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Association of firefighting exposures with lung function using a novel job exposure matrix (JEM)

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Abstract

Objectives.—Characterization of firefighters' exposures to dangerous chemicals in smoke from non-wildfire incidents, directly through personal monitoring, and indirectly from work-related records, is scarce. The aim of this study was to evaluate the association between smoke particle exposures (P) and pulmonary function.

Methods.—The study period spanned from January 2010 through September 2021. Routine firefighting particle exposures was estimated using fire incident characteristics, response data, and emission factors from a novel job exposure matrix. Linear mixed effects modelling was employed to estimate changes in pulmonary function as measured by one-second Forced Expiratory Volume (FEV_1). Models controlled for age, race/ethnicity, height, smoking, and weight.

Results.—Every 1000 kg P was associated with 13 mL lower FEV_1 (β=−13.34; 95% CI=−13.98, −12.70) over the entire 12-year follow-up period. When analyzing exposures within 3 months before PFT measurements, 1000 kg P was associated with 27 mL lower FEV_1 (β=−26.87; 95%

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CI=−34.54, −19.20). When evaluating P estimated within 3 months of a pulmonary function test (PFT), stronger associations were observed among those most highly exposed to the World Trade Center (WTC) disaster (β=−12.90; 95% CI=−22.70, −2.89); the association of cumulative exposures was similar for both highly and less highly exposed individuals.

Discussion.—Smoke particle exposures were observed to have modest short- and long-term associations with pulmonary function, particularly in those who, previously, had high levels of WTC exposure. Future work examining the association between P and pulmonary function among non-WTC exposed firefighters will be essential for disentangling the effects of aging, routine firefighting, and WTC-exposures.

Introduction

Firefighters are routinely exposed to combustion byproducts and are surveilled regularly using pulmonary function testing (PFT) (i.e., spirometry) in accordance with National Fire Protection Association (NFPA)-1582 standards.[1] Service time has been extensively used as the exposure surrogate to study the association between firefighting and longitudinal pulmonary function.[2–5] Other proxy exposure measures included retrospective self-reports of exposure, duration at fires, and the sum of career responses.[6–9] Estimates of annual rates of one-second forced expiratory volume (FEV_1) decline from routine (i.e., non-disaster) firefighting vary considerably from −24 to −110 mL/year.[10] There are challenges related to conducting exposure assessments at fire scenes due to the frequency of responses, amount of time spent at fire scenes and the unpredictable nature at which events occur. In 2015, a retrospective job exposure matrix (JEM) was constructed using fire run data and job titles among Chicago, Philadelphia, and San Francisco firefighters.[11] Expanding on this, more recently, a novel JEM was developed to estimate exposures to particulate smoke from structural and non-structural urban fires using data from the Fire Department of the City of New York (FDNY).[12] Specifically, it integrated administratively collected roster and response data which allowed for identification of which participants responded to an incident and their role in responses with particle emissions data using the United States Environmental Protection Agency (US EPA) AP-42 framework,[13, 14] a wide-ranging compilation of emission factors data.

World Trade Center (WTC)-exposed firefighters were heavily exposed to dust and other toxins at the disaster site on September 11, 2001 (9/11) and in the months that followed.[15] Additionally, most of these firefighters were chronically exposed to routine fire exposures during their tenure both before and after the attacks. Numerous studies have evaluated the acute and chronic effects of WTC exposure on lung function in the entire cohort of approximately 16,000 firefighters.[16–19]

This study had two objectives: first, using the novel JEM as an exposure surrogate, to evaluate the association of routine firefighting with pulmonary function in the short- and long-term, as measured by FEV_1; second, to determine the extent to which historical WTC-related exposures in conjunction with routine firefighting exposures were associated with reduced pulmonary function.

Methods

Study population

The source population included WTC-exposed retired firefighters who left the workforce between 9/11/2001 and 9/11/2021 (n=7,843). The population was restricted to non-Hispanic Black, non-Hispanic White, and Hispanic male participants who had at least three PFTs over the course of the study period. Race and sex exclusions were made due to small numbers in certain subgroups. These exclusions consisted of 16 female, 27 Asian, and 7 American Indian participants. Incident data were available electronically beginning in 2010. Participants who retired before 2010, prior to the period which incident response data were fully available electronically (n=4,132) and those who retired between 2010 and 2021 but did not respond to at least one incident in this period (n=540) were excluded. The analytic cohort included participants who retired between January 2010 and September 2021, and responded to at least one incident during this period (n=3,171). All study participants provided informed consent to research and this study was approved by the Albert Einstein College of Medicine Institutional Review Board. A flow of participants is described in Figure 1.

Demographic and anthropometric covariate data as well as dates of birth, hire and retirement were obtained from the FDNY employee database and from routine monitoring exams conducted through the WTC Health Program. Self-reported WTC exposure data were obtained from participants' first post-9/11 medical monitoring exam, most within one year after the attacks.[20] Smoking status was assessed at each monitoring exam as current, former, or never.

Particle exposures

Routine firefighting particle exposures (P) were estimated using fire incident characteristics, response data, and emission factors from the JEM.[12] Briefly, fire incident and response information were provided by the Bureau of Communications at FDNY.[12] Incident variables used in the JEM included fire alarm levels (i.e., 1–5, with level 5 indicating the greatest fire involvement, potential for spread and firefighter response) and incident type (e.g., structural commercial building, non-structural vehicle fire, etc.). Response data included tour roster information such as date/time of an incident and unique codes for each responding firehouse. This enabled linkage of firefighters to specific fire incidents since roster information also included firehouse and date which individuals worked. Roster data also included information regarding their role (i.e., position description). The position description was dichotomized into 'highly exposed' and 'minimally exposed' based on likelihood to be involved in first-line combat of a fire response. P, in kilograms (kg), were estimated for every combination of fire alarm level, incident type, and position description from 2010–2021 using US EPA air emissions methodological framework.[13, 14] Findings are presented per 1,000 kg of particles. For example, approximately one 3rd-5th alarm commercial dwelling fire corresponds to P=1162.94 kg, three brush fires of any alarm level correspond to P=323.86 kg × 3=971.58 kg, and nearly 29 second alarm private dwelling fires corresponds to P=35.23 kg × 29=1021.67 kg.

