Original research

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)

David G Goldfarb [1,2,3] David J Prezant,[2] Rachel Zeig-Owens [2,3,4] Theresa Schwartz,[2,3] Yang Liu,[2] Ilias G Kavouras[1]

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/oemed-2022-108549).

[1]Department of Environmental, Occupational, and Geospatial Health Sciences, CUNY Graduate School of Public Health and Health Policy, New York, New York, USA
[2]Bureau of Health Services, Fire Department of the City of New York, Brooklyn, New York, USA
[3]Department of Medicine, Montefiore Medical Center, Brooklyn, New York, USA
[4]Department of Epidemiology and Population Health, Albert Einstein College of Medicine, Bronx, NY, USA

Correspondence to
Dr David G Goldfarb, Montefiore Medical Center, Bronx, NY 10461, USA; david.goldfarb@fdny.nyc.gov

Received 29 June 2022
Accepted 15 December 2022
Published Online First 10 January 2023

Check for updates

To cite: Goldfarb DG, Prezant DJ, Zeig-Owens R, *et al. Occup Environ Med* 2023;**80**:104–110.

ABSTRACT

Objectives A refined job exposure matrix (JEM) based on incident types and severities and response characteristics was developed for firefighters to estimate quantities of smoke particles emitted during structural and non-structural fire incidents from 2010 to 2021.
Methods The cohort included a subset of 3237 Fire Department of the City of New York firefighters who responded to at least one incident between 2010 and 2021, prior to retirement. Fire incident data included dates, type, severity (alarm level) and location. Response data included dates worked, firehouse, position titles and shift lengths for each firefighter. The quantity of smoke particle mass generated during structural and non-structural fires adjusted by individual firefighter engagement was computed using the United States Environmental Protection Agency AP-42 emissions framework. Correlations between years of employment, fire responses and career total particle mass concentration by firefighter were examined. Linear regression models were fit and corresponding R^2 values were calculated.
Results Firefighters responded to a median of 424.7 (IQR=202.3–620.0) annual incidents/person; 17.6% were fire incidents (median=77.1; IQR=40.4–114.0). Structural fires were the most common type of fire incident (72.5% of annual incidents/person; median=55.9; IQR=29.6–85.5). Incident severity (alarm level) and firefighter engagement (position title) appeared to differentiate between high and low exposure regimes (R^2=0.43). Incident severity explained most of the variability of particle exposures (R^2=0.90).
Conclusions Using the JEM, job-related smoke particle concentrations were estimated to vary by incident type, incident severity and firefighter engagement, highlighting the importance of using refined measures, so that future studies can more accurately evaluate associations between firefighting and health outcomes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Smoke inhalation is a risk factor for disease among firefighters and is expected to increase in response to climate change and ageing infrastructure. Employment data have been used as an exposure metric to assess the association between firefighting and various health outcomes.

WHAT THIS STUDY ADDS

⇒ Particle concentrations from structural and non-structural fires were estimated using a refined job exposure matrix by integrating fire incident and response data with publicly available land use data. Broadly, the utilisation of this instrument can help us better understand the burden of exposure for other cohorts, cumulative dose–response relationships for different health outcomes including cancer and cardiopulmonary disease and inform exposure prevention and planning.

HOW MIGHT THIS STUDY AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study confirmed that employment data correlate poorly with smoke exposures. When considering the type, severity and fuel load at each incident, and engagement type for each firefighter, a refined measure of particle concentration, can be estimated, an improvement on prior works, which estimate exposure crudely, and, thus, increase the potential for exposure misclassification. Better quantification of smoke particle concentrations using this tool will be key in understanding the short-term and long-term effects of firefighting and, when tracked during active employment, may support the development of strategies to mitigate exposures.

