World Trade Center (WTC) Exposures and Cardiometabolic Risk Among WTC Health Program General Responders

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Objectives. To assess the association between World Trade Center (WTC) exposures, cardiometabolic diseases (CMDs), and trajectories of glucose and systolic blood pressure (SBP) among WTC Health Program general responders (WTHPGR).

Methods. We included monitoring visits (2003–2021) of WTHPGR who participated in the operations in New York City after the September 11, 2001, attack (n = 47 795). The WTC Health Program assessed WTC exposures using questionnaires and measured trajectories during monitoring study visits; CMDs were self-reported. We assessed associations with CMDs (hazard ratios and their corresponding 95% confidence intervals [CIs]) using survival analyses. We assessed associations with trajectories (odds ratios and their corresponding 95% CIs) using logistic regressions.

Results. Interquartile range (IQR) increases in the number of days on-site in the 9 months following the attack were associated with increased diabetes (1.057; 95% CI = 1.025, 1.089) and hypertension (1.035; 95% CI = 1.014, 1.057) risks. IQR increases in hours on-site during September 2001 were associated with worsening glucose (1.040; 95% CI = 1.017, 1.064) and SBP (1.006; 95% CI = 1.001, 1.010) trajectories.

Conclusions. WTC exposures are associated with higher CMD risk and worsening cardiometabolic trajectories among WTHPGR.

Public Health implications. Linking WTC exposures to emerging diseases is vital because of its impact on health care costs and treatment access among WTHPGR. (*Am J Public Health*. 2025;115(7):1120–1128. https://doi.org/10.2105/AJPH.2025.308079)

The September 11, 2001 (9/11), attacks on the World Trade Center (WTC) resulted in nearly 3000 fatalities in their immediate aftermath. Additionally, the health of responders who engaged in the search, rescue, recovery, service restoration, and cleanup operations in New York City has been negatively affected in the years since. More than 100 000 responders were exposed to smoke, fumes, dust, and debris in the air because of these attacks,[1] and to date, these exposures have not been fully described.[2] Adequate respiratory protective equipment was not consistently available, so these exposures contributed to health consequences arising years later.[3] Alongside the chemical and environmental exposures, responders have experienced psychosocial stress resulting from working long hours and completing challenging tasks in hectic environments, as well as fear for their safety, illness, or injury.[4]

The WTC Health Program provides medical monitoring, treatment, and assistance to eligible responders. In the past 2 decades, 48 389 responders were assessed, forming the General Responder Cohort. The cohort repository includes physical examinations, laboratory tests, and exposure and health questionnaires. Several studies associated WTC exposures with adverse health outcomes, focusing mostly on respiratory diseases,[5,6] cancer,[7] and mental health.[8–10] Only a few studies have investigated the associations between WTC exposures and cardiometabolic diseases. A 2013 study reported a higher risk of diabetes following 9/11 dust cloud exposure and posttraumatic stress.[11] Another study found a higher risk of cardiovascular disease among responders who arrived at the WTC on 9/11 than among those who arrived on or after September 12, 2001.[10]

Additionally, a recent investigation found higher cholesterol and glucose levels among responders categorized into a higher WTC exposure index category, which represents longer time on-site and more intense dust exposure.[12] Other studies, however, reported lower than expected cardiovascular disease,[13,14] metabolic syndrome,[15] and diabetes rates[16] compared with the general population. Furthermore, there is limited literature associating WTC exposures with cardiometabolic biomarkers.[12]

Given these mixed results, further studies are needed to understand the impact of 9/11 on long-term cardiometabolic diseases risk. Therefore, we assessed the associations of various WTC exposures with diabetes, hypertension, and coronary artery disease risk. In addition to these self-reported diseases, we investigated objective cardiometabolic biomarkers and evaluated the associations with long-term trajectories of blood glucose and systolic blood pressure (SBP).

METHODS

The study population included 47 795 WTC Health Program general responders from 2003 to 2021.

