

Original research

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

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## ABSTRACT

**Objectives** Characterisation 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 P were 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 forced expiratory volume in one second (FEV<sub>1</sub>). Models controlled for age, race/ethnicity, height, smoking and weight.

**Results** Every 1000 kg P was associated with 13 mL lower FEV<sub>1</sub> ( $\beta=-13.34$ ; 95% CI=-13.98 to -12.70) over the entire 12-year follow-up period. When analysing exposures within 3 months before PFT measurements, 1000 kg P was associated with 27 mL lower FEV<sub>1</sub> ( $\beta=-26.87$ ; 95% CI=-34.54 to -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 ( $\beta=-12.90$ ; 95% CI=-22.70 to -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-term 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 ageing, routine firefighting and WTC exposures.

## INTRODUCTION

Firefighters are routinely exposed to combustion by-products and are surveilled regularly using pulmonary function testing (PFT) (ie, spirometry) in accordance with the National Fire Protection Association 1582 standards.<sup>1</sup> Service time has been extensively used as the exposure surrogate to study the association between firefighting and longitudinal pulmonary function.<sup>2-5</sup> Other proxy exposure measures included retrospective self-reports of exposure, duration at fires and the sum of career responses.<sup>6-9</sup> Estimates of annual rates of forced expiratory volume in one second (FEV<sub>1</sub>) decline

## 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 ageing 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 THIS STUDY MIGHT 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 subclinical respiratory disease.

from routine (ie, non-disaster) firefighting vary considerably from -24 to -110 mL/year.<sup>10</sup> 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.<sup>11</sup> 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).<sup>12</sup> 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



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Agency (US EPA) AP-42 framework,<sup>13 14</sup> 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 11 September 2001 (9/11) and in the months that followed.<sup>15</sup> 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.<sup>16–19</sup>

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-term and long term, as measured by FEV<sub>1</sub>; 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

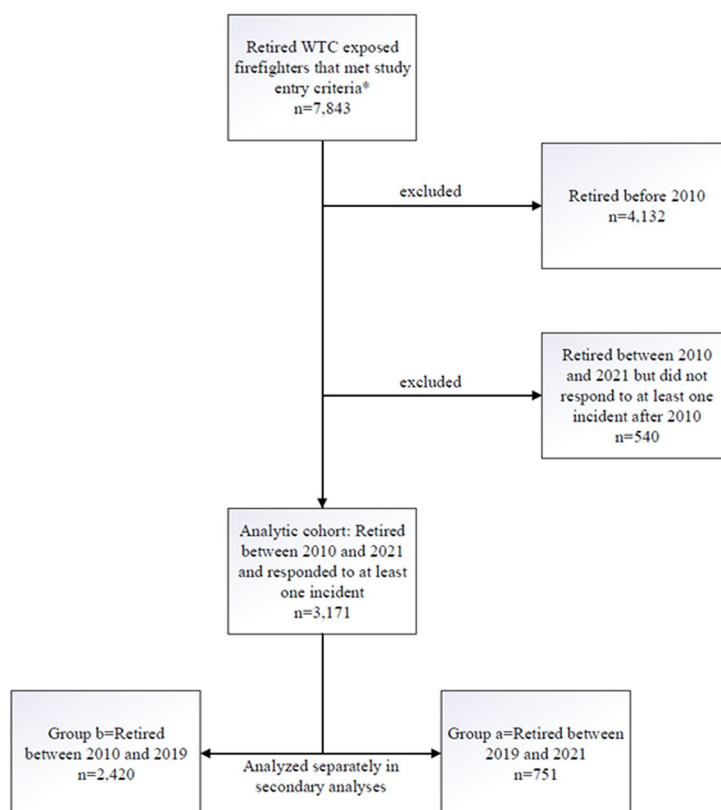
The source population included WTC-exposed retired firefighters who left the workforce between 11 September 2001 and 11 September 2021 (n=7843). The population was restricted to non-Hispanic black, non-Hispanic white and Hispanic male participants who had at least three PFTs over the course of the study 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. We excluded 4132 participants who retired before 2010 (ie, the period before incident response data were fully available electronically) as well as 540 participants who retired between 2010

and 2021 but did not respond to at least one incident in this period. The analytic cohort included participants who retired between January 2010 and September 2021, and responded to at least one incident during this period (n=3171). 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 examinations conducted through the WTC Health Program. Self-reported WTC exposure data were obtained from participants' first post-9/11 medical monitoring examination, most within 1 year after the attacks.<sup>20</sup> Smoking status was assessed at each monitoring examination 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.<sup>12</sup> Briefly, fire incident and response information were provided by the Bureau of Communications at FDNY.<sup>12</sup> Incident variables used in the JEM included fire alarm levels (ie, 1–5, with level 5 indicating the greatest fire involvement, potential for spread and firefighter response) and incident type (eg, 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 (ie, position description). The position description was dichotomised 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



