



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

Yuyan Wang^a, Ramazan Alptekin^b, Roberta M. Goldring^b, Beno W. Oppenheimer^b,
Yongzhao Shao^a, Joan Reibman^{b,*}, Mengling Liu^{a,*}

^a Department of Population Health, NYU Grossman School of Medicine, 180 Madison, New York, NY 10016, USA

^b Department of Medicine, NYU Grossman School of Medicine, 550 1st Avenue, New York, NY 10016, USA

ARTICLE INFO

Keywords:

Blood pressure
Body mass index
Environmental exposure
Survivor cohort
World Trade Center 9/11 disaster

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 multiple 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/m² with 95% confidence intervals (CI) of (1.33, 2.09), the rescue/recovery group had an increase of 3.13 kg/m² (95% CI: 2.18, 4.08), the clean-up worker group had an increase of 0.75 kg/m² (95% CI: 0.09, 1.40), and the other mixer group had an increase of 1.01 kg/m² (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.

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

[☆] This paper has been recommended for acceptance by Dr Kelly Polido Kaneshiro Olympio

* Corresponding author.

** Corresponding author.

E-mail addresses: joan.reibman@nyumc.org (J. Reibman), mengling.liu@nyulangone.org (M. Liu).

<https://doi.org/10.1016/j.envpol.2024.125414>

Received 10 April 2024; Received in revised form 1 October 2024; Accepted 27 November 2024

Available online 28 November 2024

0269-7491/© 2024 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

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

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 November 9, 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 Fig. 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' ($\text{BMI} < 18.5$), 'Normal' ($18.5 \leq \text{BMI} < 25$), 'Overweight' ($25 \leq \text{BMI} < 30$), 'Obese I' ($30 \leq \text{BMI} < 35$), 'Obese II' ($35 \leq \text{BMI} < 40$), and 'Obese III' ($40 \geq \text{BMI}$). 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' ($\text{BMI} < 25$), which now included the 'Underweight' group, 'Overweight' ($25 \leq \text{BMI} < 30$), and 'Obese' ($30 \geq \text{BMI}$) consolidating the three obese sub-categories 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

[Fig. 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 November 9, 2001 and smoking status.

[Fig. 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

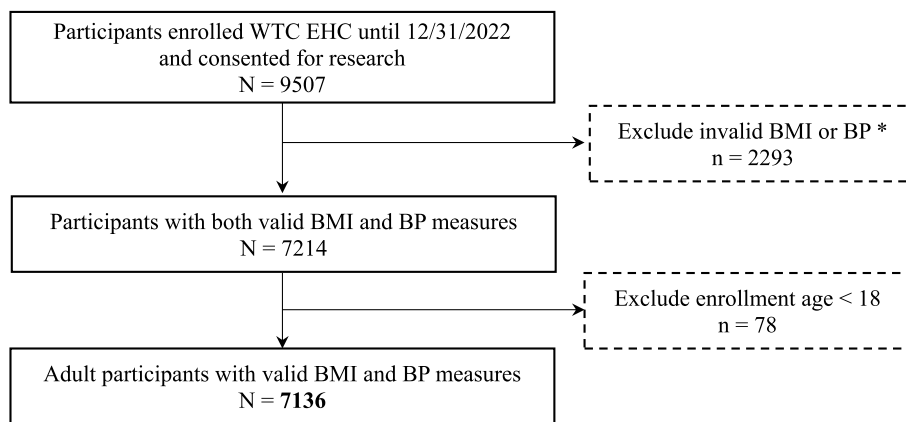


Fig. 1. Flowchart of data inclusion.

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

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. Fig. 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. Fig. 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 Fig. 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

Table 1
Characteristics of included participants by BMI group.

	Overall	Normal	Overweight	Obese	P value
N	7136	2063	2568	2505	
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

Table 1 (continued)

	Overall	Normal	Overweight	Obese	P value
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)	
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').

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 (Liroy 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