Pulmonary Function Testing (PFT) Spirometry

As part of the WTC Health Program at the FDNY routine medical monitoring exams are conducted approximately annually. During these evaluations, PFTs, specifically spirometry exams, are performed to assess lung diseases, and, for active-duty firefighters, to assess whether they are medically capable of carrying out job responsibilities. The specific spirometry protocol used at FDNY has been described elsewhere.[17, 21] EasyOne spirometers (NDD Medical Technologies) were employed as part of the medical monitoring regimen. These devices perform automatic quality grading in accordance with the American Thoracic Society standards. While PFTs measure several metrics including vital capacity, for this study the outcome of interest is FEV_1 because is the most reproducible, least effort-dependent, and is most commonly used in longitudinal analyses.[22] Spirometry data included in this study spanned from September 2001 through September 2021. Pre-9/11 data were not included in this study.

Statistical methods

Descriptive statistics

Demographic and other descriptive characteristics for the cohort were calculated as proportions/percentages and means/standard deviations (SD), as appropriate. Each component (i.e., incident type, fire alarm level/severity and highly/minimally exposed fire-runs) used for development of the JEM, and in turn estimation of P, was calculated as an annualized total per individual and was presented as medians and interquartile ranges (IQR: Q1-Q3). A cumulative sum at the end of participants' career was computed for the study period of 2010–2021.

Primary analysis: Evaluating acute and cumulative effects of firefighting exposures on pulmonary function

Linear mixed effects models were used to evaluate the association between exposure, P, and longitudinal FEV_1.[23] All covariates including P were included as fixed effects and the intercept was included as a random effect to account for intra-subject variability and correlations between repeated measures. The specific model is shown below:

$$Y_{ij} = \beta_0 + \beta_1 X_{ij} + Z_{0i} + \epsilon_{ij} \quad \text{Eq. 1}$$

where Y=FEV_1; X=P for each interval; i=each repeated observation; j=each individual participant; β_0=intercept; β_1=regression coefficient for the difference in FEV_1 per P; Z is the matrix of random effects; and ε is the vector of random errors.

Different outcomes were evaluated to assess the acute and chronic impact of particle exposure on lung function. This was done by calculating the sum of P at 15 pre-defined intervals prior to a PFT. At each exam, the sum of P was calculated during the previous 0.25 (3 months), 0.5 (6 months), and 0.75 (9 months), 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, and 10 years before each repeated PFT as well as cumulatively for the entire follow-up period. For example, when estimating exposure for an exam on 12/1/2019, the 3-month outcome will include all P estimated from 9/1/2019 through 12/1/2019. The cumulative outcome for the same exam would include all P from 1/1/2010 (i.e., beginning of follow-up) and 12/1/2019. Mock data are presented in Supplemental Table 1 to illustrate how each outcome variable was ascertained for a given period. Using P as the exposure, unadjusted and adjusted models were fit. Adjusted models included age, race/ethnicity, height, smoking, and weight as covariates. Each participant contributed all available PFT measurements from 2010 to retirement, and their first exam within one year after retirement to allow for precise estimation of lung function in relation to P. In a secondary analysis the cohort was subdivided based on period of retirement: those who left the workforce between 2019–2021 (group a), were analyzed separately from those that retired between 2010–2018 (group b). This cutoff was chosen to allow for an adequate follow-up period (at least 9 years) in terms of data availability for the JEM. Different cutoffs were considered and produced similar results; however, 9 years provided an optimal balance of follow-up time and participant numbers. A sensitivity analysis excluding post-retirement exams was conducted.

To test for effect modification of routine firefighting exposure, P, by previous WTC exposure intensity, the model below was fit (Eq. 2) which included an interaction term between P and WTC arrival time (i.e., arrived at disaster site on 9/11/2001 to 9/12/2001 vs. arrived 9/13/2001 to closing of WTC site) for each outcome. Then, models were stratified by WTC arrival time to illustrate any potential differences in the association between P and lung function by level of WTC exposure intensity.

$$Y_{ij} = \beta_0 + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \beta_3 X_{1ij} * X_{2ij} + Z_{0i} + \epsilon_{ij}$$

Eq. 2

where Y=FEV$_1$; X_1=P for each interval; X_2=WTC arrival time; i=each repeated observation; j=each individual participant; β_0=intercept; β_1=regression coefficient for the difference in FEV$_1$ per P; β_2=regression coefficient for the difference in FEV$_1$ for each level of WTC arrival time; β_3=regression coefficient for the interaction between P and WTC arrival time; Z is the matrix of random effects; and ε is the unobserved vector of random errors.

Secondary analysis: Longitudinal linear mixed effects models by period

In a secondary analysis to understand potential differences between subgroups, linear mixed effects modelling was also used to calculate changes in FEV$_1$ for groups a and b. Rather than P, the exposure measure was years of service, and all covariates were included as fixed effects and intercepts as random effects. A piecewise linear mixed effects model was fit such that the slope could be estimated for two critical periods: i) before exposure data were available - 9/11/2001–12/31/2009; ii) active service years from 2010 through retirement when exposure data were available. Models controlled for the same confounders as above.

The specific model that allows for calculation of the time effects before and after the two critical periods can be found below:

$$\mathrm{Yij} = (\beta 0 + \beta 1\mathrm{tij}) + \mathrm{Zy} + \varepsilon\mathrm{ij} \text{ if } \mathrm{t} \le \mathrm{p1} (\beta 0 + \beta 2\mathrm{k}) + (\beta 1 + \beta 2)\mathrm{tij} + \mathrm{Zy} + \varepsilon\mathrm{ij} \text{ if } \mathrm{t} > \mathrm{p1}$$

Eq 3.