Study Population and Outcome

The cohort consisted of responders who participated in rescue, recovery, and cleanup efforts following the 9/11 attack on the WTC and were monitored over more than 20 years. The WTC Health Program administered an exposure assessment questionnaire at the initial monitoring visit. The WTC Health Program administered a medical questionnaire during all annual monitoring visits, which included self-reported information on the diagnosis date of various chronic conditions. The WTC Health Program asked the responders about numerous conditions and whether a physician had ever told them they had the condition. The data additionally contain sociodemographic variables, habits (e.g., smoking, alcohol consumption), laboratory results (e.g., blood glucose, lipids), and physical examinations (e.g., body mass index and blood pressure). Details regarding study eligibility criteria are described elsewhere.[17]

Subcohorts for cardiometabolic diseases survival analyses. We constructed subcohorts to analyze long-term associations with hypertension, diabetes, and coronary artery disease. In each subcohort, we followed responders annually until disease occurrence, death, or last documented visit (whichever came first). The observation period started in 2003, and we excluded responders diagnosed with the studied outcome within 2 years of the WTC attack (1.85%) to account for the potential induction period. We assigned hypertension, diabetes, and coronary artery diseases to responders based on self-reports. We also assigned diabetes to responders with at least 2 blood glucose tests higher than 200 milligrams per deciliter (mg/dL).[18] We chose this conservative threshold to account for the possibility that the responders were not fasting before the blood test, although they were instructed to do so.

Laboratory data for trajectory analyses. To ensure sufficient measurements for the trajectory analysis, we restricted the sample to people with at least 4 measurements during the study period. Additionally, because this analysis focused on the investigation of worsening trajectories among individuals who had normal test values at baseline, we excluded responders with previously reported diabetes or hypertension, glucose greater than 140 mg/dL, or SBP greater than 130 millimeters of mercury (mm/Hg) at baseline. Finally, because glucose and SBP measurements were rare among people older than 75 years at baseline, we excluded these measurements to avoid bias.

Exposures

We a priori selected environmental and psychological WTC exposures previously related to chronic health outcomes among responders.[11,12,19] We gathered exposure information via an exposure assessment questionnaire administered during the responders' first monitoring visit. The included exposures were the following:

1. Total number of hours on-site on 9/11,
2. Presence in Lower Manhattan on the day of the attack (yes/no),
3. Total number of days on-site October 2001 to June 2002,
4. Sustained injury (yes/no),
5. Witnessed horror (yes/no),
6. Lost someone (yes/no), and
7. WTC exposure index.

The WTC exposure index is a derived exposure variable that incorporates data on the overall time working at the

WTC site, exposure to the dust cloud, and direct work on the debris pile. The "low" category included responders who worked less than 40 days, were not exposed to the dust, and did not work directly on the pile. The "intermediate" category included responders who were not exposed to the cloud but worked 40 to 90 days or directly on the pile. The "high" category included responders who were directly exposed to the cloud or worked for more than 90 days.[17]

Statistical Analysis

Survival analyses. We used separate single-exposure Cox proportional hazard regressions to study the association between each WTC exposure and each outcome (i.e., diabetes, hypertension, or coronary artery disease incidence). We adjusted the models for sociodemographic characteristics (i.e., age, sex, race, ethnicity, education, and marital status), body mass index, and census tract–level socioeconomic variables (i.e., percentage below poverty line, percentage of Black population, percentage with no high school diploma, and median household income) at the baseline visit.

Trajectory analyses. We categorized the trajectories of long-term glucose and SBP using latent class mixed models[20] and specified them as a function of the participant's age with adjustment for sex. We estimated the trajectories for each specification of trajectory shape, setting 2 to 4 groups. We used different functions to specify the random effect age distribution (i.e., linear, spline, and B) and the trajectory shapes (i.e., linear, quadratic, and cubic). The following criteria determined the best model fit: (1) smallest Bayesian information criterion, (2) no less than 2% membership in any single trajectory group, and (3) greater than 0.7 posterior probabilities in each group.[21] We achieved the best model fit for glucose by setting 3 trajectory groups (i.e., steady normal, normal to high, and normal to very high) using a B function for the trajectory shape. For SBP, we achieved the best model fit by setting 2 trajectory groups (normal to steady high and normal to very high) using a linear function for trajectory shape.

