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Association between World Trade Center disaster exposures and body mass index in community members enrolled at World Trade Center Environmental Health Center

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Abstract

Studies suggest that environmental disasters have a big impact on population health conditions including metabolic risk factors, such as obesity and hypertension. The World Trade Center (WTC) destruction from the 9/11 terrorist attack resulted in environmental exposures to community members (Survivors) with potential for metabolic effects. We now examine the impact of WTC exposure on Body Mass Index (BMI) using the data from 7136 adult participants enrolled in the WTC Environmental Health Center (EHC) from August 1, 2005, to December 31, 2022. We characterized WTC-related exposures by multiple approaches including acute dust-cloud exposure, occupational or residential exposures, and latent exposure patterns identified by synthesizing multiplex exposure questions using latent class analysis. Employing multivariable linear and quantile regressions for continuous BMI and ordered logistic regression for BMI categories, we found significant associations of BMI with WTC exposure categories or latent exposure patterns. For example, using exposure categories, compared to the group of local residents, local workers exhibited an average BMI increase of 1.71 kg/m^2 with 95% confidence

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Yuyan Wang: Writing – original draft, Conceptualization, Formal analysis, Data curation, Visualization, Methodology. **Ramazan Alptekin**: Writing – review, Investigation, Conceptualization. **Roberta M Goldring**: Writing – review, Conceptualization. **Beno W Oppenheimer**: Writing – review, Conceptualization. **Yongzhao Shao**: Writing – review & editing, Methodology, Validation, Funding acquisition. **Joan Reibman**: Writing – review & editing, Conceptualization, Supervision, Validation, Funding acquisition. **Mengling Liu**: Writing – review & editing, Conceptualization, Supervision, Validation, Funding acquisition, Methodology.

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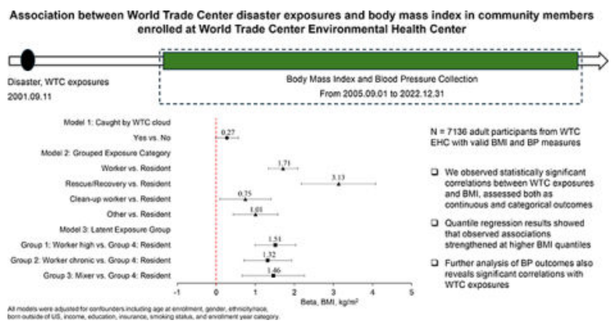
The authors have nothing to disclose.

Declaration of interests
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.

Appendix A. Supplementary data
Supplementary data to this article can be found online.

intervals (CI) of (1.33, 2.09), the rescue/recovery group had an increase of 3.13 kg/m^2 (95% CI: 2.18, 4.08), the clean-up worker group had an increase of 0.75 kg/m^2 (95% CI: 0.09, 1.40), and the other mixer group had an increase of 1.01 kg/m^2 (95% CI: 0.43, 1.58). Furthermore, quantile regression analysis demonstrated that WTC exposures adversely affected the entire distribution of BMI in the WTC EHC Survivors, not merely the average. Our analysis also extended to blood pressure and hypertension, demonstrating statistically significant associations with WTC exposures. These outcomes highlight the intricate connection between WTC exposures and metabolic risk factors including BMI and blood pressure in the WTC Survivor population.

Graphical Abstract



Keywords

blood pressure; body mass index; environmental exposure; Survivor cohort; World Trade Center 9/11 disaster

1. Introduction

The collapse of the World Trade Center (WTC) towers due to the terrorist attack on September 11, 2001, was a major environmental disaster, releasing over 10 million tons of dust and debris into the air (Lioy et al., 2002). Exposure to dust, debris, and fumes and disaster itself posed serious health and mental risks, affecting not just emergency workers but also local residents, workers, students, and others in the area. The World Trade Center Environmental Health Center (WTC EHC), recognized as a 'Center of Excellence' within the WTC Health Program (WTCHP), serves community members ('Survivors') who experienced health issues due to their exposure to the disaster (Reibman et al., 2016; Wang et al., 2023). Unlike the Centers of Excellence dedicated to Responders, the Survivor program admits individuals based on their exposure status as local workers, residents, students, or bystanders on the day of the disaster, along with the manifestation of specific certifiable mental or physical health symptoms defined by the Centers for Disease Control (https://www.cdc.gov/wtc/conditions.html). Consequently, the Survivor program encompasses a broader demographic diversity than that of the Responder cohorts (Reibman et al., 2016). Exposure to the disaster, encompassed both the immediate inhalation of dust from the towers' collapse (dust cloud) as well as the extended exposure to ongoing emissions and disturbances of debris and fumes in the subsequent months (Kahn et al., 2018; Landrigan et al., 2004; Lippmann et al., 2015). Consequently, characterizing both the acute and chronic exposures to WTC contaminants in the Survivor cohort presents a complex challenge. We and others previously described complex exposure analyses and outcomes in the Survivor population (Maslow et al., 2012; Zhang et al., 2022). Enhancing our comprehension of these complex exposures to WTC dust and fumes and examining their effects on health outcomes is crucial for the advancement of disease prevention and therapeutic strategies for Survivors and other comparable populations.

Body Mass Index (BMI) is a widely utilized metric of metabolic syndrome and is used to determine body fat, calculated from the ratio of weight to height squared (Quetelet, 1994). It is integral to obesity classification systems and employed for various purposes including monitoring global health (Collaboration, 2019; Finucane et al., 2011) to assessing individual wellness (Gutin, 2018; Nuttall, 2015). Environmental exposures are increasingly acknowledged as critical influencers of BMI and associated health issues. Research indicates that pollutants and toxic chemicals prevalent in disasters (Bell et al., 2019; Dancause et al., 2012; De Rubeis et al., 2021; Farris et al., 2016) and urban settings (Jung et al., 2014; Ribeiro et al., 2020) can disrupt the body's hormonal equilibrium and metabolic functions, potentially leading to a BMI increase. Bell and colleagues (Bell et al., 2019) have established a significant association between self-reported disaster exposure experience and BMI increase among older adults. Further studies (An et al., 2018; Kim et al., 2019; Shi et al., 2022) have shown a link between air pollution exposure and elevated BMI in adults, suggesting that airborne pollutants may interfere with endocrine functions and encourage fat accumulation (Darbre, 2017; Nappi et al., 2016; Petrakis et al., 2017). These insights highlight the complex relationship between environmental exposures and BMI.