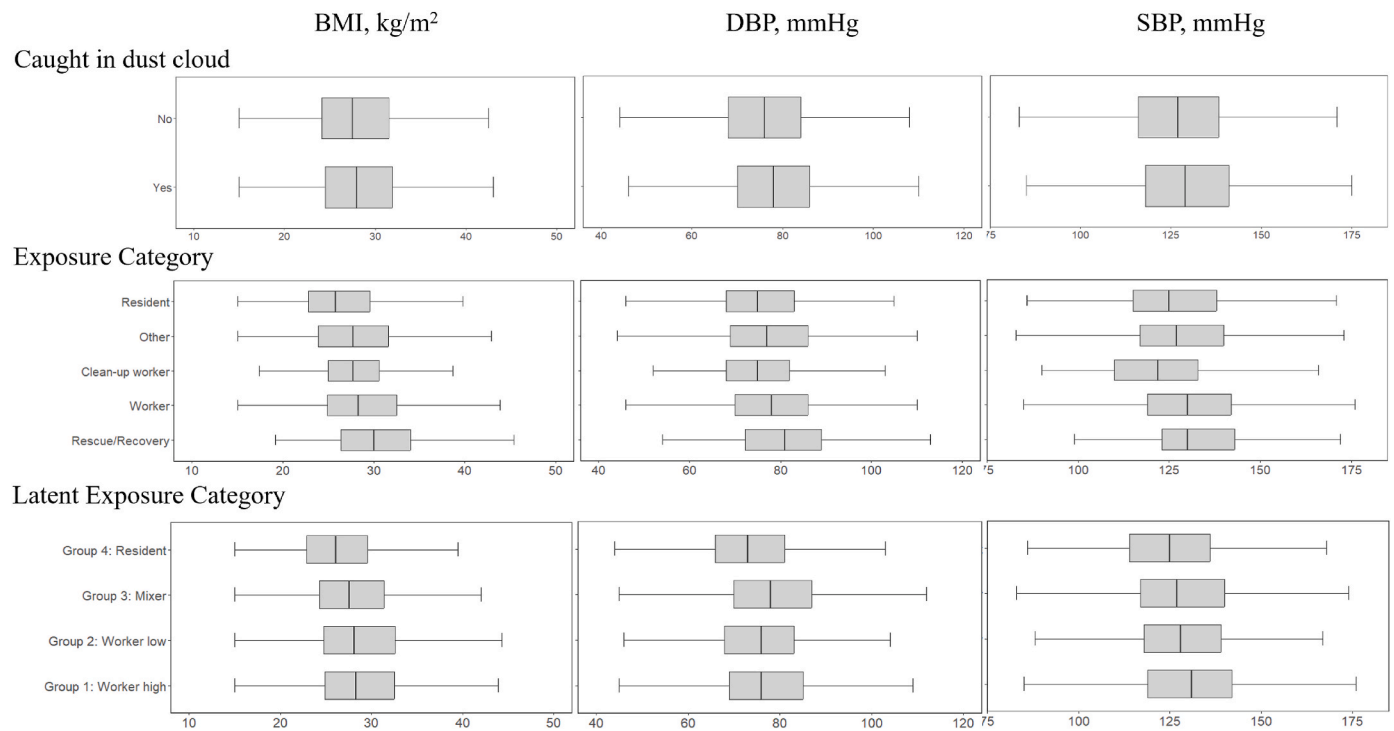


Fig. 2. Distributions of BMI, DBP, and SBP in different WTC exposure characterization subgroups.

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.

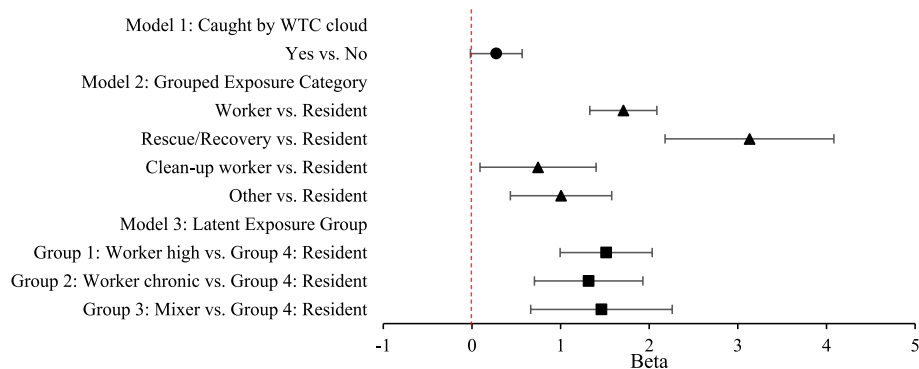


Fig. 3. Associations between different WTC exposure characterizations and continuous BMI through multivariable linear regression models.

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.

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 (Liroy et al., 2002). Moreover, the indoor dust was characterized by a higher concentration of smaller, potentially more harmful particles (Liroy 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