Where $y=FEV_1$; $p_1=2010$; t=time; β_0=adjusted mean FEV_1 at beginning of follow-up; β_1=change in FEV_1 per unit overall elapsed during the follow-up period as a fixed effect; β_2=difference in the change in FEV_1 between the late ($t>p_1$) and early ($t\leq p_1$) periods and for the slope using time elapsed where $t>p_1$;k=knot in 2010; Z is the matrix of random effects; ε is the unobserved vector of random errors; i=each repeated observation; and j=each individual participant.

R v. 4.1.3 and SAS were used for data harmonization, analysis, and graphics. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines.

Results

Study population

The primary analytic cohort included 3,171 participants (N=14,954, PFTs). Demographic characteristics are presented in Table 1. The cohort was homogenous with respect to race/ethnicity, arrival time at the WTC disaster site, height, and weight. The mean age of the cohort was 38.3 (SD=6.1), consisted of predominantly White participants (n=3,008; 94.9%) and responded to the WTC attacks on 9/11/2001–9/12/2001 (n=2,767; 87.3%). In the post-2010 period, when fire incident data (i.e., P) were available, the cohort had an average of over 6 years of follow-up (mean=6.2; SD=3.1) and over 4 PFTs (mean=4.4; SD=2.8). As expected, group a, participants who retired between 2019–2021, had the highest number of post-2010 service years (mean=10.3; SD=0.8) and the most serial PFTs (mean=7.6; SD=1.9) as compared with group b, who retired between 2010–2018 and had fewer post-2010 years of follow-up (mean=4.9; SD=2.4) and PFTs (mean=3.4; SD=2.2). The overall cohort has an average of approximately 5 PFTs (mean=5.3; SD=1.4) from 9/11/2001 through 12/31/2009. A description of participants who retired before 2010 and thus were not included in any of the main analyses can be found in Supplemental Table 2.

Description of JEM and estimation of P

On average, the cohort responded to more structural (median=56.5/year; Q1-Q3=30.9–86.0) than non-structural incidents (median=19.3/year; Q1-Q3=9.5–29.4). 1st alarm fires were the most common type of incident (median=74.2/year; Q1-Q3=39.3–110.4) and comprised 17.5% of all 1st alarm incidents which included medical responses. Firefighters had a higher frequency of responses in minimally exposed roles (median=131.7/year; Q1-Q3=4.2–423.0) than highly exposed roles (median=40.3/year; Q1-Q3=0.0–339.5). Overall, firefighters were exposed to 2,922.3 kg of P (Q1-Q3=922.8–10209.7) from routine fire incidents.

Group a responded to more events during their time of employment, annually, of all types and severities and worked in relatively more highly exposed positions, on average (Table 2). As anticipated, given the longer duration of employment during the study period, cumulative P for group a was nearly three times that of group b (median of 6,346 vs. 2,274). Additionally, group a responded to more structural, non-structural, highly exposed, minimally exposed and incidents of all severities (fire alarm levels), on average when compared to group b.

Primary analysis: Linear mixed effects models using P as the exposure variable.

After controlling for age, race/ethnicity, height, smoking, and weight, a −27 mL/1,000 kg P (β=−26.87; 95% CI=−34.54, −19.20) was observed when analyzing exposures within 3 months before PFT measurements (Figure 2a). Over the entire cumulative 12-year follow-up period, every 1000 kg P was associated with a 13 mL lower FEV_1 (β=−13.34; 95% CI=−13.98, −12.70). Sensitivity analyses excluding post-retirement exams yielded similar findings.

In our secondary analysis, this result was substantiated among those who retired both earlier (i.e., before 2019) and later in the study period (i.e., 2019–2021) (Supplemental Figure 1). For groups a (i.e., those who retired between 2019–2021) and b (i.e., those who retired between 2010–2018) 19 mL/1,000 kg P (β=−18.82; 95% CI=−30.44, −7.20) and 27 mL/1000 kg (β=−27.49; 95% CI=−36.81, −18.16) were observed when analyzing exposures within 3 months before PFT measurements, respectively. Similar trends were observed for groups a and b when analyzing exposure within 6 months through 12 years before a PFT.

Linear mixed effects models by time of arrival at WTC disaster site

A significant interaction was observed between time of arrival at the WTC site and P (β_3=−12.90; 95% CI=−22.70, −2.89) for the analysis evaluating exposures within 3 months before PFTs, only. Models stratified by time of arrival at the WTC are presented in Figure 2b. When PFTs were analyzed 3 months after routine firefighter exposure, the association between P and FEV_1 was slightly stronger for those with higher levels of WTC exposure (i.e., between 9/11–9/12/2001) (β_1=−25.89; 95% CI=−33.91, −17.89) than those with lower levels of WTC exposure (i.e., after 9/12/2001) (β_1=−12.76; 95% CI=−30.35, +4.84). The confidence intervals for the two groups overlap, which could be due to a lack of precision. The association of cumulative routine exposures was similar for both those that arrived at the WTC site early and late.

Similar associations were found for early arrivers in both groups a (β_1=−23.05; 95% CI=−35.83, −10.26) and b (β_1=−31.47; 95% CI=−42.03, −20.91) when evaluating exposures within 3 months of a PFT (Supplemental Figure 2).

Linear mixed effects models using time as the exposure

When evaluating annual rate of decline for the period where exposure data were not available (2001–2009) and active firefighting years during the period where exposure data were available (2010-retirement), differences were observed for the analytic cohort (Table 3). The overall rate of decline in the early period (β=−25.7 mL/year; 95% CI= [−26.7, −24.6]) was less than in the late period (β_1+β_2=−37.2 mL/year; 95% CI= [(−38.2, −36.2]), after controlling for age, race/ethnicity, height, smoking, and weight. Similar observations were observed for those that retired later (a) and earlier (b).