BMI's influence on numerous diseases is also well recognized (Atamna et al., 2017; Field et al., 2001), prompting research into the intricate connections between WTC exposures, BMI, and health outcomes in WTC cohorts (Caraher et al., 2017; Cleven et al., 2021; Kwon et al., 2019; Santiago-Colon et al., 2020; Tsukiji et al., 2014; Weiden et al., 2015; Wyka et al., 2020). For instance, research from the Fire Department of New York (FDNY) cohort (Kwon et al., 2021) highlighted how metabolic syndrome and WTC exposure together influence the development of lung diseases, with BMI posing a greater risk for WTC-related lung disease than other metabolic syndrome factors. In response, the FDNY cohort from the WTC Fire Department of New York has initiated the food intake restriction for health outcome support and education (FIREHOUSE) trial (Cleven et al., 2021). The above evidence emphasizes BMI's critical role in the health management for those affected by the WTC disaster. We previously showed a relationship between WTC exposure and potential metabolic-related disorders including cardiometabolic consequences in a study of adolescents exposed to WTC dust compared to NYC age-matched controls (Koshy et al., 2017). However, there is a significant gap in research concerning the BMI status within the WTC EHC Survivor population, particularly among adults.

This study focused on WTC Survivors within the WTC EHC cohort and aimed to assess the associations between complex WTC exposures and BMI. We hypothesized that heightened acute and chronic exposures to the WTC disaster would result in elevated BMI levels among the civilians affected by the WTC event. Additionally, we also examined the correlations between WTC exposures and blood pressure measures to extend our understanding of the influence of WTC exposures on metabolic risk factors among WTC Survivors.

2. Material and methods

2.1. Study population

The WTC EHC was established in 2005 and has since been recognized as a Center of Excellence within the WTCHP, which operates under the auspices of the Centers for Disease Control and Prevention (CDC) and the National Institute for Occupational Safety and Health (NIOSH), pursuant to the James Zadroga 9/11 Health and Compensation Act. Participants in the program undergo comprehensive physical and mental health evaluations upon enrollment (Reibman et al., 2016). By the legislative mandate, eligibility for this program is contingent upon a diagnosis of a WTC-related condition, which encompass a range of disorders including aerodigestive disorders, acute traumatic injuries, various cancers, post-traumatic stress disorder, depression, and anxiety. This eligibility criterion distinguishes the WTC EHC from the WTC Responder programs, ensuring a cohort with confirmed diagnostic conditions.

Inclusion in the analysis was limited to patients who consented in writing, with the research database receiving approval from the Institutional Review Board of New York University School of Medicine (NCT00404898). The study protocols conformed to the ethical guidelines and regulations outlined by the New York University School of Medicine, the 2013 Helsinki Declaration, and subsequent amendments or comparable ethical standards (World Medical, 2013).

Upon enrollment, patients provided information via a comprehensive interviewer administered questionnaire that captured demographic data, WTC-related and other occupational exposures, potential exposure categories (e.g. local workers, residents, students, passersby), and detailed accounts of symptoms affecting the respiratory system, gastroesophageal tract, neurologic and mental health. Clinical evaluations were standardized and conducted at the Bellevue Hospital site with later expansions to include additional clinical sites. The scope of this study encompasses 9507 participants who enrolled at the Bellevue Hospital site between August 1, 2005 and December 31, 2022.

2.2. World Trade Center exposures

In this study, we evaluated the WTC-related exposures through three different characterizations. The first exposure characterization was binary: patients who self-reported being caught in the dust cloud from the collapsing buildings on 9/11/2001 were classified as ‘Yes’ for caught in the WTC cloud, while those who did not were classified as ‘No’. The second type of exposure was categorical, based on the participants’ responses regarding their place of residence and workplace, leading to five groups: ‘Local Resident’ (labelled as ‘Resident’), ‘Local Worker’(labelled as ‘Worker’), ‘Rescue/Recovery’, ‘Clean-up worker’, and ‘Other’ (including student, delivery, driver, construction, journalist, passerby and volunteer et. al, labelled as ‘Other’). The third exposure categorization involved a latent class analysis (LCA) to identify distinct latent exposure pattern groups (Wang et al., 2023; Zhou et al., 2018). This analysis was based on a comprehensive evaluation of 14 exposure variables from the initial visit questionnaire of the 9507 participants. As illustrated in Supplementary Figure 1, this evaluation categorized the participants into four latent exposure pattern groups: 'Group 1: Worker with both high acute and chronic exposures' (labelled as 'Group 1: Worker high'), 'Group 2: Worker with low acute but moderate/ high chronic exposures' (labelled as 'Group 2: Worker chronic'), 'Group 3: Mixer with high missing exposures' (labelled as 'Group 3: Mixer'), 'Group 4: Resident with home exposures' (labelled as 'Group 4: Resident'). Compared with traditional environmental exposure assessments focusing on single exposures, LCA allows for a more comprehensive analysis by simultaneously considering multiple variables (Dahmer et al., 2022; Zhou et al., 2018). This method is particularly advantageous in identifying heterogeneous exposure patterns, integrating both acute and chronic exposures including missingness in data into a set of discrete latent variables. Consequently, LCA facilitates the generation of mutually exclusive groups, thereby enriching the analysis of complex exposure scenarios.

2.3. Outcomes

In this study, we assessed the BMI of participants during their initial visit by their measured weights and heights in the clinics using calibrated scales and stadiometers, respectively. BMI was calculated as weight in kilograms divided by the square of height in meters, resulting in units of kg/m^2 (Flegal et al., 2013). BMI values could be divided into six categories (Flegal et al., 2005): 'Underweight' (BMI < 18.5), 'Normal' (18.5 ≤ BMI < 25), 'Overweight' (25 ≤ BMI < 30), 'Obese I' (30 ≤ BMI < 35), 'Obese II' (35 ≤ BMI < 40), and 'Obese III' (40 ≥ BMI). Due to the small sample size in the 'Underweight' category and skewed distribution of higher BMI values in our data, the categories were furthermore simplified into three (Kushner & Kahan, 2018): 'Normal' (BMI < 25), which now included the 'Underweight' group, 'Overweight' (25 ≤ BMI < 30), and 'Obese' (30 ≥ BMI) consolidating the three obese subcategories into one. We also evaluated blood pressure measures as outcomes. Diastolic blood pressures (DBP) and systolic blood pressures (SBP) were measured for each participant at their initial visit using standard clinical inflatable cuff while the patient was in the sitting position. Hypertension was defined based on established criteria: an SBP of 130 mm Hg or higher, or a DBP of 80 mm Hg or higher (Whelton et al., 2018).