We assessed the associations between WTC exposures and glucose or SBP trajectory groups using logistic regressions. For SBP, we set the normal-to-steady-high group as a reference. For glucose, we set the steady-normal group as a reference. We conducted 2 separate models to assess the odds of assignment to the normal-to-high and normal-to-very-high categories compared with the reference group. We adjusted the models for the same set of confounders described in the survival analyses section.

Sensitivity analyses. First, because 40% of responders did not provide information regarding injuries and witnessing horror during the attack, we conducted a sensitivity analysis to ensure that this did not induce selection bias. We estimated the probability of having complete information in these variables using logistic regressions including sociodemographic characteristics (i.e., age, sex, race and ethnicity, education, and marital status), body mass index, and census tract–level socioeconomic variables (i.e., percentage below the poverty line, percentage of Black population, percentage with no high school diploma, and median household income) as predictors. Then, we incorporated the inverse probability weights into the main analyses to correct for the potential selection bias and ensure that the results did not change.

Second, we calculated the E-values for the statistically significant associations observed in the main analyses to evaluate the potential of confounding bias. The E-value is the minimum strength of association that an unmeasured confounder would need to have with both the exposure and the outcomes, conditional on the covariates, to fully explain away the associations found.[22]

RESULTS

We included 47 795 responders, of whom 13% had diabetes, 30.75% had hypertension, and 3.19% had coronary artery disease. The average age at cohort entry was approximately 40 years; most were White, and almost 86% were male. The number of glucose and SBP measurements ranged from 4 to 16, with a mean number of 8 measurements per person. In the glucose trajectory analysis, we classified 90.38% as steady normal, 3.27% as normal to high, and 6.34% as normal to very high. In the SBP trajectory analysis, we classified 96.34% as normal to very high and the rest as normal to steady high (Table 1).

Approximately half of the responders were present in Lower Manhattan during the day of the attack. The responders spent 138 hours on-site in September on average and 54 days on average in the following 9 months. About 61% of the responders were exposed to the intermediate WTC exposure index category, followed by 15% in the high exposure category and 13% in the low exposure category. Finally, 14%

TABLE 1— Descriptive Characteristics of World Trade Center Health Program General Responders in a Cardiometabolic Risk Study: New York City, 2003–2021

Variable	No. (%) or Mean ±SD
Sociodemographic characteristics	
Age at cohort entry, y	40.6 ±8.8
Marital status	
No	13 018 (27.2)
Yes	34 148 (71.4)
Unknown	626 (1.3)
Race	
Black	4 257 (8.9)
White	25 008 (52.3)
Other	5 282 (11.0)
Unknown	12 916 (27.0)
Highest education level	
Elementary school	3 144 (6.5)
High school	9 240 (19.3)
Some college	12 228 (25.5)
College graduate[a]	19 388 (40.5)
Unknown	3 792 (7.9)
Sex	
Male	41 046 (85.8)
Female	6 417 (13.4)
Body mass index, kg/m^2	30.20 ±4.4
Neighborhood characteristics	
Black population, %	0.8 ±1.5
Under the poverty line, %	9.3 ±7.6
With no high school education, %	3.9 ±3.4
Median household income	59 600 ±23 200
Outcomes	
Diabetes	6 027 (12.9)
Hypertension	13 118 (30.7)
Coronary artery disease	1 520 (3.1)
Glucose trajectory group	
Steady normal	13 167 (90.3)
Normal to high	477 (3.2)
Normal to very high	924 (6.3)
SBP trajectory group	
Normal to steady high	885 (3.6)
Normal to very high	23 338 (96.3)

Note. SBP = systolic blood pressure. The sample size was n = 47 795.
[a]Professional, bachelor's, or associate degree.

reported injuries, 52% lost someone they knew, and 26.12% reported witnessing horror (Table A, available as a supplement to the online version of this article at http://www.ajph.org). Elaborated descriptive statistics of population characteristics in each trajectory group are described in Tables B and C (available as a supplement to the online version of this article at http://www.ajph.org).