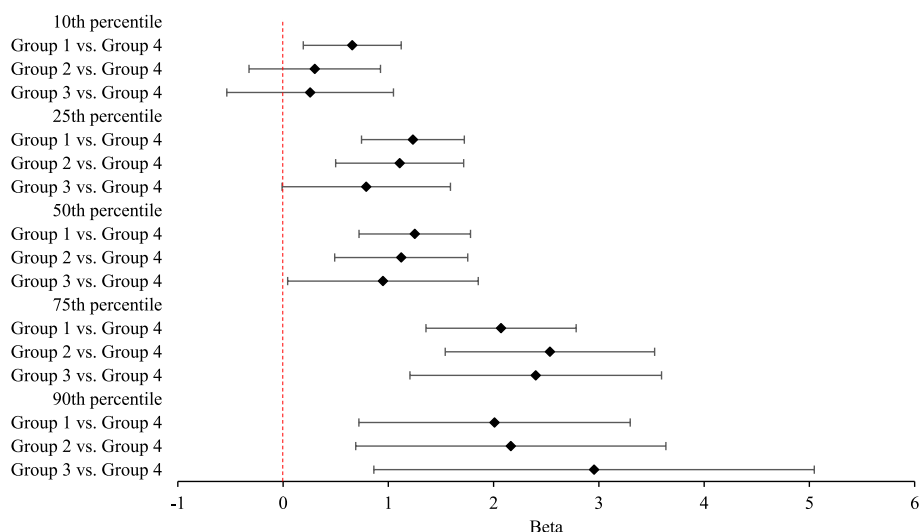


Fig. 4. Associations between WTC latent exposure pattern groups and continuous BMI through multivariable quantile regression models across different BMI quantile levels.

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.

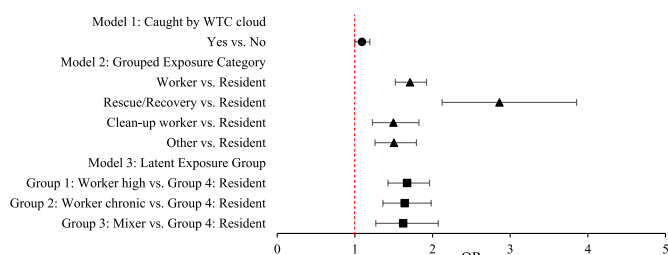


Fig. 5. Associations between different WTC exposure characterizations and categorical BMI through multivariable ordered logistic regression models.

*BMI categories were defined as Normal $<25 \text{ kg/m}^2$; Overweight $\geq 25 \text{ kg/m}^2$ and $<30 \text{ kg/m}^2$; Obese $\geq 30 \text{ kg/m}^2$. 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.

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; Kontinen 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 PM_{2.5} in Beijing was associated with increased risk of obesity (Mao et al., 2017); observed that long-term PM_{2.5} 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 occurred in Japan at 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 on Gulf of Mexico, at 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. (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.

CRedit authorship contribution statement

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

Disclosure statement

The authors have nothing to disclose.

Funding

This study was supported by U01-OH012637, R01-ES032808, U01-OH010404, U01-OH012486, CDC/NIOSH contracts 200-2017-93327 and 200-2017-93427 for the Center of Excellence at WTC EHC Clinical and Data.

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.

Acknowledgments

We thank all the community-based organizations and community members and patients who have contributed to the success of this program.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2024.125414>.

Data availability

The authors do not have permission to share data.