2.4. Covariates

In our analyses, we examined and incorporated various covariates, based on their relevance to the study and the availability of data. These covariates included: age at the enrollment in the WTC EHC (in years), gender (categorized as male or female), and race/ethnicity (classified into groups as Hispanic, non-Hispanic White, non-Hispanic Black, and non-Hispanic Other). Additional factors considered were whether the participant was born outside the United States (no or yes), annual income (categorized as less than $15,000, $15,000–$30,000, more than $30,000, and unknown), educational attainment (dichotomized as equal to or less than high school and more than high school), health insurance status (uninsured or insured), and ever smoking history (no or yes). Furthermore, the enrollment year was categorized into intervals of five years: before 2011, between 2011 and 2015, and between 2016 and 2020, acknowledging that participant characteristics may vary across different periods. We used 2011 as the initial reference point, marking the commencement of the James Zadroga 9/11 Health and Compensation Act. These covariates were included in both descriptive and multivariable analyses to ensure a comprehensive understanding of the factors influencing the outcomes of interest.

2.5. Statistical analyses

We provided summary statistics for outcomes, WTC exposures, and patient demographic characteristics, detailing counts and proportions for categorical variables, alongside means and standard deviations (SD) for continuous variables, overall and stratified by BMI groups. Comparisons across the BMI groups were conducted using the analysis of variance (ANOVA) test for continuous variables and the Chi-square test for categorical variables. To compare the distributions across different exposure groups, we presented the continuous outcomes including BMI, DBP, and SBP using boxplots. Multivariable linear regression analyses were employed to assess the mean differences in continuous BMI among various exposure groups, adjusting the potential confounders mentioned above. Additionally, multivariable quantile regression models were conducted to explore the relationship between WTC latent exposure pattern groups and BMI distributions at the 10th, 25th, 50th, 75th, and 90th percentiles. To assess the likelihood of falling into higher BMI categories among different exposure groups, multivariable ordered logistic regression analyses were conducted. For analyzing blood pressure outcomes, we also used multivariable linear regression for continuous DBP/SBP and multivariable logistic regression for binary hypertension outcome. All tests were performed as two-sided, and the threshold for statistical significance was set at a p-value of 0.05. All statistical analyses were conducted using R software (version 4.3.1).

3. Results

3.1. Patient population

Figure 1 presents a flowchart detailing the inclusion of patients in the analysis. We included a total of 9507 patients who enrolled in the WTC EHC at Bellevue Hospital and provided research consent and completed the initial questionnaire between August 1, 2005, and December 31, 2022. From this cohort, we excluded 2293 patients due to missing or erroneous outcome data of BMI and BP and 78 pediatric patients at enrollment. Consequently, 7136 patients were retained for further analysis.

3.2. Participant characteristics

Table 1 summarizes the characteristics of the final included 7136 participants overall and across three BMI categories. The distribution of the BMI categories was as follows: 2063 (28.9%) patients were in the normal BMI group, 2568 (36.0%) in the overweight group, and 2505 (35.1%) in the obese group. The WTC EHC Survivor population showed diversity, with 52.1% having been exposed to the WTC cloud, 57.2% identified as workers, and 45.2% enrolled before 2011. Gender distribution showed 49.8% female, and racial/ethnicity composition showed 25.7% Hispanic, 43.8% non-Hispanic White, 19.9% non-Hispanic Black, and 10.6% non-Hispanic Other. The majority of the participants were born in the US (60.6%), reported an annual income of over $30,000 (48.5%), had attained education beyond high school (70.7%), were insured (83.8%), and had no smoking history (60.2%).

Notably, both DBP and SBP increased alongside BMI categories, aligning with expectations. Statistical tests revealed significant differences in all characteristics across BMI groups. We also detailed the characteristics of the participants included in the analysis by the four WTC latent exposure pattern groups (Supplementary Table 1), which showed that significant differences presented in most characteristics across the latent exposure pattern groups, except for age on 9/11/2001 and smoking status.

Figure 2 presents the distributions of BMI, DBP, and SBP across various WTC exposure characterizations. Individuals caught in the WTC dust cloud exhibited marginally higher BMI, DBP, and SBP compared to those in the 'No' group. Among the occupational or residential exposure categories, clean-up worker, local worker, and rescue/recovery groups had higher levels of BMI, DBP, and SBP than the resident. In terms of latent exposure patterns, a clear ascending trend in BMI and SBP was observed, with Group 1 (worker with both high acute and chronic exposures) having the highest BMI and SBP. The boxplots underscore significant variances in BMI, DBP, and SBP measurements among the different WTC exposure groups, highlighting the impact of WTC exposures on these health indicators.

3.3. Associations between WTC exposures and BMI

We conducted separate multivariable linear regression models to estimate the effects of WTC exposures on average BMI levels adjusting for previously mentioned covariates. In these models, we used individuals not caught in the WTC cloud, resident group in exposure category, and Group 4 resident in the latent exposure patterns as references, respectively. Figure 3 displays the estimated average differences in BMI between the exposure groups, based on the three multivariable linear regression analyses (with detailed results in Supplementary Table 2). There may be an association between exposure to the WTC dust cloud and higher average BMI, as suggested by the narrow confidence interval, though the result is borderline and not statistically significant (beta = 0.27, 95% confidence interval CI: −0.02, 0.57). When comparing to the resident group, the worker group had a significant increase in average BMI of 1.71 kg/m^2 (95% CI: 1.33, 2.09), the rescue/recovery group showed an increase of 3.13 kg/m^2 (95% CI: 2.18, 4.08), the clean-up worker group showed an increase of 0.75 kg/m^2 (95% CI: 0.09, 1.40), and the other group had an increase of 1.01 kg/m^2 (95% CI: 0.43, 1.58). In the model using latent exposure pattern groups, when compared to Group 4 resident, Group 1 worker-high with both high acute and chronic exposures exhibited a significant increase in BMI of 1.51 kg/m^2 (95% CI: 1.00, 2.03), Group 2 worker-chronic with low acute but moderate/high chronic work exposures showed an increase of 1.32 kg/m^2 (95% CI: 0.70, 1.93), and Group 3 mixer exhibited an increase of 1.46 kg/m^2 (95% CI: 0.66, 2.26).