INTRODUCTION

Firefighters are at an increased risk for adverse health outcomes, including mortality from cancers of the bladder, colon, skin (melanoma), pleura, prostate, male genital tract and thyroid as well as from cardiovascular and pulmonary disease.[1–4] Carcinogens and other hazardous substances that have been identified at responses to structural and non-structural fires in urban environments include dioxins and polycyclic aromatic hydrocarbons.[5] Others that have particularly damaging effects on cardiopulmonary health include carbon monoxide, hydrogen sulphide, ammonia, sulphur dioxide, hydrogen chloride, nitrogen oxides, soot and dust.[6–10] Studies assessing the impact of firefighting exposures on pulmonary function have reported mixed findings.[11] Ascription of smoke exposure in firefighting to different health outcomes is inconclusive due to the lack of detailed exposure assessments over the course of one's career.

Characterisation of exposures to combustion byproducts is challenging due to randomness of incident characteristics (ie, type, intensity, duration), response (ie, assigned task, proximity to fire, personal protective equipment) and limited time available after an incident.[12 13] The use of traditional methods such as personal monitors may inadvertently affect firefighting performance and safety. Alternative approaches for measuring smoke exposure aimed to do so by dichotomising days worked into active-duty firefighting with potential for smoke exposure and administrative duty, without potential for smoke exposure.[14–16] One study developed a weighted metric based on job title.[17] Fire-runs and service years were also suggested as surrogate metrics of exposure;[18 19] however, Austin *et al* proposed that time spent at fires was a more reliable metric.[20] Dahm *et al* developed a job exposure matrix (JEM) by harmonising work records spanning from 1950 to 2009 for Chicago, Philadelphia and San Francisco firefighters using job-titles, fire-runs and time spent at fire responses.[21] These proxy measures were later used to evaluate associations between career exposures and mortality.[22]

In this study, we present a JEM methodology to quantitatively assess exposures to smoke particles from structural and non-structural fires by integrating incident and response information with particle emissions data, a refinement of the JEM developed previously[21] that used the exposure surrogates of exposed-days, fire-runs and fire-hours. Fire incident and response data were obtained for Fire Department of the City of New York (FDNY) firefighters that were actively employed on 1 January 2010 and had retired by 21December 2021. The US Environmental Protection Agency (US EPA) air emissions methodological framework was used to compute particle emissions from many anthropogenic activities, including combustion processes.[23] Given the known and suspected hazards of smoke particle exposure emitted during urban fires and the lack of a time-varying exposure measure in published literature, we sought to develop a tool which can be used to improve the rigour of epidemiological studies evaluating firefighting exposures and different health outcomes such as pulmonary disease and cancer.

METHODS

Data sources

Fire and non-fire incident data (ie, date, time, incident type, alarm level and location) and response data (ie, number and positions of firefighters, work-shifts) were obtained from the FDNY Bureau of Communications from 2010 to 2021.[24] Hire and retirement dates were obtained from the FDNY employment database. The study population included 3237 consented participants actively employed by FDNY on 1 January 2010, and who were no longer employed as of September 2021. All participants were members of the World Trade Center Health Program.[25] All incident and response data included in this manuscript refer to responses that this study cohort attended and not the overall FDNY population.

JEM development

The JEM was developed by integrating a combination of three dimensions: (1) fire incident type (building type and surface); (2) fire incident severity (alarm level) and (3) firefighter engagement