References

- An, R., Ji, M., Yan, H., Guan, C., 2018. Impact of ambient air pollution on obesity: a systematic review. *Int. J. Obes.* 42 (6), 1112–1126. <https://doi.org/10.1038/s41366-018-0089-y>.
- Atamna, A., Elis, A., Gilady, E., Gitter-Azulay, L., Bishara, J., 2017. How obesity impacts outcomes of infectious diseases. *Eur. J. Clin. Microbiol. Infect. Dis.* 36 (3), 585–591. <https://doi.org/10.1007/s10096-016-2835-1>.
- Bell, S.A., Choi, H., Langa, K.M., Iwashyna, T.J., 2019. Health risk behaviors after disaster exposure among older adults. *Prehosp Disaster Med* 34 (1), 95–97. <https://doi.org/10.1017/S1049023X18001231>.
- Brock, J.M., Billeter, A., Muller-Stich, B.P., Herth, F., 2020. Obesity and the lung: what we know today. *Respiration* 99 (10), 856–866. <https://doi.org/10.1159/000509735>.
- Buscemi, S., Castellini, G., Batsis, J.A., Ricca, V., Sprini, D., Galvano, F., Grosso, G., Rosaffio, G., Caravello, M., Rini, G.B., 2013. Psychological and behavioural factors associated with long-term weight maintenance after a multidisciplinary treatment of uncomplicated obesity. *Eat. Weight Disord.* 18 (4), 351–358. <https://doi.org/10.1007/s40519-013-0059-2>.
- Caraher, E.J., Kwon, S., Haider, S.H., Crowley, G., Lee, A., Ebrahim, M., Zhang, L., Chen, L.C., Gordon, T., Liu, M., Prezant, D.J., Schmidt, A.M., Nolan, A., 2017. Receptor for advanced glycation end-products and World Trade Center particulate induced lung function loss: a case-cohort study and murine model of acute particulate exposure. *PLoS One* 12 (9), e0184331. <https://doi.org/10.1371/journal.pone.0184331>.
- Cleven, K.L., Rosenzvit, C., Nolan, A., Zeig-Owens, R., Kwon, S., Weiden, M.D., Skerker, M., Halpren, A., Prezant, D.J., 2021. Twenty-year reflection on the impact of world trade center exposure on pulmonary outcomes in fire department of the city of New York (FDNY) rescue and recovery workers. *Lung* 199 (6), 569–578. <https://doi.org/10.1007/s00408-021-00493-z>.
- Collaboration, N.C.D.R.F., 2019. Rising rural body-mass index is the main driver of the global obesity epidemic in adults. *Nature* 569 (7755), 260–264. <https://doi.org/10.1038/s41586-019-1171-x>.
- Dahmer, M.K., Yang, G., Zhang, M., Quasney, M.W., Sapru, A., Weeks, H.M., Sinha, P., Curley, M.A.Q., Delucchi, K.L., Calfee, C.S., Flori, H., Restore, investigators, B.S., Pediatric Acute Lung, I., Sepsis Investigators, N., 2022. Identification of phenotypes in paediatric patients with acute respiratory distress syndrome: a latent class analysis. *Lancet Respir. Med.* 10 (3), 289–297. [https://doi.org/10.1016/S2213-2600\(21\)00382-9](https://doi.org/10.1016/S2213-2600(21)00382-9).
- Dancuse, K.N., Laplante, D.P., Fraser, S., Brunet, A., Ciampi, A., Schmitz, N., King, S., 2012. Prenatal exposure to a natural disaster increases risk for obesity in 5(1/2)-year-old children. *Pediatr. Res.* 71 (1), 126–131. <https://doi.org/10.1038/pr.2011.18>.
- Darbre, P.D., 2017. Endocrine disruptors and obesity. *Curr Obes Rep* 6 (1), 18–27. <https://doi.org/10.1007/s13679-017-0240-4>.
- de la Hoz, R.E., Liu, X., Celedon, J.C., Doucette, J.T., Jeon, Y., Reeves, A.P., San Jose Estepar, R., 2019. Association of obesity with quantitative chest CT measured airway wall thickness in WTC workers with lower airway disease. *Lung* 197 (4), 517–522. <https://doi.org/10.1007/s00408-019-00246-z>.
- De Rubeis, V., Lee, J., Anwer, M.S., Yoshida-Montezuma, Y., Andreaacchi, A.T., Stone, E., Iftikhar, S., Morgenstern, J.D., Rebinsky, R., Neil-Sztramko, S.E., Alvarez, E., Apatu, E., Anderson, L.N., 2021. Impact of disasters, including pandemics, on cardiometabolic outcomes across the life-course: a systematic review. *BMJ Open* 11 (5), e047152. <https://doi.org/10.1136/bmjopen-2020-047152>.
- Dixon, A.E., Peters, U., 2018. The effect of obesity on lung function. *Expert Rev Respir Med* 12 (9), 755–767. <https://doi.org/10.1080/17476348.2018.1506331>.
- Eze, I.C., Schaffner, E., Fischer, E., Schikowski, T., Adam, M., Imboden, M., Tsai, M., Carballo, D., von Eckardstein, A., Kunzli, N., Schindler, C., Probst-Hensch, N., 2014. Long-term air pollution exposure and diabetes in a population-based Swiss cohort. *Environ. Int.* 70, 95–105. <https://doi.org/10.1016/j.envint.2014.05.014>.