To further explore the relationship between the WTC latent exposure pattern groups and BMI across various quantile levels in the BMI distribution, we applied multivariable quantile regression models, adjusting for the same set of covariates. Figure 4 presents the estimates derived from the five quantile regressions at the 10th, 25th, 50th, 75th, and 90th percentiles, with detailed results provided in Supplementary Table 3. Overall, we observed that the entire BMI distributions across all quantile levels were shifted upwards in the latent exposure pattern Groups 1 to 3 compared with the reference Group 4 resident. These results emphasized the broad impact of WTC exposures on the entire spectrum of BMI distribution in the WTC EHC Survivor population as a whole, in addition to the average BMI. Specifically, Group 1 workers with high acute and chronic exposures showed significant differences in the 10th to the 90th percentiles compared with the Group 4 of residents: 0.66 kg/m^2 (95% CI: 0.19, 1.12), 1.23 kg/m^2 (95% CI: 0.75, 1.72), 1.25 kg/m^2 (95% CI: 0.72, 1.78), 2.07 kg/m^2 (95% CI: 1.36, 2.78), and 2.01 kg/m^2 (95% CI: 0.72, 3.30), respectively.

Additionally, we utilized multivariable ordinal logistic regression models, adjusting for the same covariates, to evaluate the impact of various WTC exposures on the probability of being categorized into higher BMI categories. The odds ratios (ORs) with 95% CI are shown in Figure 5, with the detailed values available in Supplementary Table 2. The results for categorical BMI outcomes were consistent with those obtained for continuous BMI measurements. Specifically, the odds of being classified into higher BMI categories were marginally significant for individuals exposed to the WTC dust cloud compared to those who were not (OR = 1.09, 95% CI: 1.00, 1.19). In terms of specific exposure categories, compared to the resident group, the likelihood of being in a higher BMI category significantly increased for: the worker group with an OR of 1.71 (95% CI: 1.52, 2.92); the rescue/recovery group with an OR of 2.86 (95% CI: 2.12, 3.86); the clean-up worker group with an OR of 1.50 (95% CI: 1.23, 1.82); and the other group with an OR of 1.50 (95% CI: 1.26, 1.79). When examining the latent exposure pattern groups, compared to Group 4 resident, the odds of being in a higher BMI category also significantly increased: for Group 1 worker-high, OR = 1.67 (95% CI: 1.43, 1.96); for Group 2 worker-chronic, OR = 1.64 (95% CI: 1.36, 1.98); and for Group 3 mixer, OR = 1.62 (95% CI: 1.27, 2.07).

3.4. Associations between WTC exposures and BP

In addition to BMI, we examined blood pressure outcomes using multivariable linear regression for continuous DBP and SBP, alongside multivariable logistic regression for the binary outcome of hypertension. These analyses were adjusted for the same covariates. The comprehensive results for these outcomes can be found in Supplementary Table 4. Regarding the binary exposure to the WTC dust cloud, significant increases in DBP, SBP, and the likelihood of hypertension were observed in the ‘Yes’ group compared to the ‘No’ group: for DBP, the increase was 1.54 (95% CI: 0.96, 2.12); for SBP, 2.14 (95% CI: 1.35, 2.93); and for hypertension, OR = 1.05 (95% CI: 1.03, 1.07). Across exposure categories, heightened DBP, SBP, and increased odds of hypertension were noted in the worker, rescue/recovery, and other groups in comparison to the resident reference group. Likewise, among the latent exposure categories, Group 1 worker with both high acute and chronic exposures and Group 3 mixer showed elevated DBP, SBP, and a higher probability of hypertension relative to the reference Group 4 resident.

4. Discussion

This study utilized data from the WTC EHC Survivor population, which is characterized by its substantial diversity in civilians who experienced complex acute and chronic environmental exposures as a result of the WTC disaster. Through our analyses, we explored the different types of WTC exposures and their relationship with BMI and blood pressure levels in the WTC Survivors. Our findings revealed that individuals with a greater degree of exposure to the WTC disaster are more prone to exhibit elevated BMI and blood pressure, thereby contributing valuable insights to the limited research that directly connects WTC exposures to changes in BMI and blood pressure. Furthermore, by integrating our results with those from previous studies, we highlight the urgent need to further investigate the potential mediating roles of metabolic factors, such as BMI and blood pressure, in the dynamic between disaster exposures and health outcomes.

The civilian exposure to the aftermath of the WTC disaster, involving dust, gas, and fumes, was multifaceted and cannot be adequately represented by a simple set of exposure variables. This work addressed the need to understand the impacts from both acute and chronic exposure to WTC-related environmental hazards by acknowledging the complexity of the chemical and environmental components involved. The catastrophic events of September 11, 2001, led to the release of enormous quantities of dust, gas, and fumes following the collapse of the WTC towers, posing significant environmental and occupational hazards. Initial exposure for civilians came from the debris of the buildings' destruction, leading to vast dust clouds as the buildings collapsed, with dust concentrations (Lippmann et al., 2015; Reibman et al., 2016). This exposure was most acute for those within or near the towers, including evacuees and individuals in lower Manhattan and parts of Brooklyn. In the aftermath, the risk of exposure extended to the wider community through chronic interaction with dust and fumes. This was due to the resuspension of dust particles from areas that had not been thoroughly cleaned, including outdoor and indoor spaces, ventilation systems, and from ongoing fires that persisted for four months (Lioy et al., 2006; Lippmann et al., 2015). The entry of particles into nearby buildings and the absence of a systematic cleanup protocol further complicated the situation. Workers returning to their jobs shortly after the disaster, residents, and cleanup crews faced both indoor and outdoor dust exposure. Often, the burden of cleanup fell on the individuals affected, with workers tending to their workspaces and residents their homes, without formal guidance or support. The composition of the settled dust was particularly concerning, consisting of highly alkaline materials with a pH of 11, including pulverized concrete, fiberglass, glass, plastics, and building materials laden with hazardous substances like polycyclic aromatic hydrocarbons, volatile organic compounds, lead, dioxin, and furans (Lioy et al., 2002). Moreover, the indoor dust was characterized by a higher concentration of smaller, potentially more harmful particles (Lioy et al., 2006). The diverse and prolonged nature of these exposures underscores the need for a comprehensive approach to health assessments and interventions for those affected.