**Figure 1** Flowchart of participants. \*Retired as of 2021. WTC exposed FDNY male, fire fighters that are non-Hispanic white, non-Hispanic black or Hispanic. FDNY, Fire Department of the City of New York; WTC, World Trade Center.

for every combination of fire alarm level, incident type and position description from 2010 to 2021 using US EPA air emissions methodological framework.<sup>13,14</sup> Findings are presented per 1000 kg of particles. For example, approximately 1/3–1/5 alarm commercial dwelling fire corresponds to  $p=1162.94$  kg, three brush fires of any alarm level correspond to  $p=323.86$  kg  $\times$  3=971.58 kg, and nearly 29 s alarm private dwelling fires corresponds to  $p=35.23$  kg  $\times$  29=1021.67 kg.

### PFT spirometry

As part of the WTC Health Program at the FDNY, routine medical monitoring examinations are conducted approximately annually. During these evaluations, PFTs, specifically spirometry examinations, 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.<sup>17,21</sup> 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<sub>1</sub> because it is the most reproducible, least effort dependent and is most commonly used in longitudinal analyses.<sup>22</sup> 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/SD, as appropriate. Each component (ie, 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 annualised 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<sub>1</sub>.<sup>23</sup> All covariates including P were included as fixed effects and the intercept was included as a random effect to account for intrasubject variability and correlations between repeated measures. The specific model is shown below:

$$Y_{ij} = \beta_0 + \beta_1 X_{ij} + Z_{0i} + \epsilon_{ij} \quad (1)$$

where  $Y=FEV_1$ ;  $X=P$  for each interval;  $i$ =each repeated observation;  $j$ =each individual participant;  $\beta_0$ =intercept;  $\beta_1$ =regression coefficient for the difference in FEV<sub>1</sub> per P;  $Z$  is the matrix of random effects; and  $\epsilon$  is the vector of random errors.

Different outcomes were evaluated to assess the acute and chronic impact of P on lung function. This was done by calculating the sum of P at 15 predefined intervals prior to a PFT. At each examination, 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 examination on 1 December 2019, the 3-month outcome will include all P estimated from

1 September 2019 through 1 December 2019. The cumulative outcome for the same examination would include all P from 1 January 2010 (ie, beginning of follow-up) to 1 December 2019. Mock data are presented in online 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 examination within 1 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 and 2021 (group a), were analysed separately from those who retired between 2010 and 2018 (group b). This cut-off was chosen to allow for an adequate follow-up period (at least 9 years) in terms of data availability for the JEM. Different cut-offs were considered and produced similar results; however, 9 years provided an optimal balance of follow-up time and participant numbers. A sensitivity analysis excluding postretirement examinations was conducted.

To test for effect modification of routine firefighting exposure, P, by previous WTC exposure intensity, the model below was fit (equation 2) which included an interaction term between P and WTC arrival time (ie, arrived at disaster site on 11 September 2001 to 12 September 2001 vs arrived 13 September 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.

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

where  $Y=FEV_1$ ;  $X_1=P$  for each interval;  $X_2=WTC$  arrival time;  $i$ =each repeated observation;  $j$ =each individual participant;  $\beta_0$ =intercept;  $\beta_1$ =regression coefficient for the difference in FEV<sub>1</sub> per P;  $\beta_2$ =regression coefficient for the difference in FEV<sub>1</sub> for each level of WTC arrival time;  $\beta_3$ =regression coefficient for the interaction between P and WTC arrival time;  $Z$  is the matrix of random effects; and  $\epsilon$  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<sub>1</sub> 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: (1) before exposure data were available—11 September 2001 to 31 December 2009; (2) 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:

$$Y_{ij} = \begin{cases} (\beta_0 + \beta_1 t_{ij}) + Z_y + \epsilon_{ij} & \text{if } t \leq p_1 \\ (\beta_0 - \beta_2 k) + (\beta_1 + \beta_2) t_{ij} + Z_y + \epsilon_{ij} & \text{if } t > p_1 \end{cases} \quad (3)$$

where  $y=FEV_1$ ;  $p_1=2010$ ;  $t$ =time;  $\beta_0$ =adjusted mean FEV<sub>1</sub> at beginning of follow-up;  $\beta_1$ =change in FEV<sub>1</sub> per unit overall elapsed during the follow-up period as a fixed effect;