Discussion

To estimate the association between routine firefighting exposures and short- and long-term pulmonary function among FDNY firefighters, a novel time-varying exposure metric was evaluated in relation to longitudinal spirometry measurements. We found increased exposure to routine firefighting resulted in decreased lung function in a cohort of recently retired WTC-exposed firefighters. While adherence to personal protective equipment, (i.e., SCBA masks) has improved, structural fires continue to generate harmful byproducts of combustion at higher levels than ever and volatile compounds that evaporate from PPE can be inhaled after responding to an incident.[24, 25] Further, the potential toxicity is determined by the dose, size distribution, and reactivity of the smoke particles and given the high fraction of ultrafine particle exposures (PM 0.1) during overhaul firefighter duties, when SCBA is typically not used, the importance of these factors with regard to toxicity is significant.[26] Profuse quantities of these harmful substances are present at fire scenes and tend to induce inflammatory responses.[27–30] Inhalation of smoke, insoluble vapors, irritant gases, dust, and fumes all influence pulmonary function decline.[31, 32] Airflow obstruction tends to be among the most common conditions that develop as a result of recurrent exposures.[33, 34]

The first finding of this study was that when controlling for important confounders, lung function was diminished in the short-term (i.e., within 3-months of a PFT) after being acutely exposed to smoke particle exposures resulting from firefighting. This decline persisted but was slightly attenuated when analyzed over the entire (i.e., cumulative) follow-up period. The short-term diminution in lung function followed by a period of recovery is consistent with other studies of both urban and wildland firefighters.[35, 36] The second was that participants who were most highly exposed to the WTC-disaster (i.e., that arrived at the site between 9/11/2001 and 9/12/2001), were more susceptible to routine smoke exposures in the short-term, when compared with their counterparts that arrived at the disaster site later. Despite these notable findings, the lack of precision around these estimates, particularly during the first few months of exposure, as evidenced by wide confidence intervals, requires caution when interpreting results. Analyses of longer time periods (e.g., >2 years) resulted in narrower confidence intervals because more fire incidents were included in those calculations. Although overlapping confidence intervals do not always imply a lack of statistical significance, the consistent overlap across all time periods for the analysis evaluating the interaction of WTC exposure and P with lung function suggests that drawing broad conclusions about the synergistic relationship between these two exposure proxies is not appropriate.

Age-related lung function decline and cumulative exposure are highly correlated which makes modelling both, jointly, difficult. The findings from this study, however, suggest a portion of lung function decline previously ascribed to the aging process may be related to workplace exposures. It should be noted that associations between P and lung function may be offset by an amplified “healthy worker effect”.[5, 37, 38] The FDNY cohort is subject to intensive pre-employment screening that consists of FEV_1 % predicted values >80% and no history of asthma. The analytic cohort, despite exposures to the WTC disaster, as well as years of pre- and post-9/11 routine firefighting exposures, remained in the active workforce so it may be inferred that they are uniquely fit and mount robust responses to workplace exposures even in relation to the rest of the active workforce.

The observed association of higher P with lower lung function in the short-term were sustained yet attenuated over the follow-up period. Notably, this cohort is younger and healthier than other WTC-exposed participants, some of whom retired shortly after 2001. The group that retired before 2010 also had higher WTC dust cloud exposure, greater pre-9/11 firefighting exposure, weighed more and smoked more. Thus, the main analytic cohort, analyzed in relation to P may not be fully representative of the overall cohort and thus selection bias may have been introduced in the analysis.

There were several strengths of this study. It was the first to apply this novel JEM, developed to estimate exposures from combustion emissions at fire incidents, to a longitudinal health outcome. Years of service and number of fire responses were shown to be poor surrogates for particle exposure in the first study that developed the JEM, and while alarm level served as a better proxy for exposure concentrations, it was still inferior to our refined estimate that used emission factors.[12] To estimate particle concentration, incident type, alarm level, and position title must all be considered together. Second, both data used to create the exposure index and PFT data were collected prospectively primarily for healthcare surveillance and administrative purposes, irrespective of any specific scientific questions, effectively eliminating the potential for recall bias. Related to this point, the data preserved any temporal relationships (i.e., exposure preceding outcomes) such that P was captured at different intervals prior to each repeated measurement. Third, most participants had many repeated PFT measurements, which improves the precision of our regression estimates for both short- and long-term exposure.[39] Finally, observations were consistent, for groups that retired early (before 2019) and later (in 2019 and later) and after controlling for confounders such as smoking and age. While those who retired earlier might have been expected to have worse lung function due to more cumulative exposure, it is plausible that the consistent findings are due in part to differences in personal protective equipment use between early and late retirees.

This study was not without limitations. First, the follow-up period examined a small proportion of each participants' career. The mean years of employment for this cohort was between 20 and 26 years. Further, since data for the JEM were only available from 2010 to 2021, these data were only available for a maximum of 11.7 years, and for many participants fewer than that. This potentially introduces selection bias since older and sicker participants may have been excluded. Additionally, younger, recently hired firefighters may respond to slightly different types of fire incidents. Second, and related to this point are the unknown effects of firefighting exposure during the period from 2001 through 2009 and prior to 9/11, prevented us from studying those periods rigorously in relation to P. Third, investigating medical leave from active duty was beyond the scope of this foundational study evaluating the effects of firefighting exposure and lung function, however, by not including it in the analysis it may present a bias by way of informative missingness (i.e., lower observed exposure among participants on leave due to a respiratory or other chronic illness). Fourth, since components used to develop the JEM are not collected and not as assiduously vetted in other metropolitan departments, these findings and this methodology may lack transportability to other urban departments outside the FDNY. However, fire alarm level, alone, may have strong predictive validity for estimating particulate exposure.[12] Fifth, pack year data were not available for all participants during the follow-up period so smoking as a risk factor for lung function decline was determined crudely using ever vs. never. Sixth, while our WTC exposure measure (i.e., arrival time) has the potential for measurement error, it has been used in multiple other lung function studies and is a proxy for the severity of particle exposure at the disaster site.[2, 17, 21] Seventh, all participants in this study had some level of WTC exposure, which may limit generalizability to non-exposed participants. However, newly hired non-WTC exposed firefighters were subjected to the same stringent FDNY hiring standards particularly with respect to lung function.[1] Finally, we cannot rule out the impact of unmeasured confounders such as adherence to using personal protective equipment and exposures resulting from non-work-related sources of air pollution which may vary based on place of residence. In general, because of regulations directed at reducing automobile-related air pollution in NYC, emissions decreased during the 2000s.[40]