In our study within the WTC Survivors cohort, it is critical to highlight that all participants experienced some level of exposure to the WTC disaster, which could be acute, chronic, a combination of both, work-related, and/or from residence. The WTC EHC does not include a 'pure' no-exposure reference group, and thus we acknowledge that the absence of an unexposed control precludes a direct estimation of the health impacts directly attributable to WTC exposure versus those not exposed. Given this context, we opted to designate the 'resident' group as our reference, as the group encountered a comparatively lower degree of acute WTC exposure. However, it's important to note that this group was not only exposed to WTC exposures but also demonstrated demographic and socioeconomic distinctions, including a higher proportion of non-Hispanic White individuals, a greater likelihood of being born in the U.S., higher levels of education, and elevated income brackets. Moreover, these individuals had extremely complex exposures as some moved in or out of their residences. These factors, acknowledged as potential confounders, were systematically accounted for in our analytical models to mitigate their impact on the study's outcomes. To further elucidate the effect of WTC exposure on BMI and BP, we conducted a comparative analysis by matching our 'resident' group with counterparts from the National Health and Nutrition Examination Survey (NHANES) dataset on a 1:1 basis according to recruitment year, age, gender, and race/ethnicity (data not shown). This comparison revealed that BMIs in our 'resident' group were significantly higher than those in the matched NHANES group, suggesting a tangible impact of WTC exposure on this health outcome. These results underscore the influence of even minimal WTC exposure levels on health indicators such as BMI, reinforcing the importance of considering a wide array of exposure experiences in assessing the long-term health consequences of the WTC disaster.

Environmental disasters such as the 9/11 attacks carry profound and often overlooked implications for public health like obesity (De Rubeis et al., 2021; Gray & MacDonald, 2016; Hikichi et al., 2019; Jia et al., 2021). The disruption caused by such events extends beyond immediate health hazards, leading to long-term lifestyle alterations that influence BMI. In the aftermath of the attacks, individuals exposed to the disaster faced acute chemical exposures from the release of toxic substances when the buildings collapsed. While the direct causal relationship between specific WTC exposure components and BMI increase is not fully established, there is emerging evidence suggesting potential mechanisms. For example, many of the compounds present in the WTC dust, such as polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans, are known endocrine disruptors (Trasande et al., 2012). EDCs can interfere with hormonal regulation, potentially affecting metabolism and weight gain (Heindel et al., 2017). The WTC dust contained high levels of fine and ultrafine particulate matter, and studies have shown associations between PM exposure and increased risk of obesity and metabolic syndrome (Eze et al., 2014; Wei et al., 2016). Dioxins and furans presented in the WTC dust are classified as POPs, and POPs have been associated with adipose tissue dysfunction and obesity (Lee et al., 2014). Based on the above evidence, it is plausible that the combination of chemical exposures, particulate matter, and associated stress could contribute to the observed increases in BMI among WTC-exposed individuals. Moreover, there is evidence from both animal and human metabolomics studies that link environmental pollutants to metabolic alterations that may predispose individuals to obesity. For instance, (Teppala et al., 2012) conducted a metabolomics study in humans, finding that bisphenol A exposure was associated with altered metabolic pathways related to obesity and diabetes. Additionally, the trauma and chronic stress endured by survivors and those grieving lost loved ones has been linked to long-term psychological effects, including post-traumatic stress disorder (PTSD), anxiety, and depression (Rosen et al., 2022; Rosen et al., 2019). Such conditions often result in modified eating behaviors, with a tendency toward consuming high-calorie, low-nutrient foods, and a reduction in physical activity—both critical determinants of BMI (Buscemi et al., 2013; Konttinen et al., 2019). Stress-induced hormonal changes, especially elevated cortisol levels, are also known to contribute to weight gain (Hewagalamulage et al., 2016; Vicennati et al., 2009). The disaster's aftermath also triggered lifestyle changes, such as displacement, the loss of recreational spaces, and disruptions to daily routines. These changes led to decreased physical activity and altered dietary habits, including an increased dependence on convenience foods, thereby contributing to a rising trend in BMI among the affected populations (Hewagalamulage et al., 2016). Thus, the relationship between the exposures resulting from the WTC attacks and BMI is intricate, influenced by a blend of environmental, psychological, and lifestyle factors, highlighting the complex ways in which such disasters can impact health and well-being.

There are many studies that have found associations between BMI and exposure to particulate matter or dust. A notable WTC-specific study is that of (Kwon et al., 2021), who conducted a longitudinal cohort study on WTC-exposed firefighters and found that metabolic risk factors, including BMI, were associated with WTC exposure and subsequent lung disease. In addition, (Wei et al., 2016) found that long-term exposure to high levels of PM2.5 in Beijing was associated with increased risk of obesity; (Mao et al., 2017) observed that long-term PM2.5 exposures were associated with increased BMI in adults in China; and (Shamy et al., 2017) reported that exposure to desert dust in Saudi Arabia was associated with increased BMI in adults. These studies, conducted in various populations and settings, consistently show associations between particulate matter or dust exposure and increased BMI or related metabolic outcomes. The findings align with our results on WTC exposure, suggesting a broader pattern of how environmental particulate exposures may impact body weight. Meanwhile, there are studies on other disasters that provide relevant comparisons, suggesting that exposure to various types of environmental disasters can have long-term impacts on metabolic health, including increased BMI and related conditions. For example, (Ohira et al., 2016) found that evacuees from the Fukushima disaster (Japan, 2011) had increased BMI and higher risks of diabetes and hyperlipidemia compared to non-evacuees, and (Strelitz et al., 2019) reported that clean-up workers exposed to the oil spill had a higher prevalence of obesity and related metabolic conditions years after the disaster (Gulf of Mexico, 2010).

