovascular conditions are not currently covered by the WTCHP, potentially limiting the program's ability to influence cardiovascular outcomes. Similarly, unlike aerodigestive and mental health conditions, cancer was not initially covered under the James Zadroga 9/11 Health and Compensation Act of 2010 and was only officially added in 2012 [27]. As a result, cancer-related services were not available at no out-of-pocket cost to WTCHP members during the early years of the WTCHP. Additionally, most cancer diagnoses in this cohort occurred after 9/11, which may suggest that there has not been sufficient follow-up time for long-term mortality outcomes to emerge. Increased cancer screening following WTC dust exposure that contained carcinogens may have also led to earlier cancer detection and treatment across the entire WTC-exposed population, potentially minimizing differences in cancer-related mortality between WTCHP members and non-members. Furthermore, potential heterogeneity in cancer types, with varying prognoses and treatment responses, may have further limited our ability to identify significant differences in cancer-related mortality between WTCHP members and non-members. Taken together, these considerations highlight the importance of continued follow-up and more granular analyses to better understand the long-term effects of WTCHP membership on cancer-specific outcomes.

Table 3
Association of WTC Health Program membership status with all-cause, and selected cause-specific mortality.

Mortality	No. of deaths	Hazard ratio (95 % Confidence Interval)		
		Unadjusted	Adjusted (Model 1)[a,c]	Adjusted (Model 2)[b,c]
All-cause mortality				
Overall	1657	0.91 (0.81, 1.02)	0.80 (0.71, 0.91)	0.87 (0.77, 0.98)
Male	1429	0.79 (0.70, 0.89)	0.78 (0.68, 0.88)	0.85 (0.75, 0.96)
Female	228	1.30 (0.90, 1.88)	1.12 (0.77, 1.63)	1.16 (0.80, 1.68)
P-value for interaction term		0.012	0.061	0.118
Smoking-related mortality§				
Overall	784	0.87 (0.74, 1.03)	0.78 (0.64, 0.99)	0.83(0.69, 0.99)
Male	681	0.78 (0.66, 0.93)	0.78 (0.64, 0.95)	0.84 (0.69, 1.02)
Female	103	0.83 (0.43, 1.59)	0.72 (0.37, 1.38)	0.71 (0.37, 1.39)
P-value for interaction term		0.868	0.799	0.646
Cancer-specific mortality				
Overall	559	0.91 (0.75, 1.10)	0.90 (0.72, 1.12)	0.90 (0.72, 1.12)
Male	467	0.81 (0.66, 0.99)	0.86 (0.68, 1.08)	0.85 (0.68, 1.07)
Female	92	1.35 (0.76, 2.39)	1.35 (0.76, 2.40)	1.43 (0.81, 2.53)
P-value for interaction term		0.097	0.145	0.095
Heart disease-related mortality				
Overall	365	0.90 (0.71, 1.14)	0.76 (0.58, 0.99)	0.87 (0.67, 1.13)
Male	330	0.79 (0.62, 1.01)	0.77 (0.58, 1.01)	0.88 (0.67, 1.15)
Female	35	0.70 (0.21, 2.28)	0.60 (0.18, 1.98)	0.74 (0.24, 2.25)
P-value for interaction term		0.841	0.693	0.758

* Model 1: Adjusted for race/ethnicity, smoking status, date of first arrival at WTC site, and whether worked on the debris pile anytime during the 10-month WTC rescue, recovery and cleanup effort.

† Model 2: Applied the weights of comorbidities to Model 1.

‡ Gender was only included in Model 1 and Model 2 when we estimated adjusted HR and 95 % CI for the overall sample.

§ Not exclusive: contains some of the heart disease- and cancer-related deaths.

The present study has several strengths, most notably our control for multiple comorbidities using a rigorous weighting method. Moreover, to provide a more accurate assessment of mortality risk associated with WTCHP membership, we accounted for the time-dependent nature of WTCHP membership status using the counting process format. In addition, WTCHP membership was identified from FDNY and GRC cohorts via linkage with the WTCHR data and deduplication by the NYS cancer registry as an honest broker, ensuring the validity of the WTCHP membership status [11].