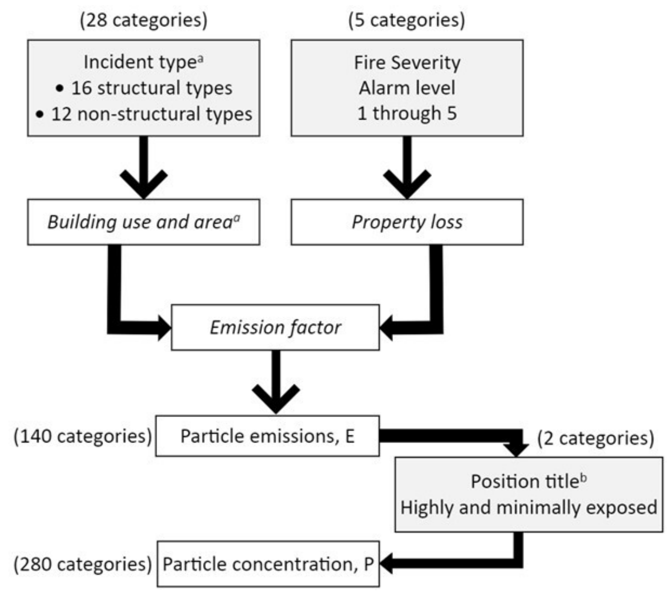

Figure 1 Dimensions of job exposure matrix (JEM) for computing quantities of particle emissions. The grey rectangles denote data obtained from Fire Department of the City of New York (FDNY) Bureau of Communications. Rectangles with italic fonts denote data obtained from independent sources [a] Online supplemental table S2; [b]Online supplemental table S3.

(position title) to estimate the quantity of particle mass released and the proximity of the firefighter for each fire incident (figure 1).

- *Fire incident types* distinguish between types of responses and building characteristics (eg, structural, non-structural, non-fire) and included 16 broad categories for structural fires and 12 categories for non-structural fires. The US EPA air emission methodological framework was used to compute particle emissions from many anthropogenic activities, including combustion processes.[23] It relies on emissions factors (EF) (ie, quantity of particle mass released/unit of activity) and process information for more than 200 point and non-point (area) source categories and preferred/alternative methodologies to estimate source activity and emission reductions. Because EFs are computed as an average of emissions for different source and microenvironmental conditions, particle emissions may deviate from actual releases but, nonetheless, provide a reliable estimate of the magnitude and relative importance of each source. The Compilation of Air Pollutant Emissions Factors (AP-42) includes a wide-ranging collection of EPA's EF data.[23] It contains source and process descriptions, emission factors and controls for particulate matter, volatile organic compounds, hazardous organic pollutants and greenhouse gas emissions from point and non-point sources.[23] The EFs used in this study are presented in online supplemental information 1.
- *Fire incident severity*: alarm levels (five categories: 1st–5th alarm) classify severity of fires and correspond to number of responding units, with a 5-alarm fire being the most severe type of incident that involves the mobilisation of 20 engine companies, 11 ladder companies, 10 battalion chief units and 1 deputy chief unit (online supplemental table S1). Loss rate is defined as the proportion of structural contents damaged as a result of a fire incident. 3rd–5th alarm responses are difficult to contain and require more time to extinguish leading to total loss of property (loss

rate, L=1).[26] The L values, derived from US Fire administration data, were set to 0.015 for small-scale first alarm fires (minimal damage) and 0.103 for all other first alarm structural fires (moderate damage), with an average of 7.3% property loss.[27] The average area for each building type was obtained from the New York City (NYC) Planning extensive land use and geographic data at the tax lot level database.[28] We obtained the building classes, and median areas assigned as commercial, residential, office retail and factory and the number of residential units for each building in NYC. The linkage between structural fire incident types and building types is displayed in online supplemental table S2.

- *Firefighter engagement* classification scheme relied on the potential for exposure by position title.[20 21] There were 227 position titles which were assigned into two categories of highly and minimally exposed (online supplemental table S3). Position titles involved in first-line combat related to knockdown and/or overhaul were classified as highly exposed to smoke. Position titles related to supervisory and other non-combat positions (eg, chiefs, chauffeurs) were minimally exposed. For highly exposed positions, a multiplier of 1 was set because of the very close proximity of firefighters to smoke plume. For minimally exposed positions, a conversion factor of 0.11 was computed using the mass conservation equation assuming a uniform concentration in smoke plumes at the downwind location, and the mean concentration was proportional to released particles and inversely proportional to wind speed (U, ie, 1 min/s) and cross-sectional area (H×W) (online supplemental table S4). In this study, W was the smoke plume width (equal to 0.1×d, where d was distance from the fire) and H was smoke plume depth (ie, height of the fire). In NYC, the width of avenues and cross streets were 30.5 m and 18.3 m, respectively. We assumed a distance from the fire of d=9.15 m (half the width of cross streets) to account for fire trucks and other equipment for minimally exposed positions (online supplemental table S4). A breakdown of the distribution of person-responses by incident type is presented in online supplemental table S5.