**Table 1** Selected demographic characteristics of the cohort

Retirement period	2010–2021	a: 2019–2021	b: 2010–2018
n	3171	751	2420
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 to 9/12	2767 (87.3)	650 (86.6)	2117 (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 11 September 2001	10.3 (6.7)	7.9 (6.2)	11.0 (6.7)
Active years 11 September 2001 to 31 December 2009	8.3 (0.0)	8.3 (0.0)	8.3 (0.0)
Active years post 1 January 2010	6.2 (3.1)	10.3 (0.8)	4.9 (2.4)
Pulmonary function tests mean, SD			
11 September 2001 to 31 December 2009	5.3 (1.4)	5.3 (1.4)	5.3 (1.4)
1 January 2010 to 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 examination	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 examination)	72 (2.3)	12 (1.6)	60 (2.5)
Former (as of most recent examination)	858 (27.1)	195 (26.0)	663 (27.4)
Groupings: a=subcohort that retired between 2019 and 2021; b=subcohort that retired between 2010 and 2018.			
9/12, 12 September 2001; 9/11 AM, morning of 11 September 2001; 9/13 or later, 13 September 2001 or later; 9/11 PM, afternoon of 11 September 2001; WTC, World Trade Center.			

$\beta_2$ =difference in the change in FEV<sub>1</sub> 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;  $\varepsilon$  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 harmonisation, analysis and graphics. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology reporting guidelines.

## RESULTS

### Study population

The primary analytic cohort included 3171 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 years ( $SD=6.1$ ), consisted of predominantly white participants ( $n=3008$ ; 94.9%) and responded to the WTC attacks on 11 September 2001 to 12 September 2001 ( $n=2767$ ; 87.3%). In the post-2010 period, when fire incident data (ie, 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 and 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 and 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 11 September 2001 through 31 December 2009. A description of participants who retired before 2010 and thus were not included in any of the main analyses can be found in online 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;  $Q1-Q3=9.5-29.4$ ). First 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 first 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 2922.3 kg of P ( $Q1-Q3=922.8-10\,209.7$ ) 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 6346 vs 2274). 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 with 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/1000 kg P ( $\beta=-26.87$ ; 95%  $CI=-34.54$  to  $-19.20$ ) was observed when analysing 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<sub>1</sub> ( $\beta=-13.34$ ; 95%  $CI=-13.98$  to  $-12.70$ ). Sensitivity analyses excluding postretirement examinations yielded similar findings.