Current studies within WTC cohorts are diligently exploring the intricate relationship between WTC exposures, BMI, and health outcome such as lung function (Caraher et al., 2017; Cleven et al., 2021; Kwon et al., 2019). It is established that exposure to the WTC disaster is linked to decreased lung function in both FDNY and Survivor cohorts (Cleven et al., 2021; Liu et al., 2012; Wang et al., 2023). Concurrently, there is a recognized correlation where an increase in BMI is associated with a reduction in critical pulmonary function metrics—a finding consistently observed worldwide, across genders, in both healthy individuals and those suffering from conditions such as chronic obstructive pulmonary disease (COPD) (Brock et al., 2020; Dixon & Peters, 2018; Mafort et al., 2016). Significantly, research by de la Hoz et al. (de la Hoz et al., 2019) has identified a direct correlation between BMI and quantitative chest CT measured airway wall thickness in WTC workers, underscoring the interactive effect of BMI and WTC exposures on lung function. Similarly, Kwon et al. (Kwon et al., 2021) have determined that BMI is a leading metabolic factor contributing to the development of lung disease related to the

WTC disaster. Integrating this body of evidence with our findings suggests BMI's potential role as a mediator in the relationship between WTC exposures and lung function diseases. This insight lays the groundwork for our forthcoming research direction, aiming to further elucidate this connection.

This study has several significant advantages. The extensive sample size, varied population demographics, and diverse exposure scenarios within the WTC EHC present a unique platform for examining the impacts of complex disaster exposure on obesity. To the best of our knowledge, this study is the first attempt in WTC cohorts to explicitly quantify the relationships between WTC exposures, BMI, and blood pressure. It also lays a crucial foundation for future investigations into how BMI and other metabolic factors might serve as potential mediators in the relationship of WTC exposures on lung function and other health outcomes. However, this study is not without its limitations. The research may be influenced by selection and recall biases, given its reliance on a self-referred cohort, where participation hinged on a pre-existing diagnosis and potential exposure to WTC dust. We acknowledge that BMI has limitations as an indicator of obesity, as it does not differentiate among body compositions or account for factors such as muscle mass, bone density, and overall body fat distribution. Despite these limitations, BMI remains a widely used and easily obtainable measure in large-scale epidemiological studies, providing a useful, albeit imperfect, proxy for overall adiposity and allowing for comparisons across different populations and with other studies in the field of WTC health research. In this analysis, only BMI and blood pressure readings taken during the initial visit were considered. Future research endeavors will expand to include repeated measures, aiming to assess their impact on longitudinal health changes. It's also noteworthy that this study did not account for occupational exposures or exposures stemming from other natural or man-made disasters, marking an area for potential future exploration.

5. Conclusions

We assessed the relationships between WTC exposures and BMI among the WTC Survivors. The findings from our multivariable linear, quantile, and logistic regression analyses indicated that participants who experienced higher levels of acute and chronic WTC exposures had increased BMI and blood pressure levels. These results underscore the complex interplay between WTC exposures and metabolic risk factors. This study not only broadens our understanding of the impact of disaster-related exposures on health but also emphasizes the complexity of these relationships, underscoring the importance of comprehensive evaluations in related research. Future research should aim to uncover the underlying mechanisms of these impacts. Additionally, conducting longitudinal studies and mediation analyses would be beneficial in investigating the influence of metabolic factors such as BMI and blood pressure in the relationships between WTC exposures and health conditions in WTC cohorts or other related populations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

The datasets used in this paper are from the clinical databases at the WTC EHC Data Center. We only used de-identified and anonymized information. The datasets are not publicly available, but the de-identified and anonymized information is potentially available upon reasonable request to the WTC EHC Data Center.

Abbreviation list

BMI	body mass index
BP	blood pressure
CI	confidence interval
DBP	diastolic blood pressures
IQR	interquartile range
OR	odds ratio
SBP	systolic blood pressures
WTC	World Trade Center
WTC EHC	World Trade Center Environmental Health Center
WTCHP	World Trade Center Health Program

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Highlights

- Environmental disasters have a big impact on population health like metabolic risk factors
- WTC EHC Survivors had complex exposures to WTC dust and fumes
- Higher levels of WTC exposure are related to increased BMI and blood pressure levels
- There is a complex interplay between WTC exposures and metabolic risk factors

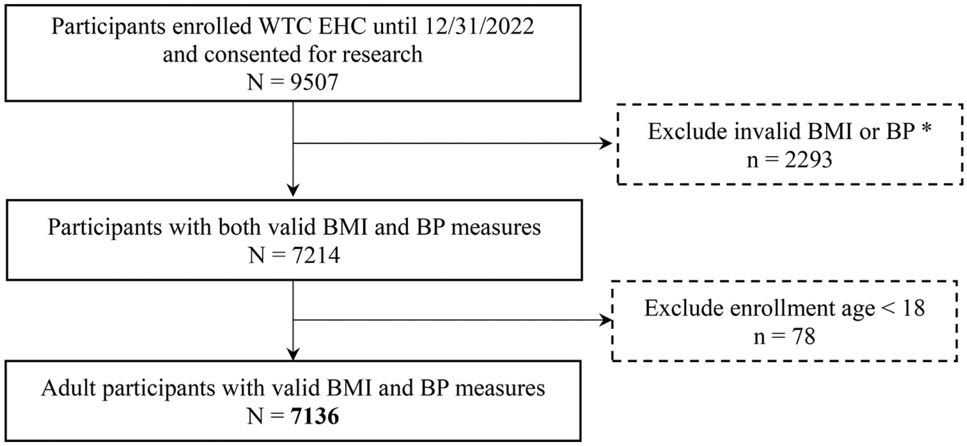

Figure 1:

Flowchart of data inclusion.

* Data collection experienced a considerable disruption throughout the pandemic period.