- Farris, S.G., Paulus, D.J., Gonzalez, A., Mahaffey, B.L., Bromet, E.J., Luft, B.J., Kotov, R., Zvolensky, M.J., 2016. Posttraumatic stress symptoms and body mass index among World Trade Center disaster-exposed smokers: a preliminary examination of the role of anxiety sensitivity. *Psychiatry Res* 241, 135–140. <https://doi.org/10.1016/j.psychres.2016.04.074>.
- Field, A.E., Coakley, E.H., Must, A., Spadano, J.L., Laird, N., Dietz, W.H., Rimm, E., Colditz, G.A., 2001. Impact of overweight on the risk of developing common chronic diseases during a 10-year period. *Arch. Intern. Med.* 161 (13), 1581–1586. <https://doi.org/10.1001/archinte.161.13.1581>.
- Finucane, M.M., Stevens, G.A., Cowan, M.J., Danaei, G., Lin, J.K., Paciorek, C.J., Singh, G.M., Gutierrez, H.R., Lu, Y., Bahalim, A.N., Farzadfar, F., Riley, L.M., Ezzati, M., Global Burden of Metabolic Risk Factors of Chronic Diseases Collaborating, G., 2011. National, regional, and global trends in body-mass index since 1980: systematic analysis of health examination surveys and epidemiological studies with 960 country-years and 9.1 million participants. *Lancet* 377 (9765), 557–567. [https://doi.org/10.1016/S0140-6736\(10\)62037-5](https://doi.org/10.1016/S0140-6736(10)62037-5).
- Flegal, K.M., Graubard, B.I., Williamson, D.F., Gail, M.H., 2005. Excess deaths associated with underweight, overweight, and obesity. *JAMA* 293 (15), 1861–1867. <https://doi.org/10.1001/jama.293.15.1861>.
- Flegal, K.M., Kit, B.K., Orpana, H., Graubard, B.I., 2013. Association of all-cause mortality with overweight and obesity using standard body mass index categories: a systematic review and meta-analysis. *JAMA* 309 (1), 71–82. <https://doi.org/10.1001/jama.2012.113905>.
- Gray, L., MacDonald, C., 2016. Morbid obesity in disasters: bringing the "conspicuously invisible" into focus. *Int J Environ Res Public Health* 13 (10). <https://doi.org/10.3390/ijerph13101029>.
- Gutin, I., 2018. In BMI we trust: reframing the body mass index as a measure of health. *Soc Theory Health* 16 (3), 256–271. <https://doi.org/10.1057/s41285-017-0055-0>.
- Heindel, J.J., Blumberg, B., Cave, M., Machtinger, R., Mantovani, A., Mendez, M.A., Nadal, A., Palanza, P., Panzica, G., Sargis, R., Vandenberg, L.N., Vom Saal, F., 2017. Metabolism disrupting chemicals and metabolic disorders. *Reprod. Toxicol.* 68, 3–33. <https://doi.org/10.1016/j.reprotox.2016.10.001>.
- Hewagalamulage, S.D., Lee, T.K., Clarke, I.J., Henry, B.A., 2016. Stress, cortisol, and obesity: a role for cortisol responsiveness in identifying individuals prone to obesity. *Domest. Anim. Endocrinol.* 56 (Suppl. 1), S112–S120. <https://doi.org/10.1016/j.domaniend.2016.03.004>.
- Hikichi, H., Aida, J., Kondo, K., Tsuboya, T., Kawachi, I., 2019. Residential relocation and obesity after a natural disaster: a natural experiment from the 2011 Japan Earthquake and Tsunami. *Sci. Rep.* 9 (1), 374. <https://doi.org/10.1038/s41598-018-36906-y>.
- Jia, P., Dai, S., Rohli, K.E., Rohli, R.V., Ma, Y., Yu, C., Pan, X., Zhou, W., 2021. Natural environment and childhood obesity: a systematic review. *Obes. Rev.* 22 (Suppl. 1), e13097. <https://doi.org/10.1111/obr.13097>. Suppl. 1.
- Jung, K.H., Perzanowski, M., Rundle, A., Moors, K., Yan, B., Chillrud, S.N., Whyatt, R., Camann, D., Perera, F.P., Miller, R.L., 2014. Polycyclic aromatic hydrocarbon exposure, obesity and childhood asthma in an urban cohort. *Environ. Res.* 128, 35–41. <https://doi.org/10.1016/j.envres.2013.12.002>.
- Kahn, L.G., Han, X., Koshy, T.T., Shao, Y., Chu, D.B., Kannan, K., Trasande, L., 2018. Adolescents exposed to the World Trade Center collapse have elevated serum dioxin and furan concentrations more than 12years later. *Environ. Int.* 111, 268–278. <https://doi.org/10.1016/j.envint.2017.11.026>.
- Kim, J.S., Chen, Z., Alderete, T.L., Toledo-Corral, C., Lurmann, F., Berhane, K., Gilliland, F.D., 2019. Associations of air pollution, obesity and cardiometabolic health in young adults: the Meta-AIR study. *Environ. Int.* 133 (Pt A), 105180. <https://doi.org/10.1016/j.envint.2019.105180>.