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

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

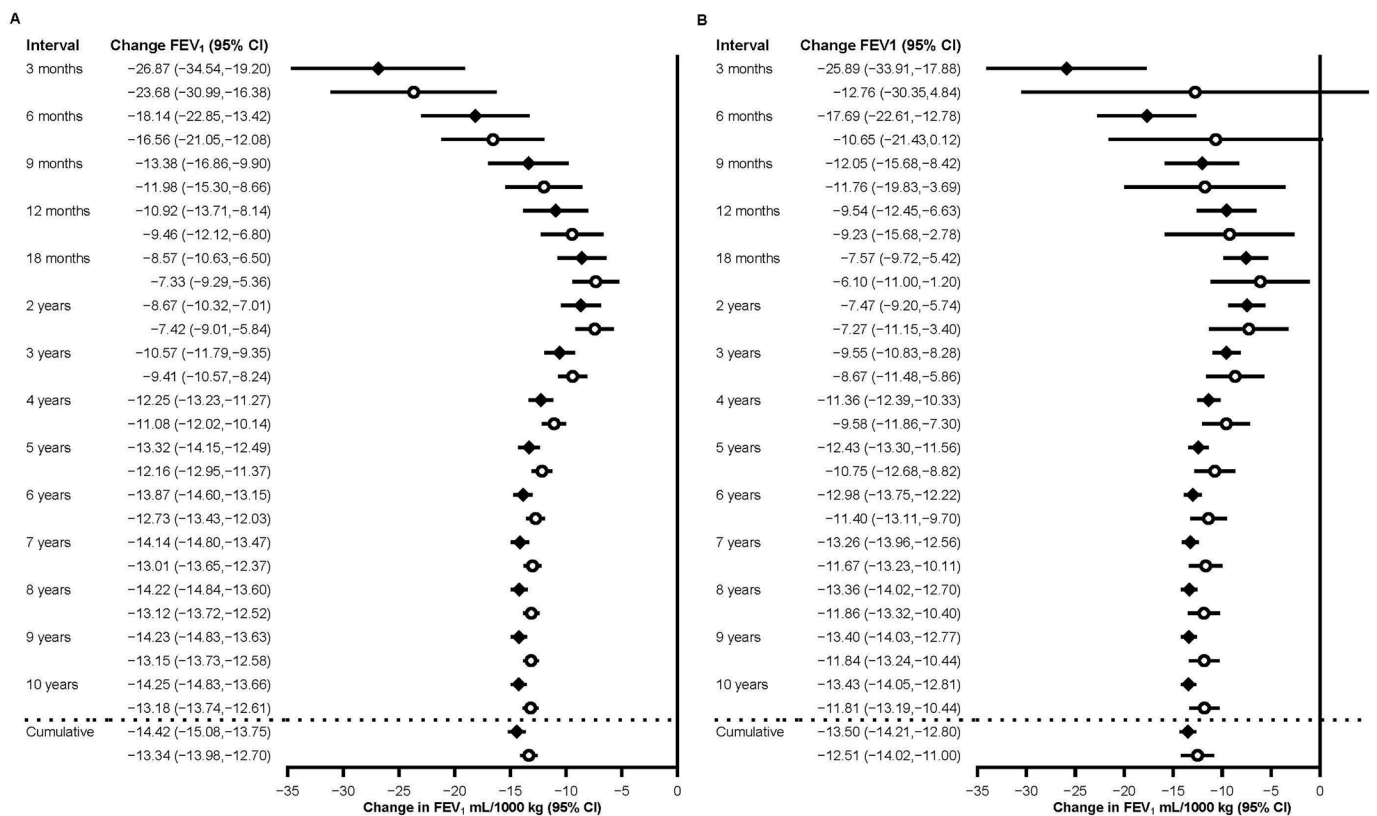
A significant interaction was observed between time of arrival at the WTC site and P ( $\beta_3=-12.90$ ; 95%  $CI=-22.70$  to  $-2.89$ ) for the analysis evaluating exposures within 3 months before PFTs, only. Models stratified by time of arrival at the WTC are presented in [figure 2B](#). When PFTs were analysed 3 months after routine firefighter exposure, the association between P and FEV<sub>1</sub> was slightly stronger for those with higher levels of WTC exposure (ie, between 11 September 2001 and 12 September 2001)

**Table 2** Description of exposure data from 2010 to 2021

Retirement period median (Q1–Q3)	2010–2021	a: 2019–2021	b: 2010–2018
Particle exposures, P (kg)*	2922.3 (922.8, 10 209.7)	6345.6 (2939.7, 22 537.1)	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)			
First	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)
Second	1.9 (0.9, 3.0)	2.2 (1.3, 3.1)	1.8 (0.8, 3.0)
Third	0.6 (0.2, 1.0)	0.7 (0.4, 1.0)	0.5 (0.2, 1.0)
Fourth	0.2 (0.0, 0.5)	0.3 (0.1, 0.5)	0.2 (0.0, 0.5)
Fifth	0.3 (0.0, 0.5)	0.3 (0.2, 0.6)	0.2 (0.0, 0.5)
Firefighter engagement (n/year)			
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)

Groupings: a=subcohort that retired between 2019 and 2021; b=subcohort that retired between 2010 and 2018. Particle exposures (P) were calculated using fire incident characteristics, response data and emission factors from the job exposure matrix. Fire incident types differentiate between different categories of responses and building features (eg, structural, non-structural) and contain 16 categories for structural fires and 12 categories for non-structural fires. Alarm levels (five categories: first–fifth alarm) categorise fire intensity and correspond to the number of responding units, with a five-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.

\*Cumulative sum at the end of career.



**Figure 2** (A) Differences in absolute forced expiratory volume in one second (FEV<sub>1</sub>) 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<sub>1</sub> per 1000 kg of particle exposure (P). (B) Differences in absolute FEV<sub>1</sub> for exposures within 3 months to 12 years prior to pulmonary function tests by time of arrival at World Trade Center (WTC) disaster site. Arrived at the World Trade Center site between 11 September 2001 and 12 September 2001. (◆) Arrived at WTC site after 12 September 2001. (○) Models control for age, race/ethnicity, height, smoking and weight. Change is presented in mL FEV<sub>1</sub> per 1000 kg of P.