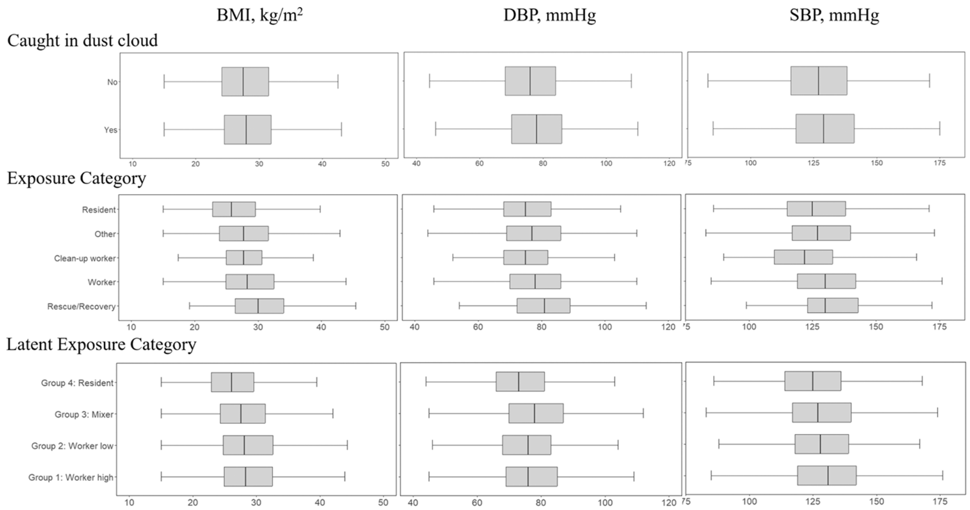

Figure 2.

Distributions of BMI, DBP, and SBP in different WTC exposure characterization subgroups. The upper and lower whiskers of the box plots represent the largest value within 1.5 times the IQR above the 75th percentile and the smallest value within 1.5 times IQR below the 25th percentile, respectively. Dots beyond these bars are not displayed.

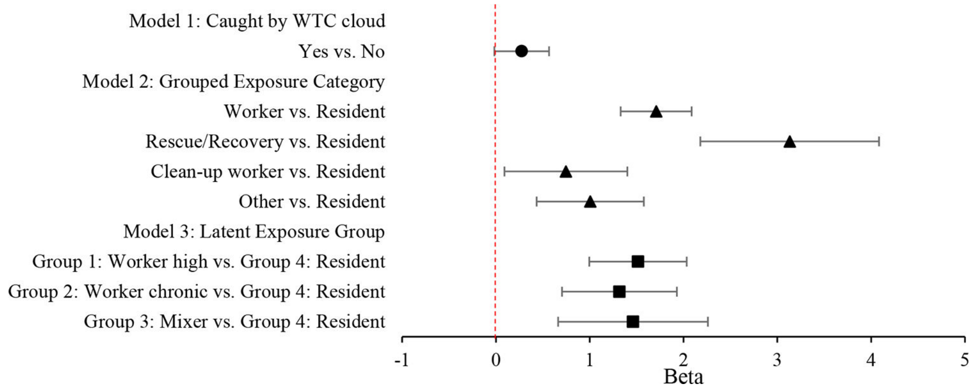

Figure 3.

Associations between different WTC exposure characterizations and continuous BMI through multivariable linear regression models.

All models were adjusted for confounders including age at enrollment, gender, ethnicity/race, born outside of US, income, education, insurance, smoking status, and enrollment year category.

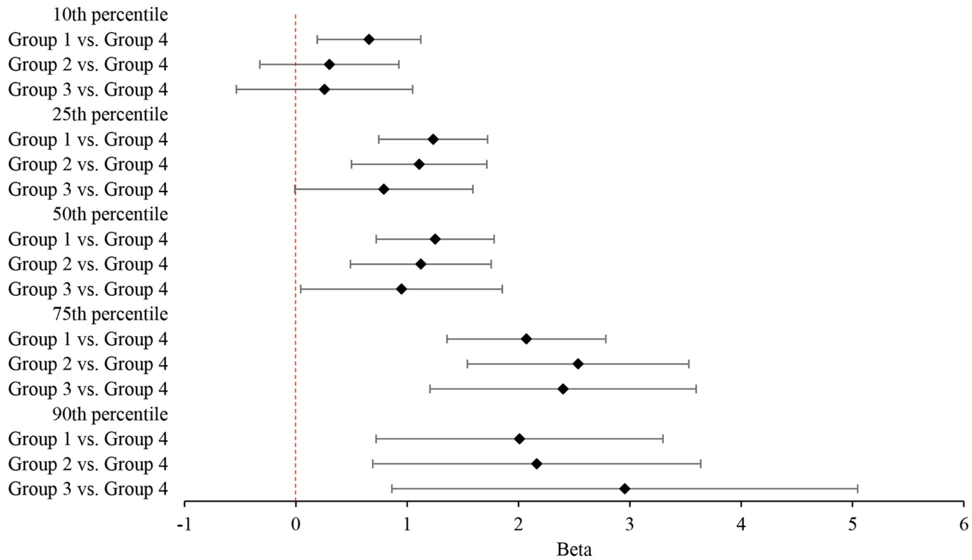

Figure 4.

Associations between WTC latent exposure pattern groups and continuous BMI through multivariable quantile regression models across different BMI quantile levels.

Group 1: Worker with both high acute and chronic exposures (labelled as 'Group 1: Worker high'); Group 2: Worker with low acute but moderate/high chronic exposures (labelled as 'Group 2: Worker chronic'); Group 3: Mixer with high missing exposures (labelled as 'Group 3: Mixer'); Group 4: Resident with home exposures (labelled as 'Group 4: Resident').

All models were adjusted for confounders including age at enrollment, gender, ethnicity/race, born outside of US, income, education, insurance, smoking status, and enrollment year category.

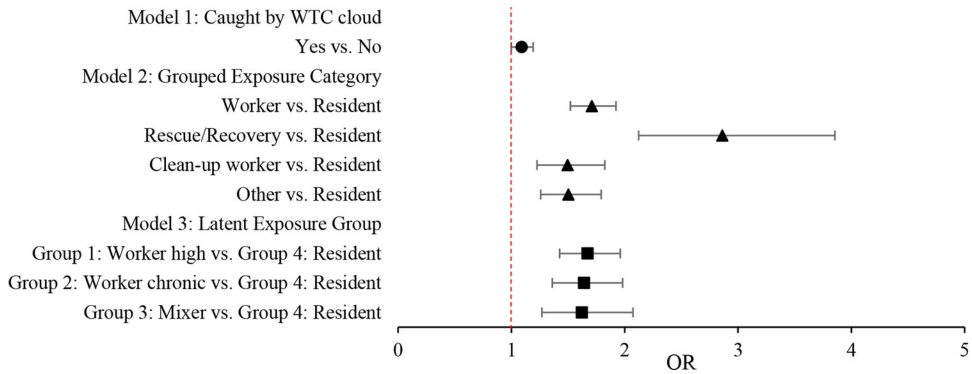

Figure 5.