- Kontinen, H., van Strien, T., Mannisto, S., Jousilahti, P., Haukka, A., 2019. Depression, emotional eating and long-term weight changes: a population-based prospective study. *Int J Behav Nutr Phys Act* 16 (1), 28. <https://doi.org/10.1186/s12966-019-0791-8>.
- Koshy, T.T., Attina, T.M., Ghassabian, A., Gilbert, J., Burdine, L.K., Marmor, M., Honda, M., Chu, D.B., Han, X., Shao, Y., Kannan, K., Urbina, E.M., Trasande, L., 2017. Serum perfluoroalkyl substances and cardiometabolic consequences in adolescents exposed to the World Trade Center disaster and a matched comparison group. *Environ. Int.* 109, 128–135. <https://doi.org/10.1016/j.envint.2017.08.003>.
- Kushner, R.F., Kahan, S., 2018. Introduction: the state of obesity in 2017. *Med Clin North Am* 102 (1), 1–11. <https://doi.org/10.1016/j.mcna.2017.08.003>.
- Kwon, S., Crowley, G., Caraher, E.J., Haider, S.H., Lam, R., Veerappan, A., Yang, L., Liu, M., Zeig-Owens, R., Schwartz, T.M., Prezant, D.J., Nolan, A., 2019. Validation of predictive metabolic syndrome biomarkers of world trade center lung injury: a 16-year longitudinal study. *Chest* 156 (3), 486–496. <https://doi.org/10.1016/j.chest.2019.02.019>.
- Kwon, S., Lee, M., Crowley, G., Schwartz, T., Zeig-Owens, R., Prezant, D.J., Liu, M., Nolan, A., 2021. Dynamic metabolic risk profiling of world trade center lung disease: a longitudinal cohort study. *Am. J. Respir. Crit. Care Med.* 204 (9), 1035–1047. <https://doi.org/10.1164/rccm.202006-2617OC>.
- Landrigan, P.J., Lioy, P.J., Thurston, G., Berkowitz, G., Chen, L.C., Chillrud, S.N., Gavett, S.H., Georgopoulos, P.G., Geyh, A.S., Levin, S., Perera, F., Rappaport, S.M., Small, C., Group, N.W.T.C.W., 2004. Health and environmental consequences of the world trade center disaster. *Environ. Health Perspect.* 112 (6), 731–739. <https://doi.org/10.1289/ehp.6702>.
- Lee, D.H., Porta, M., Jacobs Jr., D.R., Vandenberg, L.N., 2014. Chlorinated persistent organic pollutants, obesity, and type 2 diabetes. *Endocr. Rev.* 35 (4), 557–601. <https://doi.org/10.1210/er.2013-1884>.
- Lioy, P.J., Pellizzari, E., Prezant, D., 2006. The World Trade Center aftermath and its effects on health: understanding and learning through human-exposure science. *Environ. Sci. Technol.* 40 (22), 6876–6885. <https://doi.org/10.1021/es062980e>.
- Lioy, P.J., Weisel, C.P., Millette, J.R., Eisenreich, S., Vallero, D., Offenberger, J., Buckley, B., Turpin, B., Zhong, M., Cohen, M.D., Prophete, C., Yang, I., Stiles, R., Chee, G., Johnson, W., Porcja, R., Alimokhtari, S., Hale, R.C., Weschler, C., Chen, L.C., 2002. Characterization of the dust/smoke aerosol that settled east of the World Trade Center (WTC) in lower Manhattan after the collapse of the WTC 11 September 2001. *Environ. Health Perspect.* 110 (7), 703–714. <https://doi.org/10.1289/ehp.02110703>.
- Lippmann, M., Cohen, M.D., Chen, L.C., 2015. Health effects of World Trade Center (WTC) Dust: an unprecedented disaster's inadequate risk management. *Crit. Rev. Toxicol.* 45 (6), 492–530. <https://doi.org/10.3109/10408444.2015.1044601>.
- Liu, M., Qian, M., Cheng, Q., Berger, K.I., Shao, Y., Turetz, M., Kazeros, A., Parsia, S., Goldring, R.M., Caplan-Shaw, C., Elena Fernandez-Beros, M., Marmor, M., Reibman, J., 2012. Longitudinal spirometry among patients in a treatment program for community members with World Trade Center-related illness. *J. Occup. Environ. Med.* 54 (10), 1208–1213. <https://doi.org/10.1097/JOM.0b013e31826bb78e>.
- Mafort, T.T., Rufino, R., Costa, C.H., Lopes, A.J., 2016. Obesity: systemic and pulmonary complications, biochemical abnormalities, and impairment of lung function. *Multidiscip Respir Med* 11, 28. <https://doi.org/10.1186/s40248-016-0066-z>.
- Mao, G., Nachman, R.M., Sun, Q., Zhang, X., Koehler, K., Chen, Z., Hong, X., Wang, G., Caruso, D., Zong, G., Pearson, C., Ji, H., Biswal, S., Zuckerman, B., Wills-Karp, M., Wang, X., 2017. Individual and joint effects of early-life ambient exposure and maternal prepregnancy obesity on childhood overweight or obesity. *Environ. Health Perspect.* 125 (6), 067005. <https://doi.org/10.1289/EHP261>.
- Maslow, C.B., Friedman, S.M., Pillai, P.S., Reibman, J., Berger, K.I., Goldring, R., Stellman, S.D., Farfel, M., 2012. Chronic and acute exposures to the world trade