An interquartile range (IQR) increase in the number of days spent on-site during the 9 months following the attack was associated with increased diabetes (hazard ratio [HR] = 1.057; 95% confidence interval [CI] = 1.025, 1.089) and hypertension (HR = 1.035; 95% CI = 1.014, 1.057) risks. Diabetes risk was also associated with reported injuries (HR = 1.131; 95% CI = 1.040, 1.229). We also observed hypertension associations with reported injuries (HR = 1.123; 95% CI = 1.058, 1.192), the loss of someone (HR = 1.106; 95% CI = 1.063, 1.151), and exposure to the high WTC exposure index category (HR = 1.107; 95% CI = 1.036, 1.184). Finally, the associations with coronary artery disease were all positive but not statistically significant (Table 2).

The trajectory analyses included 14 178 people with glucose measurements and 27 455 people with SBP measurements. Figure 1 shows the mean glucose and SBP values by age in each trajectory group. In the steady-normal glucose trajectory group, glucose values did not exceed 110 mg/dL and remained within the normal range throughout the observation period. In the normal-to-high group, values reached as high as 175 mg/dL and then decreased, and in the normal-to-very-high group, values linearly increased with age. In the normal-to-steady-high SBP trajectory group, values gradually increased but did not exceed 135 mm/Hg. In the normal-to-very-high group, values increased linearly with age, exceeding 160 mm/Hg.

Compared with a steady-normal trajectory, an IQR increase in the total number of hours on-site during September 2001 (odds ratio [OR] = 1.040;

TABLE 2— Associations Between World Trade Center Exposures and Cardiometabolic Disease Incidence: New York City, 2003–2021

Exposure	Diabetes, HR (95% CI)	Hypertension, HR (95% CI)	Coronary Artery Disease, HR (95% CI)
WTC exposure index[a]			
Low (Ref)	1	1	1
Intermediate	0.98 (0.90, 1.06)	1.00 (0.94, 1.06)	1.18 (0.98, 1.42)
High	0.98 (0.89, 1.08)	1.10 (1.03, 1.18)	1.20 (0.97, 1.48)
Hours on-site in Sep 2001	0.99 (0.94, 1.05)	1.00 (0.96, 1.03)	1.03 (0.93, 1.14)
Presence in Lower Manhattan	1.02 (0.96, 1.08)	1.02 (0.99, 1.06)	1.07 (0.95, 1.20)
Days on-site (Oct 2001—Jun 2002)	1.05 (1.02, 1.08)	1.03 (1.01, 1.05)	1.01 (0.95, 1.08)
Injuries	1.13 (1.04, 1.22)	1.12 (1.05, 1.19)	1.15 (0.97, 1.37)
Lost someone	1.01 (0.95 1.07)	1.10 (1.06, 1.15)	1.11 (0.99, 1.25)
Witnessed horror	1.03 (0.96, 1.10)	1.02 (0.97, 1.06)	0.97 (0.85, 1.11)

Note. CI = confidence interval; HR = hazard ratio; WTC = World Trade Center. We used the Cox proportional HR models to study the associations between each single WTC exposure and each outcome. We adjusted models for sex, age, race, education, marital status, body mass index, and neighborhood sociodemographic variables during the first year of follow-up. We weighted the models assessing the risks associated with having injuries and witnessing horror during the attack by the inverse probability of being included in the analytical data set to minimize selection bias attributable to/because of/owing to a high percentage of missing values. The associations with the total number of hours on-site in September 2001 and total number of days on-site during October 2001–June 2002 are presented per interquartile range increments (176 hours and 68 days). The sample size was n = 47 795.

[a]The low category includes responders who worked < 40 days, were not exposed to the dust, and did not work directly on the pile. The intermediate category includes responders who were not exposed to the cloud but worked 40–90 days or directly on the pile. The high category includes responders who were directly exposed to the cloud or worked for > 90 days.