Associations between different WTC exposure characterizations and categorical BMI through multivariable ordered logistic regression models.

*BMI categories were defined as Normal < 25 kg/m^2; Overweight ≥ 25 kg/m^2 and < 30 kg/m^2; Obese ≥ 30 kg/m^2.

All models were adjusted for confounders including age at enrollment, gender, ethnicity/race, born outside of US, income, education, insurance, smoking status, and enrollment year category.

Table 1.

Characteristics of included participants by BMI group.

N	Overall 7136	Normal 2063	Overweight 2568	Obese 2505	P value
BMI, kg/m^2, mean (SD)	28.73 (6.42)	22.23 (2.08)	27.38 (1.43)	35.47 (5.44)	<0.001
DBP, mmHg, mean (SD)	77.34 (12.82)	73.63 (12.88)	77.61 (12.07)	80.13 (12.77)	<0.001
SBP, mmHg, mean (SD)	129.54 (17.95)	122.51 (17.59)	129.24 (16.58)	135.65 (17.41)	<0.001
Caught in WTC cloud, n (%)					0.038
No	3419 (47.9)	1032 (50.0)	1229 (47.9)	1158 (46.2)	
Yes	3717 (52.1)	1031 (50.0)	1339 (52.1)	1347 (53.8)	
Exposure Category, n (%)					<0.001
Resident	1497 (21.0)	640 (31.0)	503 (19.6)	354 (14.1)	
Worker	4085 (57.2)	1016 (49.2)	1456 (56.7)	1613 (64.4)	
Rescue/Recovery	188 (2.6)	27 (1.3)	65 (2.5)	96 (3.8)	
Clean-up worker	716 (10.0)	173 (8.4)	323 (12.6)	220 (8.8)	
Other	650 (9.1)	207 (10.0)	221 (8.6)	222 (8.9)	
Latent exposure pattern group, n (%)					<0.001
Group 1: Worker high	1985 (27.8)	495 (24.0)	716 (27.9)	774 (30.9)	
Group 2: Worker low	811 (11.4)	209 (10.1)	281 (10.9)	321 (12.8)	
Group 3: Mixer	3581 (50.2)	1048 (50.8)	1303 (50.7)	1230 (49.1)	
Group 4: Resident	759 (10.6)	311 (15.1)	268 (10.4)	180 (7.2)	
Enrollment year category, n (%)					0.037
Before 2011	3226 (45.2)	942 (45.7)	1189 (46.3)	1095 (43.7)	
Between 2011 and 2015	1582 (22.2)	488 (23.7)	549 (21.4)	545 (21.8)	
Between 2016 and 2020	2328 (32.6)	633 (30.7)	830 (32.3)	865 (34.5)	
Age at enrollment, years, mean (SD)	53.62 (12.49)	52.26 (13.64)	53.78 (12.49)	54.57 (11.35)	<0.001
Age at 911, years, mean (SD)	42.64 (11.63)	41.48 (12.88)	42.89 (11.39)	43.33 (10.68)	<0.001
Gender, n (%)					<0.001
Female	3553 (49.8)	1221 (59.2)	1063 (41.4)	1269 (50.7)	
Male	3583 (50.2)	842 (40.8)	1505 (58.6)	1236 (49.3)	
Ethnicity/Race, n (%)					<0.001
Hispanic	1836 (25.7)	400 (19.4)	736 (28.7)	700 (27.9)	
Non-Hispanic White	3125 (43.8)	994 (48.2)	1124 (43.8)	1007 (40.2)	
Non-Hispanic Black	1418 (19.9)	280 (13.6)	446 (17.4)	692 (27.6)	
Non-Hispanic Other	757 (10.6)	389 (18.9)	262 (10.2)	106 (4.2)	
Born outside of US, n (%)					<0.001
No	4322 (60.6)	1204 (58.4)	1436 (55.9)	1682 (67.1)	
Yes	2814 (39.4)	859 (41.6)	1132 (44.1)	823 (32.9)	
Income, n (%)					0.001
Less than or equal to $15,000/year	2394 (33.5)	763 (37.0)	842 (32.8)	789 (31.5)	
$15,001 – $30,000/year	1039 (14.6)	304 (14.7)	381 (14.8)	354 (14.1)	
More than $30,000/year	3459 (48.5)	920 (44.6)	1260 (49.1)	1279 (51.1)	

	Overall	Normal	Overweight	Obese	P value
N	**7136**	**2063**	**2568**	**2505**	
Do not know/Refused	244 (3.4)	76 (3.7)	85 (3.3)	83 (3.3)	
Education, n (%)					0.002
Equal or less than high school	2094 (29.3)	546 (26.5)	797 (31.0)	751 (30.0)	
More than high school	5042 (70.7)	1517 (73.5)	1771 (69.0)	1754 (70.0)	
Insurance, n (%)					<0.001
Uninsured	1156 (16.2)	407 (19.7)	457 (17.8)	292 (11.7)	
Insured	5980 (83.8)	1656 (80.3)	2111 (82.2)	2213 (88.3)	
Smoking status, n (%)					0.009
No	4294 (60.2)	1285 (62.3)	1558 (60.7)	1451 (57.9)	
Yes	2842 (39.8)	778 (37.7)	1010 (39.3)	1054 (42.1)	

Group 1: Worker with both high acute and chronic exposures (labelled as ‘Group 1: Worker high’); Group 2: Worker with low acute but moderate/high chronic exposures (labelled as ‘Group 2: Worker chronic’); Group 3: Mixer with high missing exposures (labelled as ‘Group 3: Mixer’); Group 4: Resident with home exposures (labelled as ‘Group 4: Resident’)