For each of the 280 unique JEM categories (28 fire incident types×5 fire severity×2 exposure conditions), particle mass (P_{ijk}, quantity of particles emitted, in kilogram) during the *i*-th fire incident type with *j*-th fire severity, for a firefighter at *k*-th exposure condition) for each fire event (n=1 through m) were computed using the EPA emission inventory development framework as follows[29]:

$$P_{ijk,n} = EF_i \cdot \left(M_{s,i} + M_{b,i}\right) \cdot S_i \cdot L_j \cdot E_k \cdot 10^{-3} \quad (1)$$

where EF_i is the particle generation factor, $M_{s,i}$ (79.7 kg/m^2) and $M_{b,i}$ (38.7 kg/m^2) are the combustible structural materials and building contents over the course of a participants' active duty service in the study period (ie, 2010 through retirement), and S_i is the average surface of the building type (m^2) for each fire type (i=1–28, online supplemental table S2), L_j is the average loss rate (%) per fire (j=1–5, based on fire alarm) and E_k is the exposure adjustment (k=1 for highly exposed positions, 0.11 for minimally exposed positions, see online supplemental table S3).[25 29] The total particle concentration (P_{total}) is the sum of particle mass for each fire incident for each firefighter.

$$P_{total} = \sum_{n=1}^{m} \sum_{i=1}^{28} \sum_{j=1}^{5} \sum_{k=1}^{2} P_{ijk} \quad (2)$$

We tested the feasibility of a two-dimensional JEM using fire severity, fire engagement and a constant EF of 5.14 kg/fire when detailed fire incident type (eg, building type and surface) is not available for each firefighter by event ($P_{ijk,n,alarm}$) and total ($P_{total,alarm}$). The alarm level of individual incidents has been consistently used by fire departments.

$$P_{ijk,n,alarm} = EF_i \cdot L_j \cdot E_k \cdot 10^{-3} \quad (3)$$

$$P_{total,alarm} = \sum_{i=1}^{16} \sum_{j=1}^{5} \sum_{k=1}^{2} P_{ijk,n,\ alarm} \quad (4)$$

Since time spent at the incident and PPE data were not available, we were unable to compute personal exposures; however, the value P_{ijk} may be proportional to personal exposures, assuming similar levels of compliance across individuals. The importance of calculating P_{ijk} for an individual lies within our ability to adjust the quantity of particles generated for firefighter engagement at a given incident. It allows for the calculation of daily exposures to particles in order to better understand the time-varying association between smoke exposure and different health outcomes.

Statistical analyses

Statistics of central tendency were evaluated for each dimension of the JEM. Normality was assessed graphically and using the Shapiro-Wilk test. When data were non-normally distributed, medians and IQRs were reported for each alarm level, incident classification and position title, by firefighter, annually. The following correlational analyses were conducted and plotted as a scatter diagram: years of firefighting service after 1 January 2010 versus number of career responses; years of firefighting service versus $P_{total,alarm}$; years of firefighting service versus P_{total}; number of fire responses versus $P_{total,alarm}$; number of fire responses versus P_{total} and P_{total} versus $P_{total,alarm}$. This was done by conducting simple linear regressions and calculating adjusted R^2 values. Post-2010 employment was calculated as the difference between retirement date and 1 January 2010.