In summary, modest differences in pulmonary function were observed, in the short-term and cumulatively, when analyzed in relation to estimated particle exposure concentrations. This discovery was strongest among participants who arrived at the WTC disaster site earliest, demonstrating that even among the healthiest WTC-exposed firefighters (i.e., those who remained on the active workforce from 2010–2021) there may have been greater sensitivity to routine firefighting exposures. Future directions include validating the JEM by using sampling devices to better understand particle size distributions at urban fire scenes. This is important because fine and ultrafine particles have different effects on pulmonary inflammation. While these findings were striking, this framework may be even more suitable for cohorts that were hired after 2010 and were not acutely exposed to a disaster, so that the risk attributable to routine exposures can be isolated.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Technical Committee on Fire Service Occupational Safety and Health. NFPA 1582, Standard on Comprehensive Occupational Medical Program for Fire Departments. Quincy, USA: National Fire Protection Association; 2018. 11–12..
2. Aldrich TK, et al. , Longitudinal pulmonary function in newly hired, non-World Trade Center-exposed fire department City of New York firefighters: the first 5 years. Chest, 2013. 143(3): p. 791–797. [PubMed: 23188136]
3. Humans, I.W.G.o.t.E.o.C.R.t., Painting, firefighting, and shiftwork. IARC Monogr Eval Carcinog Risks Hum, 2010. 98: p. 9–764. [PubMed: 21381544]
4. Musk AW, Petters JM, and Wegman DH, Lung function in fire fighters, II: a five year follow-up fo retirees. Am J Public Health, 1977. 67(7): p. 630–3. [PubMed: 879391]
5. Sherman CB, et al. , Firefighting acutely increases airway responsiveness. Am Rev Respir Dis, 1989. 140(1): p. 185–90. [PubMed: 2665585]
6. Schermer TR, et al. , Change in lung function over time in male metropolitan firefighters and general population controls: a 3-year follow-up study. J Occup Health, 2013. 55(4): p. 267–75. [PubMed: 23796594]

7. Burgess JL, et al. , Longitudinal decline in lung function: evaluation of interleukin-10 genetic polymorphisms in firefighters. J Occup Environ Med, 2004. 46(10): p. 1013–22. [PubMed: 15602175]

8. Baris D, et al. , Cohort mortality study of Philadelphia firefighters. Am J Ind Med, 2001. 39(5): p. 463–76. [PubMed: 11333408]

9. Demers PA, et al. , Cancer incidence among firefighters in Seattle and Tacoma, Washington (United States). Cancer Causes Control, 1994. 5(2): p. 129–35. [PubMed: 8167259]

10. Slattery F, et al. , The long-term rate of change in lung function in urban professional firefighters: a systematic review. BMC Pulm Med, 2018. 18(1): p. 149. [PubMed: 30189854]

11. Dahm MM, et al. , Creation of a retrospective job-exposure matrix using surrogate measures of exposure for a cohort of US career firefighters from San Francisco, Chicago and Philadelphia. Occup Environ Med, 2015. 72(9): p. 670–7. [PubMed: 26163543]

12. Goldfarb DG, et al. , Development of a job-exposure matrix (JEM) for exposure to smoke particle mass among firefighters of the Fire Department of the City of New York (FDNY). Occup Environ Med, 2023. 80(2): p. 104–110. [PubMed: 36635097]

13. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, AP-42 5th Edition Compilation of Air Pollutants Emissions Factors, Volume I: Stationary Point and Area Sources, 1995.

14. Fire Department of the City of New York (FDNY). Communications Manual. In. Chapter 5: Alarm Assignments 2010.

15. Centers for Disease, C. and Prevention, Occupational exposures to air contaminants at the World Trade Center disaster site--New York, September-October, 2001. MMWR Morb Mortal Wkly Rep, 2002. 51(21): p. 453–6. [PubMed: 12054422]

16. Schwartz T, Zeig-Owens R, Halpren A, et al. FDNY World Trade Center Health Program: Health Impacts on FDNY Rescue/Recovery Workers 20 Years: 2001 to 2021. 2021.

17. Aldrich TK, et al. , Lung function in rescue workers at the World Trade Center after 7 years. N Engl J Med, 2010. 362(14): p. 1263–72. [PubMed: 20375403]

18. Aldrich TK, et al. , Bronchial Reactivity and Lung Function After World Trade Center Exposure. Chest, 2016. 150(6): p. 1333–1340. [PubMed: 27445092]

19. Banauch GI, et al. , Accelerated spirometric decline in New York City firefighters with alpha(1)-antitrypsin deficiency. Chest, 2010. 138(5): p. 1116–24. [PubMed: 20634282]

20. Prezant DJ, et al. , Cough and bronchial responsiveness in firefighters at the World Trade Center site. N Engl J Med, 2002. 347(11): p. 806–15. [PubMed: 12226151]

21. Aldrich TK, et al. , Lung Function Trajectories in World Trade Center-Exposed New York City Firefighters Over 13 Years: The Roles of Smoking and Smoking Cessation. Chest, 2016. 149(6): p. 1419–27. [PubMed: 26836912]

22. Vollmer WM, et al. , Long-term reproducibility of tests of small airways function. Comparisons with spirometry. Chest, 1990. 98(2): p. 303–7. [PubMed: 2376162]

23. Laird NM and Ware JH, Random-effects models for longitudinal data. Biometrics, 1982. 38(4): p. 963–74. [PubMed: 7168798]

24. Fent KW, et al. , Firefighters' absorption of PAHs and VOCs during controlled residential fires by job assignment and fire attack tactic. J Expo Sci Environ Epidemiol, 2020. 30(2): p. 338–349. [PubMed: 31175324]

25. Lacey S, Alexander BM, and Baxter CS, Plasticizer contamination of firefighter personal protective clothing--a potential factor in increased health risks in firefighters. J Occup Environ Hyg, 2014. 11(5): p. D43–8. [PubMed: 24467725]