Despite the robustness of our methodology in assessing morality risk associated with WTCHP membership, some limitations should be considered. First, we were unable to assess how WTCHP utilization may have influenced outcomes among enrolled members because data on frequency of WTCHP visits and services received during the study period were not available in the combined cohort. Second, information on physical and mental comorbidities, except for cancer diagnoses, was self-reported. The lack of clinical confirmation of non-cancer

comorbidities introduces the possibility of misclassification and incomplete control for confounding. Attrition over the three WTCHR follow-up surveys may also have contributed to differential misclassification of comorbidities, given that drop-out rates were higher in non-members compared to WTCHP members over time. However, our sensitivity analyses provided consistent results with our main findings. Moreover, because non-cancer comorbidities were based on self-reported physician diagnoses, undiagnosed conditions were not captured. As a result, our data may partly reflect differences in healthcare access between WTCHP members and non-members, given that members have greater access to healthcare services through the WTCHP. Nevertheless, our findings indicate that while under-reporting of health conditions among non-members is possible, it is unlikely to fully account for the observed differences in mortality risk. Another limitation is that some of the WTCHP non-members could have been enrolled into FDNY or GRC cohorts after 2016, or into the WTCHP through entities outside of FDNY or GRC [28]. However, such potential misclassification of WTCHP membership status is expected to bias the estimates of mortality risk towards null. Lastly, while multiple comparisons across the three cause-specific mortality outcomes could lead to statistically significant findings by chance, the observed reduction in all-cause mortality suggests that such comparisons are unlikely to bias our results.

Conclusions

The present study provides evidence of a significant reduction in all-cause and smoking-related mortality among members of the WTCHP. These survival benefits remained after accounting for differences in comorbidities over a decade of follow-up, suggesting that the WTCHP itself may offer a protective advantage. Extrapolating the findings of this study to the 76,543 WTCHP responder members as of 2020 [1], we estimate that continuing the WTCHP could lead to approximately 720 fewer deaths over the next 10 years. These findings highlight the potential value of long-term, comprehensive health monitoring and treatment services for disaster-relief responders exposed to environmental and occupational hazards. Further investigation is needed to clarify the mechanisms driving this protective association, to identify potential population subgroups that may benefit most from the program, and to assess longer-term outcomes as additional follow-up data become available.

Human subjects review

This study was reviewed and approved by the Biomedical Research Alliance of New York (BRANY), serving as the single Institutional Review Board (IRB) for this project [IRB protocol number: 22–08–614–1285]. All human subject research procedures followed ethical guidelines in accordance with federal regulations and institutional policies.

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CRediT authorship contribution statement

Hall Charles B: Writing – review & editing. **Paolo Boffetta:** Writing – review & editing. **Farfel Mark R:** Resources, Writing – review & editing. **Tabassum Insaf:** Resources, Writing – review & editing. **Rachel Zeig-Owens:** Data curation, Writing – review & editing, Resources. **Shapiro Moshe Z:** Data curation, Writing – review & editing. **Kehm Rebecca:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Baozhen Qiao:** Data curation, Methodology, Writing – review & editing. **Cone James E:** Writing – review & editing. **Todd Andrew C:** Writing – review & editing, Resources. **Jiehui Li:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Goldfarb David G:** Data curation, Writing – review & editing. **Afroza Parvin:** Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.

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 are available upon reasonable request to the corresponding author once permission is granted by the United States National Death Index (NDI) that supplied the mortality data, and the request is approved by the Principal Investigators of the original cohorts and the steering committee for the combined cohort in accordance with the official data sharing plan.

References

[1] Azofeifa A, Martin GR, Santiago-Colón A, Reissman DB, Howard J. World Trade Center health program - United States, 2012-2020. MMWR Surveill Summ 2021;70(4):1–21.
[2] Calvert GM, Anderson K, Cochran J, Cone JE, Harrison DJ, Haugen PT, et al. The World Trade Center health program: an introduction to best practices. Arch Environ Occup Health 2023;78(4):199–205.
[3] Li J, Brackbill RM, Stellman SD, Farfel MR, Miller-Archie SA, Friedman S, et al. Gastroesophageal reflux symptoms and comorbid asthma and posttraumatic stress disorder following the 9/11 terrorist attacks on World Trade Center in New York City. J Am Coll Gastroenterol | ACG 2011;106(11):1933–41.
[4] Wisnivesky JP, Teitelbaum SL, Todd AC, Boffetta P, Crane M, Crowley L, et al. Persistence of multiple illnesses in World Trade Center rescue and recovery workers: a cohort study. Lancet 2011;378(9794):888–97.
[5] Bromet EJ, Hobbs MJ, Clouston SAP, Gonzalez A, Kotov R, Luft BJ. DSM-IV post-traumatic stress disorder among World Trade Center responders 11–13 years after the disaster of 11 September 2001 (9/11). Psychol Med 2016;46(4):771–83.
[6] Yip J, Webber MP, Zeig-Owens R, Vossbrinck M, Singh A, Kelly KJ, et al. FDNY and 9/11: Clinical services and health outcomes in World Trade Center-exposed firefighters and EMS workers from 2001 to 2016. Am J Ind Med 2016;59(9):695–708.
[7] Sloan NL, Shapiro MZ, Sabra A, Dasaro CR, Crane MA, Harrison DJ, et al. Cardiovascular disease in the World Trade Center health program general responder cohort. Am J Ind Med 2021;64(2):97–107.
[8] Webber MP, Singh A, Zeig-Owens R, Salako J, Skerker M, Hall CB, et al. Cancer incidence in World Trade Center-exposed and non-exposed male firefighters, as compared with the US adult male population: 2001-2016. Occup Environ Med 2021;78(10):707–14.
[9] Boffetta P, Hall CB, Todd AC, Goldfarb DG, Schymura MJ, Li J, et al. Cancer risk among World Trade Center rescue and recovery workers: a review. CA Cancer J Clin 2022;72(4):308–14.
[10] Sisti JS, Dhanya A, Alper HE, Millet N, Ahmadi A, Brackbill RM. Exposure to the World Trade Center disaster, health, and health-related quality of life nearly 20 years after 9/11. Am J Ind Med 2025;68(5):413–27.
[11] Brackbill RM, Kahn AR, Li J, Zeig-Owens R, Goldfarb DG, Skerker M, et al. Combining three cohorts of World Trade center rescue/recovery workers for assessing cancer incidence and mortality. Int J Environ Res Public Health 2021;18(4).