Table 1 Demographic, employment and fire response characteristics of firefighters during the 2010–2021 period (n=3237)

Demographic characteristic	Mean (SD)
Age as of 1 January 2010	46.4 (6.1)
Years employed post 1 January 2010	6.1 (3.1)
Caucasian Race, n (%)	3064 (94.7)
Annual responses by incident characteristic	Median (IQR)
Alarm level	
First/all hands*	420.0 (199.9–614.8)
First alarm fire incidents only	73.5 (37.5–109.8)
Second	1.9 (0.8–3.0)
Third	0.6 (0.2–1.0)
Fourth	0.2 (0.0–0.5)
Fifth or higher	0.2 (0.0–0.5)
Incident classification	
Structural	55.9 (29.7–85.5)
Non-structural	19.0 (8.9–29.2)
Non-fire incidents	341.7 (166.2–511.4)
Highly exposed position†	34.3 (0.0–332.3)

Alarm levels correspond with incident severity; participants who responded to fires in highly exposed positions were assumed to have been exposed to higher levels of particle concentration when compared with those in lesser exposed positions.
*Includes non-fire medical responses.
†Based on position, or engagement at a fire, the median number of times participants were exposed to high levels of smoke particles during the study period from 2010 to 2021.

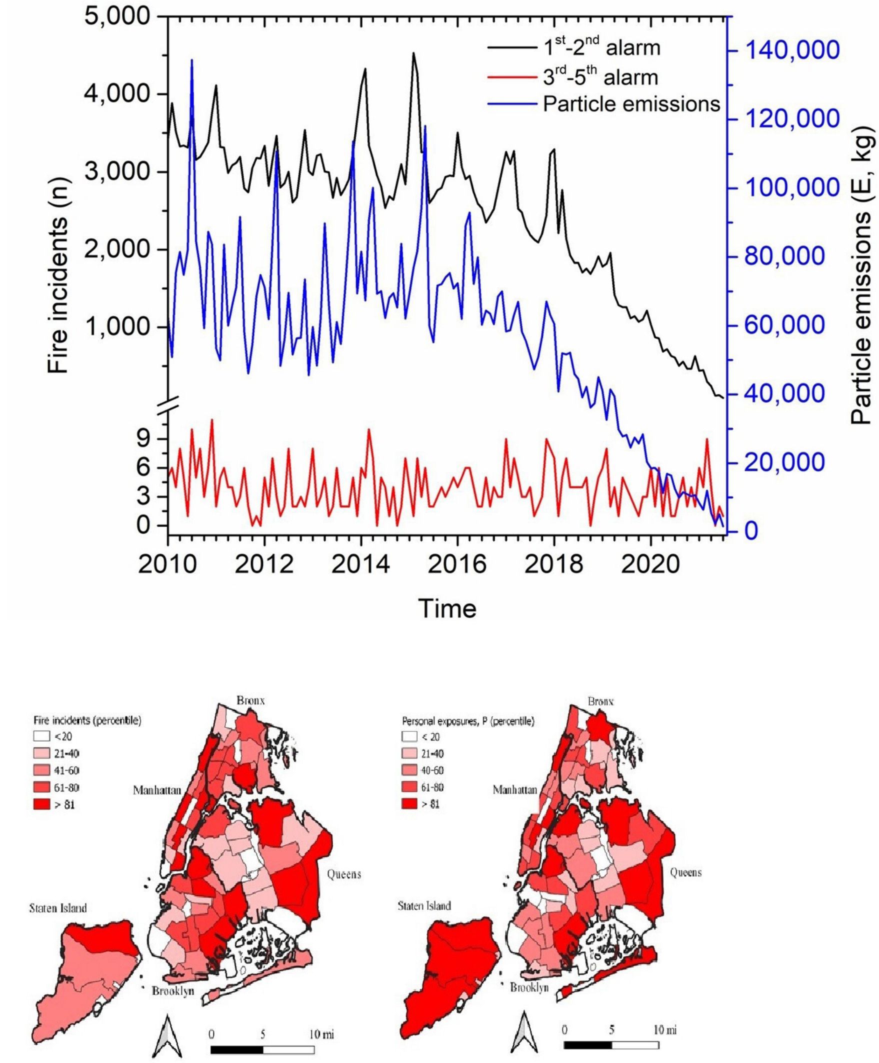

Figure 2 Temporal and spatial patterns of smoke exposure. (A) Monthly trend of fire incidents by alarm level and particle emissions during the 2010–2021 period; (B) spatial pattern of fire incidents and particle emissions.