- center disaster and lower respiratory symptoms: area residents and workers. *Am J Public Health* 102 (6), 1186–1194. <https://doi.org/10.2105/AJPH.2011.300561>.
- Nappi, F., Barrea, L., Di Somma, C., Savanelli, M.C., Muscogiuri, G., Orio, F., Savastano, S., 2016. Endocrine aspects of environmental "obesogen" pollutants. *Int J Environ Res Public Health* 13 (8). <https://doi.org/10.3390/ijerph13080765>.
- Nuttall, F.Q., 2015. Body mass index: obesity, BMI, and health: a critical review. *Nutr. Today* 50 (3), 117–128. <https://doi.org/10.1097/NT.0000000000000092>.
- Ohira, T., Hosoya, M., Yasumura, S., Satoh, H., Suzuki, H., Sakai, A., Ohtsuru, A., Kawasaki, Y., Takahashi, A., Ozasa, K., Kobashi, G., Hashimoto, S., Kamiya, K., Yamashita, S., Abe, M., Fukushima Health Management Survey, G., 2016. Evacuation and risk of hypertension after the great east Japan earthquake: the Fukushima health management Survey. *Hypertension* 68 (3), 558–564. <https://doi.org/10.1161/HYPERTENSIONAHA.116.07499>.
- Petrakis, D., Vassilopoulou, L., Mamoulakis, C., Psycharakis, C., Anifantaki, A., Sifakis, S., Docea, A.O., Tsiaoussis, J., Makrigrannakis, A., Tsatsakis, A.M., 2017. Endocrine disruptors leading to obesity and related diseases. *Int J Environ Res Public Health* 14 (10). <https://doi.org/10.3390/ijerph14101282>.
- Quetelet, L.A., 1994. A treatise on man and the development of his faculties. 1842. *Obes. Res.* 2 (1), 72–85. <https://doi.org/10.1002/j.1550-8528.1994.tb00047.x>.
- Reibman, J., Levy-Carrick, N., Miles, T., Flynn, K., Hughes, C., Crane, M., Lucchini, R.G., 2016. Destruction of the world trade center towers. Lessons learned from an environmental health disaster. *Ann Am Thorac Soc* 13 (5), 577–583. <https://doi.org/10.1513/AnnalsATS.201509-572PS>.
- Ribeiro, C.M., Beserra, B.T.S., Silva, N.G., Lima, C.L., Rocha, P.R.S., Coelho, M.S., Neves, F.A.R., Amato, A.A., 2020. Exposure to endocrine-disrupting chemicals and anthropometric measures of obesity: a systematic review and meta-analysis. *BMJ Open* 10 (6), e033509. <https://doi.org/10.1136/bmjopen-2019-033509>.
- Rosen, R., Shao, Y., Zhang, Q., Bao, J., Zhang, Y., Masurkar, A., Wisniewski, T., Urban, N., Reibman, J., 2022. Cognitive function among world trade center-exposed community members with mental health symptoms. *Int J Environ Res Public Health* 19 (6). <https://doi.org/10.3390/ijerph19063440>.
- Rosen, R., Zhu, Z., Shao, Y., Liu, M., Bao, J., Levy-Carrick, N., Reibman, J., 2019. Longitudinal change of PTSD symptoms in community members after the world trade center destruction. *Int J Environ Res Public Health* 16 (7). <https://doi.org/10.3390/ijerph16071215>.
- Santiago-Colon, A., Daniels, R., Reissman, D., Anderson, K., Calvert, G., Caplan, A., Carreon, T., Katruska, A., Kubale, T., Liu, R., Nembhard, R., Robison, W.A., Yiin, J., Howard, J., 2020. World trade center health program: first decade of research. *Int J Environ Res Public Health* 17 (19). <https://doi.org/10.3390/ijerph17197290>.
- Shamy, M., Alghamdi, M., Khoder, M.I., Mohorjy, A.M., Alkhatim, A.A., Alkhalaf, A.K., Brocato, J., Chen, L.C., Thurston, G.D., Lim, C.C., Costa, M., 2017. Association between exposure to ambient air particulates and metabolic syndrome components in a Saudi arabian population. *Int J Environ Res Public Health* 15 (1). <https://doi.org/10.3390/ijerph15010027>.
- Shi, X., Zheng, Y., Cui, H., Zhang, Y., Jiang, M., 2022. Exposure to outdoor and indoor air pollution and risk of overweight and obesity across different life periods: a review. *Ecotoxicol. Environ. Saf.* 242, 113893. <https://doi.org/10.1016/j.ecoenv.2022.113893>.
- Strelitz, J., Sandler, D.P., Keil, A.P., Richardson, D.B., Heiss, G., Gammon, M.D., Kwok, R. K., Stewart, P.A., Stenzel, M.R., Engel, L.S., 2019. Exposure to total hydrocarbons during cleanup of the deepwater horizon oil spill and risk of heart attack across 5 Years of follow-up. *Am. J. Epidemiol.* 188 (5), 917–927. <https://doi.org/10.1093/aje/kwz017>.