95% CI = 1.017, 1.064) and injuries (OR = 1.037; 95% CI = 1.003, 1.072) were associated with higher odds of a normal-to-very-high glucose trajectory (Table 3). Compared with a normal-to-steady-high trajectory, an IQR increase in the total number of hours on-site during September 2001 (OR = 1.006; 95% CI = 1.001, 1.010) and the loss of someone (OR = 1.006; 95% CI = 1.001, 1.011) were associated with higher odds of a normal-to-very-high SBP trajectory (Table 3).

The results obtained from the models, including inverse probability weights to account for incomplete injuries and witnessing horror information, were very similar to those of the main analyses (Figure A, available as a supplement to the online version of this article at http://www.ajph.org). Additionally, our E-value calculations show that the effects needed to completely explain our associations are relatively large. For example, the effect estimates needed to completely cancel out the association with diabetes and worse glucose trajectories were 1.515 for injuries and 1.161 for longer duration on-site in September 2001 (Table D, available as a supplement to the online version of this article at http://www.ajph.org).

DISCUSSION

This study shows that WTC exposures are associated with increased cardiometabolic risk among responders more than the 20 years after 9/11. Specifically, our findings provide additional evidence of elevated diabetes and hypertension risk among responders with greater exposure to various WTC exposures. Longer on-site duration in the 9 months after the attack, injuries, and personal loss were associated with heightened risks of developing these conditions. To ensure the robustness of these findings, we examined time-varying clinical biomarkers of cardiometabolic risk. Our results show that extended hours on-site after the attack, injuries, and personal loss were also associated with worsening glucose and SBP trajectories.

Longer duration on-site was the most consistent predictor of cardiometabolic risk in our analysis. This WTC exposure was previously found to be associated with various health outcomes,[23] specifically respiratory symptoms[9] and cancer.[7] Duration on-site captures various aspects of the complex chemical and nonchemical exposures experienced by the responders. It represents a longer duration of exposure to the high levels of particulate matter pollution containing cement remnants, glass,