Spatial distributions were analysed for 71 NYC Community Districts for distinct structural fires (first-second; third-fifth presented, separately), distinct non-structural fires and overall person responses. Quantiles were used to distinguish between each gradient level (k=5). Those that left the workforce between 2019 and 2021, were analysed separately from those that retired between 2010 and 2018. This cut-off was chosen to allow for an adequate follow-up period (≥9 years) regarding the availability of data used for particle concentration calculations. Additionally, given that participants tend to respond to fewer incidents towards the end of a career, it was important to identify a subgroup that could be followed for an extended period of time. This subgroup of later retirees represents approximately 23% (n=755) of the study cohort that retired after 2010 and responded to at least one fire incident. Analyses were conducted in SAS V.9.4, R V.4.1.2 and QGIS V.3.16.4.

This study followed the Strengthening the Reporting of Observational Studies in Epidemiology reporting guidelines and was approved by the Institutional Review Boards at the City University of New York and the Albert Einstein College of Medicine, and all participants provided informed written consent. Data that support the findings of the study may be obtained from the coauthors on reasonable request.

RESULTS

Participants

The study cohort included 3237 participants who responded to at least one incident in the 2010–2021 period (table 1). The mean age on 1 January 2010 was 46.4 years old (SD=6.1) with 10.3 (SD=6.8) years of pre-9/11 firefighting experience and 14.4 years (SD=3.1) of post-9/11 firefighting experience, of which 6.1 years (SD=3.1) were after 1 January 2010. The cohort was predominantly Caucasian (n=3064; 94.7%) and entirely men.

Incidents

Among responses for participants included in this study, only there were 2454 (SD=1048) first-second alarm and 3.9 (SD=2.4) third-fifth alarm fire incidents/month during the 2010–2021 period (figure 1A). The numbers of fire incidents declined by 10.6%/year for the entire period and up to 41%/year for the 2017–2021 period. The median monthly particle emissions (E) from both structural and non-structural fires for the 2010–2021 period were 60 061 (IQR=41 375–71 371) kg of particles and declined by 10.3%/year with higher emissions in spring and fall. High emission third-fifth alarm incidents were relatively infrequent. This was consistent with differences in spatial distribution

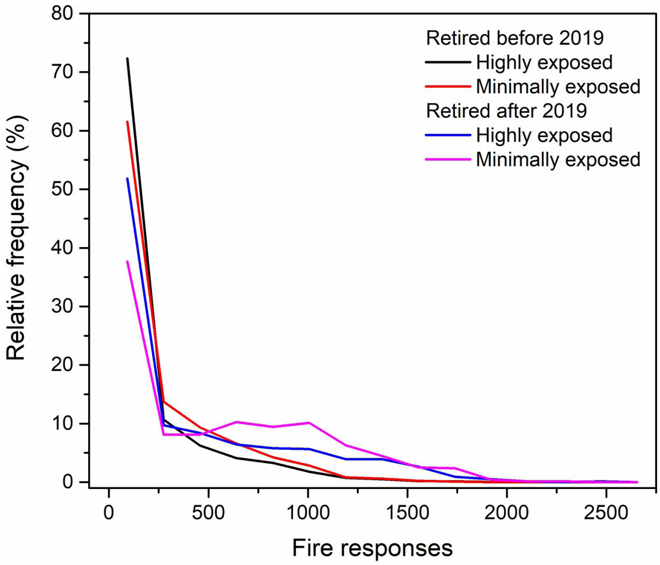

Figure 3 Relative frequency of fire responses by firefighters in highly and minimally exposed positions by retirement period.