26. Baxter CS, et al. , Ultrafine particle exposure during fire suppression--is it an important contributory factor for coronary heart disease in firefighters? J Occup Environ Med, 2010. 52(8): p. 791–6. [PubMed: 20657302]

27. Gianniou N, et al. , Acute effects of smoke exposure on airway and systemic inflammation in forest firefighters. J Asthma Allergy, 2018. 11: p. 81–88. [PubMed: 29719412]

28. Summerhill EM, et al. , An Official American Thoracic Society Workshop Report: Chemical Inhalational Disasters. Biology of Lung Injury, Development of Novel Therapeutics, and Medical Preparedness. Ann Am Thorac Soc, 2017. 14(6): p. 1060–1072. [PubMed: 28418689]

29. McKay CA Jr., Toxin-induced respiratory distress. Emerg Med Clin North Am, 2014. 32(1): p. 127–47. [PubMed: 24275172]
30. Brandt-Rauf PW, et al. , Health hazards of firefighters: acute pulmonary effects after toxic exposures. Br J Ind Med, 1989. 46(3): p. 209–11. [PubMed: 2930733]
31. de Jong K, et al. , Association of occupational pesticide exposure with accelerated longitudinal decline in lung function. Am J Epidemiol, 2014. 179(11): p. 1323–30. [PubMed: 24780843]
32. Almeida AG, et al. , [Pulmonary function in Portuguese firefighters]. Rev Port Pneumol, 2007. 13(3): p. 349–64. [PubMed: 17632674]
33. Jakobsson JKF, et al. , Altered deposition of inhaled nanoparticles in subjects with chronic obstructive pulmonary disease. BMC Pulm Med, 2018. 18(1): p. 129. [PubMed: 30081885]
34. Sonnappa S, et al. , Risk of pneumonia in obstructive lung disease: A real-life study comparing extra-fine and fine-particle inhaled corticosteroids. PLoS One, 2017. 12(6): p. e0178112. [PubMed: 28617814]
35. Jacquin L, et al. , Short-term spirometric changes in wildland firefighters. Am J Ind Med, 2011. 54(11): p. 819–25. [PubMed: 22006591]
36. Large AA, Owens GR, and Hoffman LA, The short-term effects of smoke exposure on the pulmonary function of firefighters. Chest, 1990. 97(4): p. 806–9. [PubMed: 2323250]
37. Glass DC, et al. , Mortality and cancer incidence among male volunteer Australian firefighters. Occup Environ Med, 2017. 74(9): p. 628–638. [PubMed: 28391245]
38. Choi BC, A technique to re-assess epidemiologic evidence in light of the healthy worker effect: the case of firefighting and heart disease. J Occup Environ Med, 2000. 42(10): p. 1021–34. [PubMed: 11039166]
39. Hnizdo E, et al. , The precision of longitudinal lung function measurements: monitoring and interpretation. Occup Environ Med, 2005. 62(10): p. 695–701. [PubMed: 16169915]
40. Jung KH, et al. , Time trends of polycyclic aromatic hydrocarbon exposure in New York City from 2001 to 2012: assessed by repeat air and urine samples. Environ Res, 2014. 131: p. 95–103. [PubMed: 24709094]

What is already known on this topic?

Particle exposures resulting from firefighting may have deleterious consequences on respiratory health. Prior works have demonstrated lung function declines in excess of what was expected from routine aging among firefighters.

What this study adds?

Most studies evaluating the association between firefighting and pulmonary function use crude measures such as years of service as an exposure surrogate. This study leverages a novel job exposure matrix (JEM) that was developed to estimate smoke exposures from structural and non-structural urban fire incidents among firefighters in New York to more precisely evaluate the longitudinal association between smoke particle exposures and lung function.

How might this study affect research, practice, or policy?

This proof-of-concept study demonstrates the value of using this novel JEM which, in conjunction with routine surveillance of pulmonary function, may inform exposure prevention and planning as well as identification of sub-clinical respiratory disease.