[12] Goldfarb DG, Zeig-Owens R, Kristjansson D, Li J, Brackbill RM, Farfel MR, et al. Cancer survival among World Trade Center rescue and recovery workers: a collaborative cohort study. Am J Ind Med 2021;64(10):815–26.
[13] Li J, Hall CB, Yung J, Kehm RD, Zeig-Owens R, Singh A, et al. A 15-year follow-up study of mortality in a pooled cohort of World Trade Center rescue and recovery workers. Environ Res 2023;219:115116.
[14] Schubauer-Berigan MK, Hein MJ, Raudabaugh WM, Ruder AM, Silver SR, Spaeth S, et al. Update of the NIOSH life table analysis system: a person-years analysis program for the windows computing environment. Am J Ind Med 2011;54(12):915–24.
[15] U.S. Department of Health and Human Services (US HHS). The Health consequences of smoking: 50 years of progress. A Report of the Surgeon General. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion. Office on Smoking and Health Printed.2014.
[16] Yoshida K., Bartel A., Chipman J.J., Bohn J., McGowan L.D., Barrett M., et al. tableone: Create 'Table 1' to Describe Baseline Characteristics with or without Propensity Score Weights (Version 0.13.2) [R package]. The Comprehensive R Archive Network (CRAN).2022. Available from: https://cran.r-universe.dev/tableone/doc/manual.html (accessed 11 July).
[17] Guo C., So Y. Cause-Specific Analysis of Competing Risks Using the PHREG Procedure. https://support.sas.com/resources/papers/proceedings18/2159-2018.pdf (accessed 14 July 2025)2018 Available from: https://support.sas.com/resources/papers/proceedings18/2159-2018.pdf (accessed 14 July 2025).
[18] Korn EL, Graubard BI, Midthune D. Time-to-event analysis of longitudinal follow-up of a survey: choice of the time-scale. Am J Epidemiol 1997;145(1):72–80.
[19] Allison PD. Survival Analysis Using SAS: A Practical Guide. Second ed. Cary NC: SAS Institute Inc; 2010.
[20] Xu S, Ross C, Raebel MA, Shetterly S, Blanchette C, Smith D. Use of stabilized inverse propensity scores as weights to directly estimate relative risk and its confidence intervals. Value Health 2010;13(2):273–7.
[21] Schoenfeld D. Partial residuals for the proportional hazards regression model. Biometrika 1982;69(1):239–41.
[22] Gan H, Hou X, Zhu Z, Xue M, Zhang T, Huang Z, et al. Smoking: a leading factor for the death of chronic respiratory diseases derived from global burden of disease study 2019. BMC Pulm Med 2022;22(1):149.
[23] Loretan CG, Cornelius ME, Jamal A, Cheng YJ, Homa DM. Cigarette smoking among US adults with selected chronic diseases associated with smoking, 2010-2019. Prev Chronic Dis 2022;19:E62.
[24] Scherübl H. Smoking tobacco and cancer risk. Dtsch Med Woche 2021;146(6):412–7.
[25] Ishida M, Sakai C, Kobayashi Y, Ishida T. Cigarette smoking and atherosclerotic cardiovascular disease. J Atheroscler Thromb 2024;31(3):189–200.
[26] Lilly G, Calvert GM. The World Trade Center health program: smoking cessation. Arch Environ Occup Health 2023;78(4):249–52.
[27] 9/11 Health Watch. 2025. Cancer Coverage under the 9/11 Health and Compensation Act. https://www.911healthwatch.org/cancer/ (accessed 14 July 2025)
[28] Santiago-Colón A, Daniels R, Reissman D, Anderson K, Calvert G, Caplan A, et al. World Trade Center health program: first decade of research. Int J Environ Res Public Health 2020;17(19).