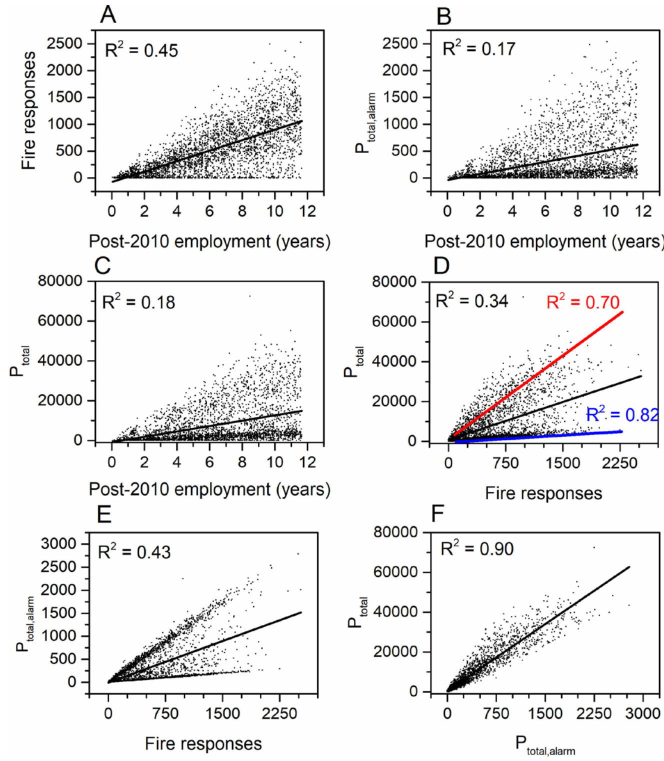

Figure 4 Correlational analyses (A) Post-2010 [difference between 1 January 2010, and retirement date] employment (X) versus fire responses (Y); (B) Post-2010 employment versus crudely adjusted particle mass ($P_{total,alarm}$); (C) Post-2010 employment versus particle mass (P_{total}); (D) Fire responses versus P_{total}; (E) Fire responses versus $P_{total,alarm}$; (F) $P_{total,alarm}$ versus P_{total}. The red and blue lines distinguish between differing exposure regimes. The red line represents a simple linear regression for firefighters involved in firefighting duties with high levels of particle emissions; blue line represents a simple linear regression for firefighters involved in firefighting duties with minimal levels of particle emissions. The black line represents all participants regardless of position.

of fire incidents and particle concentrations, P (figure 2B) with areas of low fire activity but high exposures (eg, Staten Island and eastern Queens) and the opposite, high fire activity but low levels of exposures (eg, eastern Brooklyn).

Responses

In addition to demographics, table 1 also displays descriptive statistics for annual responses per person. The previous section refers to unique incidents among firehouses that contained participants in the current study and, thus, was counted once. Responses, however, are counted for each time a unique study participant attends an emergency. Participants responded to a median of 424.7 (IQR=202.3–620.0) annual responses per person. Approximately, 77.1 (17.6%) annual responses/person (IQR=40.4–114.0) were fire-related. Thus, despite the high frequency of responses, the majority (82.4%) was not fire related (eg, medical responses). Structural fires were the most common type of fire incident (72.5%; median=55.9 annual responses/person; IQR=29.6–85.5).

Figure 3 displays relative frequencies of responses in highly and minimally exposed positions for firefighters retired before and after 2019. For those who retired before 2019, an exponential decline for frequency of fire responses was observed for both minimally and highly exposed positions. However, a substantial proportion of firefighters who retired in 2019 or later and worked in minimally and highly exposed positions responded to at least 1000 fire responses with about 25% of them responding to at least 1000 responses/year.

Particle concentrations

The median P_{total} over the course of an individuals' career was 2922 kg of particles (IQR=882–10,424), or 8 kg particles/response (IQR=3.5–24.1). Correlational analyses are displayed in figure 4. Three exposure regimes were identified when comparing P_{total} and fire incidents (figure 4D), for those assigned in mostly highly exposed positions (R^2=0.70), in mostly minimally exposed positions (R^2=0.82) and those in transition (ie, from highly to minimally exposed), with an overall R^2=0.34. This finding was commensurate with declining percentages of firefighters in highly exposed positions. The relationship between fire incidents and $P_{total,alarm}$ also highlighted the distinction between participants primarily in minimally exposed, highly exposed and those in transition (figure 4E). Most of the variability in P_{total} was explained by $_{total,alarm}$ as illustrated in figure 4F (R^2=0.90).