- Teppala, S., Madhavan, S., Shankar, A., 2012. Bisphenol A and metabolic syndrome: results from NHANES. *Int J Endocrinol* 2012, 598180. <https://doi.org/10.1155/2012/598180>.
- Trasande, L., Attina, T.M., Blustein, J., 2012. Association between urinary bisphenol A concentration and obesity prevalence in children and adolescents. *JAMA* 308 (11), 1113–1121. <https://doi.org/10.1001/2012.jama.11461>.
- Tsukiji, J., Cho, S.J., Echevarria, G.C., Kwon, S., Joseph, P., Schenck, E.J., Naveed, B., Prezant, D.J., Rom, W.N., Schmidt, A.M., Weiden, M.D., Nolan, A., 2014. Lysophosphatidic acid and apolipoprotein A1 predict increased risk of developing World Trade Center-lung injury: a nested case-control study. *Biomarkers* 19 (2), 159–165. <https://doi.org/10.3109/1354750X.2014.891047>.
- Vicennati, V., Pasqui, F., Cavazza, C., Pagotto, U., Pasquali, R., 2009. Stress-related development of obesity and cortisol in women. *Obesity* 17 (9), 1678–1683. <https://doi.org/10.1038/oby.2009.76>.
- Wang, Y., Berger, K.I., Zhang, Y., Shao, Y., Goldring, R.M., Reibman, J., Liu, M., 2023. Novel approach to studying effects of inhalational exposure on lung function in civilians exposed to the World Trade Center disaster. *Sci. Rep.* 13 (1), 3218. <https://doi.org/10.1038/s41598-023-30030-2>.
- Wei, Y., Zhang, J.J., Li, Z., Gow, A., Chung, K.F., Hu, M., Sun, Z., Zeng, L., Zhu, T., Jia, G., Li, X., Duarte, M., Tang, X., 2016. Chronic exposure to air pollution particles increases the risk of obesity and metabolic syndrome: findings from a natural experiment in Beijing. *FASEB J* 30 (6), 2115–2122. <https://doi.org/10.1096/fj.201500142>.
- Weiden, M.D., Kwon, S., Caraher, E., Berger, K.I., Reibman, J., Rom, W.N., Prezant, D.J., Nolan, A., 2015. Biomarkers of world trade center particulate matter exposure: physiology of distal airway and blood biomarkers that predict FEV(1) decline. *Semin. Respir. Crit. Care Med.* 36 (3), 323–333. <https://doi.org/10.1055/s-0035-1547349>.
- Whelton, P.K., Carey, R.M., Aronow, W.S., Casey Jr., D.E., Collins, K.J., Dennison Himmelfarb, C., DePalma, S.M., Gidding, S., Jamerson, K.A., Jones, D.W., MacLaughlin, E.J., Muntner, P., Ovbigele, B., Smith Jr., S.C., Spencer, C.C., Stafford, R.S., Taler, S.J., Thomas, R.J., Williams, K.A. Sr., Wright Jr., J.T., 2018. 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APHA/ASH/ASPC/NMA/PCNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: a report of the American college of cardiology/American heart association task force on clinical practice guidelines. *Hypertension* 71 (6), e13–e115. <https://doi.org/10.1161/HYP.0000000000000065>.
- World Medical, A., 2013. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *JAMA* 310 (20), 2191–2194. <https://doi.org/10.1001/jama.2013.281053>.
- Wyka, K., Friedman, S.M., Jordan, H.T., 2020. Probable posttraumatic stress disorder and lower respiratory symptoms among rescue/recovery workers and community members after the 9/11 world trade center attacks-A longitudinal mediation analysis. *Psychosom. Med.* 82 (1), 115–124. <https://doi.org/10.1097/PSY.0000000000000731>.
- Zhang, Y., Rosen, R., Reibman, J., Shao, Y., 2022. Posttraumatic stress disorder mediates the association between traumatic world trade center dust cloud exposure and ongoing systemic inflammation in community members. *Int J Environ Res Public Health* 19 (14). <https://doi.org/10.3390/ijerph19148622>. Article 35886474.
- Zhou, M., Thayer, W.M., Bridges, J.F.P., 2018. Using latent class analysis to model preference heterogeneity in health: a systematic review. *Pharmacoeconomics* 36 (2), 175–187. <https://doi.org/10.1007/s40273-017-0575-4>.