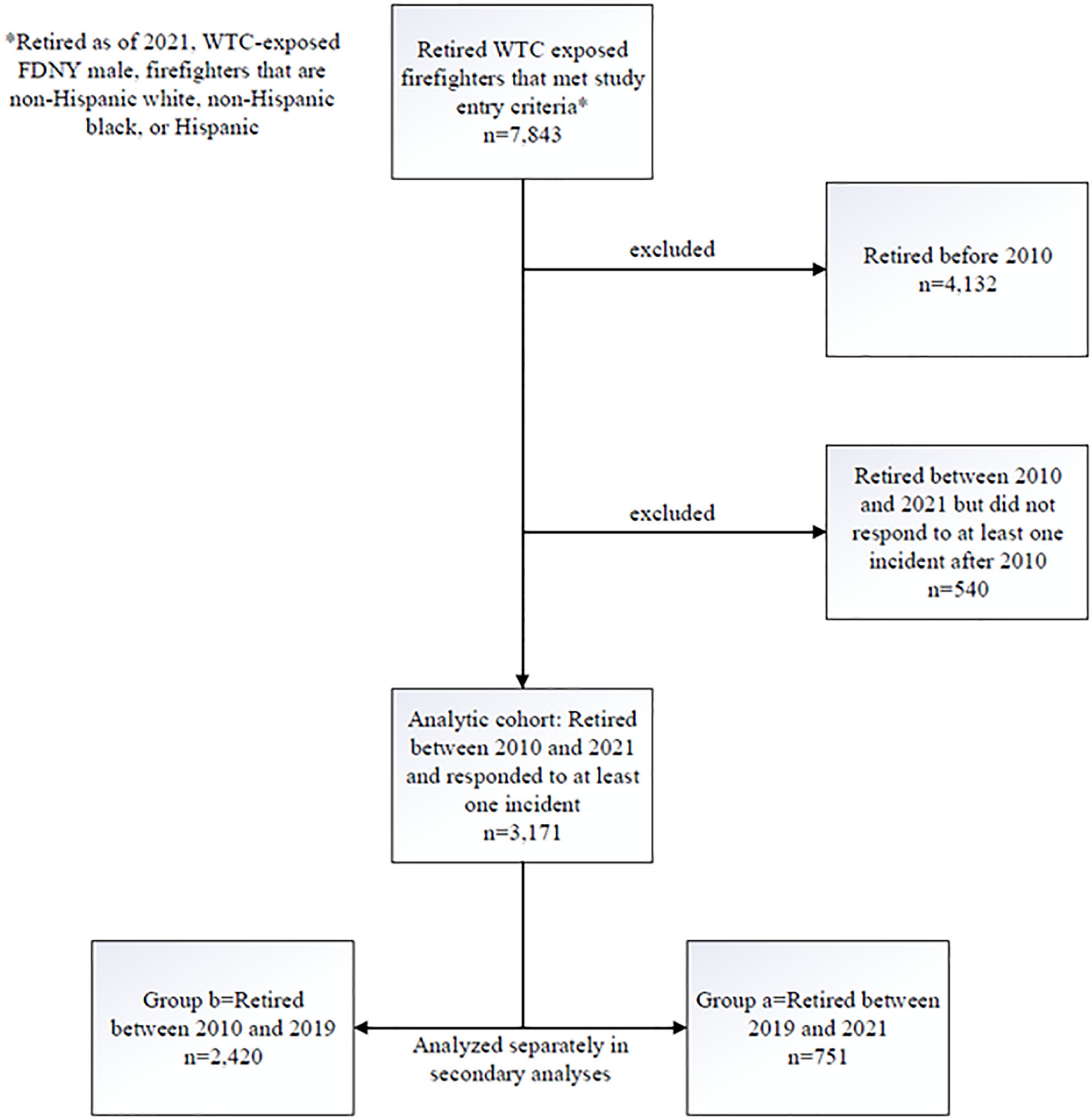

Figure 1.

Flowchart of participants

Abbreviations: WTC=World Trade Center

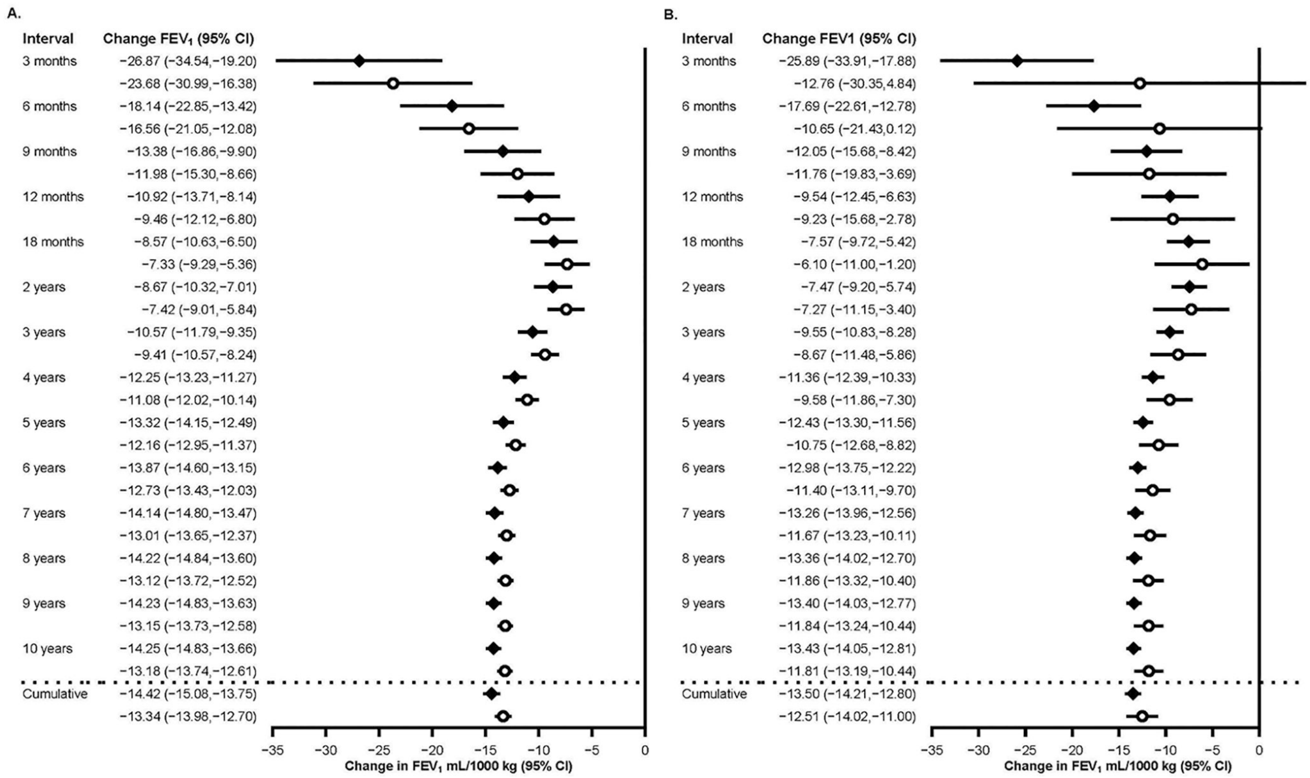

Figure 2a:

Differences in absolute FEV_1 for exposures within 3-months to 12-years prior to pulmonary function tests

Unadjusted (♦) and adjusted (○) for age, race/ethnicity, height, smoking, and weight; Change is presented in mL FEV_1 per 1000 kg of particle exposure (P). Abbreviations: FEV_1=One-second Forced Expiratory Volume

Figure 2b. Differences in absolute FEV_1 for exposures within 3-months to 12-years prior to pulmonary function tests by time of arrival at WTC disaster site

Arrived at the World Trade Center site between 9/11/2001–9/12/2001 (♦) Arrived at WTC site after 9/12 (○) All models control for age, race/ethnicity, height, smoking, and weight. Change is presented in mL FEV_1 per 1000 kg of particle exposure (P) Abbreviation: FEV_1=One-second Forced Expiratory Volume

Table 1.