**Table 3** Forced expiratory volume in one second rates of change in mL/year (and 95% CIs) 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 to –30.4)	–27.3 (–29.2 to –25.3)	–32.5 (–33.7 to –31.3)
2010 to retirement	–38.7 (–39.8 to –37.7)	–37.9 (–39.5 to –36.3)	–40.5 (–41.9 to –39.1)
Adjusted*			
2001–2009	–25.7 (–26.7 to –24.6)	–21.0 (–23.0 to –19.0)	–26.8 (–28.0 to –25.6)
2010 to retirement	–37.2 (–38.2 to –36.2)	–35.4 (–36.9 to –33.9)	–39.6 (–41.0 to –38.2)

Groupings: a=subcohort who retired between 2019 and 2021; b=subcohort who retired between 2010 and 2018.  
\*Models control for age, race/ethnicity, height, smoking and weight.

( $\beta_1 = -25.89$ ; 95% CI =  $-33.91$  to  $-17.89$ ) than those with lower levels of WTC exposure (ie, after 12 September 2001) ( $\beta_1 = -12.76$ ; 95% CI =  $-30.35$  to  $4.84$ ). The CIs 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 who arrived at the WTC site early and late.

Similar associations were found for early arrivers in both groups a ( $\beta_1 = -23.05$ ; 95% CI =  $-35.83$  to  $-10.26$ ) and b ( $\beta_1 = -31.47$ ; 95% CI =  $-42.03$  to  $-20.91$ ) when evaluating exposures within 3 months of a PFT (online 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 to retirement), differences were observed for the analytic cohort (table 3). The overall rate of decline in the early period ( $\beta = -25.7$  mL/year; 95% CI =  $-26.7$  to  $-24.6$ ) was less than in the late period ( $\beta_1 + \beta_2 = -37.2$  mL/year; 95% CI =  $-38.2$  to  $-36.2$ ), after controlling for age, race/ethnicity, height, smoking and weight. Similar observations were observed for those who retired later (a) and earlier (b).

#### DISCUSSION

To estimate the association between routine firefighting exposures and short-term 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 (PPE) (eg, self-contained breathing apparatus (SCBA)) has improved, structural fires continue to generate harmful by-products of combustion at higher levels than ever and volatile compounds that evaporate from PPE can be inhaled after responding to an incident.<sup>24 25</sup> 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.<sup>26</sup> Profuse quantities of these harmful substances are present at fire scenes and tend to induce inflammatory responses.<sup>27–30</sup> Inhalation of smoke, insoluble vapours, irritant gases, dust and fumes all influence pulmonary function decline.<sup>31 32</sup> Airflow obstruction tends to be among the most common conditions that develop as a result of recurrent exposures.<sup>33 34</sup>

The first finding of this study was that when controlling for important confounders, lung function was diminished in the short-term (ie, 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 analysed over the entire (ie, 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.<sup>35 36</sup> The second was that participants who were most highly exposed to the WTC disaster (ie, who arrived at the site between 11 September 2001 and 12 September 2001) were more susceptible to routine smoke exposures in the short-term, when compared with their counterparts who 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 CIs, requires caution when interpreting results. Analyses of longer time periods (eg, >2 years) resulted in narrower CIs because more fire incidents were included in those calculations. Although overlapping CIs 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 ageing 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’.<sup>5 37 38</sup> The FDNY cohort is subject to intensive pre-employment screening that consists of FEV<sub>1</sub> % predicted values >80% and no history of asthma. The analytic cohort, despite exposures to the WTC disaster, as well as years of pre-9/11 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 was 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, analysed 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 P 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.<sup>12</sup> 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 (ie, 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-term and long-term exposure.<sup>39</sup> 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 PPE 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 were 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, 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 (ie, 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.<sup>12</sup> 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 versus never. Sixth, while our WTC exposure measure (ie, 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 P at the disaster site.<sup>2 17 21</sup> Seventh, all participants in this study had some level of WTC exposure, which may limit generalisability 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.<sup>1</sup> Finally, we cannot rule out the impact of unmeasured confounders such as adherence to using PPE 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.<sup>40</sup>

In summary, modest differences in pulmonary function were observed, in the short-term and cumulatively, when analysed in relation to estimated P concentrations. This discovery was

strongest among participants who arrived at the WTC disaster site earliest, demonstrating that even among the healthiest WTC-exposed firefighters (ie, those who remained on the active workforce from 2010 to 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.

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