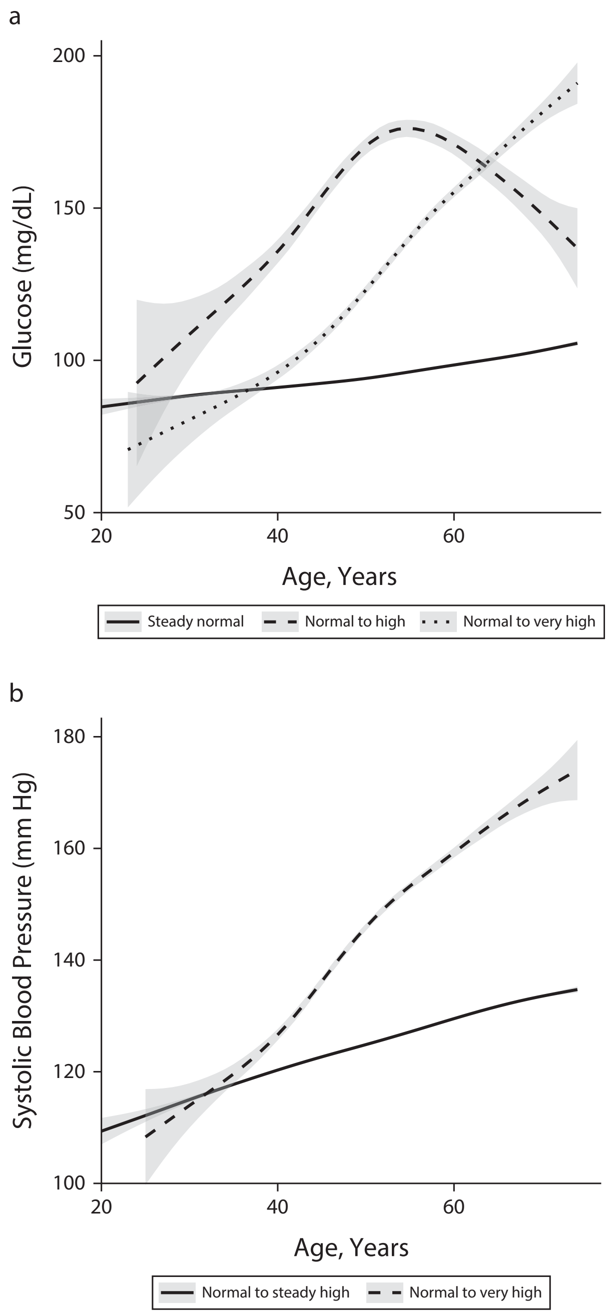

FIGURE 1— Latent Class Mixed Model Categorization of Long-Term Trajectories of (a) Glucose and (b) Systolic Blood Pressure: New York City, 2003–2021

Note. We categorized the trajectories of long-term glucose and systolic blood pressure (SBP) using latent class mixed models and specified as a function of the participant's age with adjustment for sex. For each specification of trajectory shape, we estimated the trajectories setting 2–4 groups. We used different functions to specify the random effect age distribution (i.e., linear, spline, and B) and the trajectory shapes (i.e., linear, quadratic, and cubic). The following criteria determined the best model fit: (1) smallest Bayesian information criterion, (2) ≥ 2% membership in any single trajectory group, and (3) > 0.7 posterior probabilities in each group. We achieved the best model fit for glucose by setting 3 trajectory groups (steady normal, normal to high, and normal to very high), using a B function for the trajectory shape. For SBP, we achieved the best model fit by setting 2 trajectory groups (normal to steady high and normal to very high), using a linear function for trajectory shape. Gray shading represents confidence intervals.

TABLE 3— Associations Between World Trade Center Exposures and Glucose or Systolic Blood Pressure Trajectories: New York City, 2003–2021

Exposure	Glucose (n = 14 178)		SBP (n = 27 455), Normal to Very High Exposure,[a] OR (95% CI)
	Normal to High Exposure,[a] OR (95% CI)	Normal to Very High Exposure,[a] OR (95% CI)	
WTC exposure index[b]			
Low (Ref)	1	1	1
Intermediate	1.00 (0.99, 1.01)	0.99 (0.95, 1.03)	1.00 (0.99, 1.01)
High	0.99 (0.98, 1.01)	1.01 (0.96, 1.05)	1.00 (0.99, 1.01)
Hours on-site (September 2001)	1.00 (0.99, 1.01)	1.04 (1.01, 1.06)	1.006 (1.001, 1.010)
Presence in Lower Manhattan	1.00 (0.99, 1.01)	1.00 (0.98, 1.03)	1.004 (0.999, 1.008)
Days on-site (October 2001–June 2002)	1.00 (0.99, 1.004)	1.00 (0.99, 1.02)	1.002 (0.995, 1.009)
Injuries	0.99 (0.99, 1.01)	1.037 (1.003, 1.072)	1.002 (0.995, 1.009)
Lost someone	1.00 (0.99, 1.01)	1.00 (0.97, 1.02)	1.006 (1.001, 1.011)
Witnessed horror	1.00 (0.99, 1.01)	1.02 (0.93, 1.05)	1.003 (0.997, 1.008)

Note. CI = confidence interval; OR = odds ratio; SBP = systolic blood pressure; WTC = World Trade Center. We used logistic regressions to estimate the odds of being in each trajectory group compared with the normal-to-steady-high group. The glucose analysis included the 3 glucose trajectory groups. The SBP analysis included the 2 trajectory groups. We adjusted the models for sex, age, race, education, marital status, body mass index, and neighborhood sociodemographic variables during the first year of follow-up. We weighed the models assessing the risks associated with having injuries and witnessing horror during the attack by the inverse probability of being included in the analysis. The associations with the total number of hours on-site in September 2001 and total number of days on-site during October 2001–June 2002 are presented per interquartile range increments (176 hours and 68 days).
[a]Steady normal is the reference.
[b]The low category includes responders who worked < 40 days, were not exposed to the dust, and did not work directly on the pile. The intermediate category includes responders who were not exposed to the cloud but worked 40–90 days or directly on the pile. The high category includes responders who where directly exposed to the cloud or worked for > 90 days.