Selected demographic characteristics of the cohort.

Retirement period	2010–2021	a: 2019–2021	b: 2010–2018
n	3,171	751	2,420
Age on 9/11 mean, SD	38.3 (6.1)	36.0 (5.7)	39.0 (6.1)
Race/ethnicity n, %			
White	3008 (94.9)	703 (93.6)	2305 (95.3)
African American/Black	61 (1.9)	16 (2.1)	45 (1.9)
Hispanic	102 (3.2)	32 (4.3)	70 (2.9)
Arrival at WTC disaster site n, %			
Early - 9/11 AM - 9/12	2,767 (87.3)	650 (86.6)	2,117 (87.5)
Late - 9/13 or later	404 (12.7)	101 (13.4)	303 (12.5)
Follow-up time mean, SD			
Overall years of service	24.7 (6.8)	26.3 (6.3)	24.2 (6.9)
Active years pre-9/11/2001	10.3 (6.7)	7.9 (6.2)	11.0 (6.7)
Active years 9/11/2001–12/31/2009	8.3 (0.0)	8.3 (0.0)	8.3 (0.0)
Active years post-2010	6.2 (3.1)	10.3 (0.8)	4.9 (2.4)
Pulmonary Function Tests mean, SD			
9/11/2001–12/31/2009	5.3 (1.4)	5.3 (1.4)	5.3 (1.4)
1/1/2010 - retirement	4.4 (2.8)	7.6 (1.9)	3.4 (2.2)
Height (cm) mean, SD	177.1 (6.3)	177.0 (6.3)	177.1 (6.4)
Weight (kg) mean, SD			
First post-2010 exam	90.2 (11.9)	89.9 (11.4)	90.3 (12.0)
Smoking n, %			
Ever	930 (29.3)	207 (27.6)	723 (29.9)
Current (as of most recent exam)	72 (2.3)	12 (1.6)	60 (2.5)
Former (as of most recent exam)	858 (27.1)	195 (26.0)	663 (27.4)

WTC=World Trade Center; SD=Standard Deviation; kg=kilograms; 9/11 AM= morning of 9/11/2001; 9/11 PM=afternoon of 9/11/2001; 9/12=9/12/2001; 9/13 or later=9/13/2001 or later.

Groupings: a=sub-cohort that retired between 2019–2021; b=sub-cohort that retired between 2010–2019

Table 2.

Description of exposure data from 2010–2021

Retirement period median (Q1-Q3)	2010–2021	a: 2019–2021	b: 2010–2018
Particle exposures, P (kg)*	2922.3 (922.8, 10209.7)	6345.6 (2939.7, 22537.1)	2274.1 (648.8, 7211.4)
Type (n/year)			
Structural	56.5 (30.9, 86.0)	68.5 (44.5, 93.1)	52.2 (27.0, 83.0)
Non-structural	19.3 (9.5, 29.4)	23.8 (14.2, 32.3)	18.0 (8.2, 28.2)
Severity (n/year)			
1st	425.3 (213.8, 618.8)	536.3 (339.6, 689.7)	392.1 (183.7, 587.9)
Fire-only	74.2 (39.3, 110.4)	91.8 (56.8, 119.7)	68.5 (33.4, 106.7)
2nd	1.9 (0.9, 3.0)	2.2 (1.3, 3.1)	1.8 (0.8, 3.0)
3rd	0.6 (0.2, 1.0)	0.7 (0.4, 1.0)	0.5 (0.2, 1.0)
4th	0.2 (0.0, 0.5)	0.3 (0.1, 0.5)	0.2 (0.0, 0.5)
5th			
Firefighter engagement (n/year)	0.3 (0.0, 0.5)	0.3 (0.2, 0.6)	0.2 (0.0, 0.5)
Highly exposed	40.3 (0.0, 339.5)	88.6 (0.5, 402.3)	30.3 (0.0, 315.0)
Minimally exposed	131.7 (4.2, 423.0)	253.2 (12.2, 502.9)	97.2 (3.3, 396.4)

*Cumulative sum at end of career

Groupings: a=sub-cohort that retired between 2019–2021; b=sub-cohort that retired between 2010–2019

Particle exposures (P) were calculated using fire incident characteristics, response data, and emission factors from the job exposure matrix (JEM). Fire incident types differentiate between different categories of responses and building features (e.g., structural, non-structural), and contain 16 categories for structural fires and 12 categories for non-structural fires. Alarm levels (five categories: 1st-5th alarm) categorize fire intensity and correspond to the number of responding units, with a 5-alarm fire being the most serious type of occurrence. The first alarm category includes non-fire medical emergencies. The classification scheme for firefighter engagement was based on the potential for exposure by position title. Job titles were divided into two categories: highly exposed and minimally exposed. The median overall P, in kg, as well as the first and third quartiles are reported for the study period. The median number of occurrences for incident type, severity, and engagement classification at a fire incident were reported on an annual basis.

Table 3.

One-second Forced Expiratory Volume (FEV_1) rates of change in mL/year (and 95% confidence intervals) before and after 2010, overall and by retirement period

Retirement period	2010–2021	a: 2019–2021	b: 2010–2018
Unadjusted			
2001–2009	−31.4 (−32.4, −30.4)	−27.3 (−29.2, −25.3)	−32.5 (−33.7, −31.3)
2010-Retirement	−38.7 (−39.8, −37.7)	−37.9 (−39.5, −36.3)	−40.5 (−41.9, −39.1)
Adjusted*			
2001–2009	−25.7 (−26.7, −24.6)	−21.0 (−23.0, −19.0)	−26.8 (−28.0, −25.6)
2010-Retirement	−37.2 (−38.2, −36.2)	−35.4 (−36.9, −33.9)	−39.6 (−41.0, −38.2)

* Models control for age, race/ethnicity, height, smoking, and weight

Groupings: a=sub-cohort that retired between 2019–2021; b=sub-cohort that retired between 2010–2019