asbestos, and many toxic metals and organics sustained in the air in the lower parts of Manhattan.[2] It also represents a higher probability of experiencing injuries and witnessing disturbing scenes, which can profoundly affect one's mental well-being. Finally, this measure is less affected by recall bias and possibly better captures the variation in WTC exposures.[24]

The epidemiological evidence and mechanistic underpinnings linking air pollution with cardiometabolic diseases have been reported in numerous studies, for example the 2024 review of Rajagopalan et al.[25] Our study found that a high WTC exposure index, indicative of dust exposure, is associated with an increased risk of hypertension but not diabetes, coronary artery disease, or cardiometabolic trajectories. Unlike our study, a recent analysis among the cohort responders showed elevated glucose and cholesterol levels associated with exposure to a higher WTC exposure index.[12] These mixed results may be related to the challenges in studying WTC-related health effects, especially dust-related effects, owing to the lack of nonexposed comparison groups, reliance on self-reported exposure questionnaires, and lack of direct dust exposure measurements.

Another interesting finding of our study is the consistently higher cardiometabolic disease risk associated with exposures that suggest intense stress (i.e., witnessing horror and the loss of someone). A large group of studies reported that a longer duration working at the site after the attack on the WTC is associated with an increased risk of posttraumatic stress disorder[26] and depression.[19] Studies also show that these mental health conditions are associated with an increased risk of diabetes[27,28] and hypertension.[29–31] The association with diabetes may be related to stress-induced cortisol secretion, which increases blood glucose levels and insulin resistance.[32] The association with blood pressure levels may be related to autonomic function dysregulation affecting heart rate.[33] To date, the links between mental health, trauma, and cardiovascular risk are unclear,[34] and further studies are needed to fully investigate these associations.

Limitations

Our study has several limitations. First, the self-reported data may have been affected by recall bias. However, multiple studies have observed high levels of agreement between self-reported outcomes and medical records.[35] Moreover, the similar WTC exposure associations found with self-reported outcomes and clinical biomarkers support the robustness of our findings. Second, as in any epidemiologic study, our results may be biased because of residual confounding. However, our sensitivity analysis shows that the effect sizes needed to cancel out the associations observed in our study are very large and unlikely.

Public Health Implications

Federally funded health care is provided to responders only for certified diseases related to 9/11 exposure, and cardiometabolic diseases are not currently certified. This has vast implications for health care costs and accessibility of treatment for WTC responders and survivors. By highlighting the elevated cardiometabolic risks linked to greater WTC-related exposures, this study contributes to the growing body of evidence needed to support the certification of these conditions.

Conclusions

Our study indicates that prolonged on-site presence, injuries, and personal loss among WTC responders are associated with increased cardiometabolic risks in the years following 9/11. Linking WTC-related exposures to emerging diseases is critical, as the certification of these conditions has significant implications for health care costs and treatment accessibility for responders. AJPH

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CONTRIBUTORS

H. Krasnov performed the formal analyses, conducted the investigation, curated the data, created the analysis codes, and wrote the original draft of the article. K. A. Patel contributed to the investigation. P. Knobel contributed to the initial data curation. P. Knobel, H.-H. L. Hsu, S. L. Teitelbaum, M. McLaughlin, and M. Y. Sade wrote and edited the article. H.-H. L. Hsu, S. L. Teitelbaum, M. McLaughlin, and M. Y. Sade conceptualized the study and developed the methodology. A. C. Just supported software and code validation. M. Y. Sade supervised the study. All authors reviewed and approved the final version of the article.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

HUMAN PARTICIPANT PROTECTION

This study was approved by the Mount Sinai School of Medicine institutional review board (STUDY-20-02018-MOD004), and consent for the secondary analysis was waived. We restricted the population to responders who consented to data aggregation for research (STUDY-11-02030, World Trade Center Health Program General Responder Data Center).

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