DISCUSSION

This study developed a novel JEM to quantify exposures to smoke particles for urban firefighters that integrated administratively collected incident and response information and particle emission data for structural and non-structural fires. The quantity of particles released from each fire considered the type (ie, structural, non-structural), severity (ie, alarm/property loss) and fuel load (ie, building type/size, structural and building combustible content) for each incident. Firefighters' position/rank was used as a proxy for engagement at a fire and allowed for further refinement when estimating particle concentration. The JEM was applied to a cohort of FDNY firefighters who were active in 2010 and retired by 2021 to build on prior works[21] by quantitatively estimating smoke particle concentration using a continuous metric.

We observed that the frequency of fire incidents and exposures decreased over time and were weakly associated due to attrition in the cohort (ie, participants retiring and/or transitioning from highly to minimally exposed roles). Service years were previously shown to correlate poorly with fire responses.[21 30] While particle emissions and exposures are thought to be reasonably explained by the total number of fire incidents, exposure misclassification may occur when using incident counts (ie, fire-runs) as an exposure metric. We observed periods with high densities of first and second alarm fire incidents in the winter, which corresponds to low particle emissions; however, sporadic but large third-fifth alarm fires needed to have a higher weight considering the severity and fuel loads of such incidents. Long-lasting fires of high-rise buildings with heavy loads of combustible structural building material generate large quantities of particles. Considering the monthly distribution of incidents and associated particle emissions, exposure conditions may be overestimated by 5% (SD=27%) when using fire incidents only (ie, the difference of the monthly normalised exposure metric). The error may be greater at the individual level due to differences in the frequency of responses by severity and type of firefighter engagement over time.

We also observed different engagement profiles for firefighters transitioning to retirement over the 11-year study period. Most firefighters near retirement responded to incidents in minimally exposed positions but some were, exclusively, in highly exposed positions. Significant exposures for responders on the periphery of fire incidents, particularly for third-fifth alarm fires, with those near the fire being at risk for elevated exposures were previously observed.[31] The variability of severity, type of fire incidents and engagement type were revealed in three exposure regimes, high, transient and low, all of which were highly correlated with fire incidents. This highlights the need to consider incident and response characteristics to describe exposure conditions and variability over time. At minimum, exposures weighted by incident severity could be a reliable metric, if detailed incident type and building characteristics are not available.

The main strength of this study was its ability to refine JEM methodology to quantitatively assess smoke particle emissions from structural and non-structural fires by integrating incident and response information with publicly available land use data. Additional strengths were the high quality of incident, response and building data used to estimate quantities of particles. The availability of detailed building data may be limited in other jurisdictions of the USA. This framework may be directly applied to other cohorts including retrospective career-long exposures with detailed incident-type information and/or alarm level, alone. This study expanded on prior work[21] that used a JEM with multiple dimensions to estimate urban firefighting exposures, however, did not evaluate exposure using a continuous measure of particle concentration. Furthermore, it could not be used to estimate exposure in a time-varying fashion. It should be noted that the number of incidents and their spatiotemporal distribution correspond to data from this selected cohort and is *not* necessarily reflective of overall fire incidents in NYC during this period.

The most significant limitation of this study is that this tool has not yet been validated; however, this was beyond the scope of this initial study. Personal air monitors can be used for validation in follow-up work. Another limitation is the representativeness of the cohort when compared with the overall active workforce. The overall active cohort is younger and, thus, are more likely to be involved in first-line combat duties. Nonetheless, the World Trade Center-exposed cohort was used to demonstrate proof-of-concept that this method can be used broadly and flexibly as a tool for other urban firefighter cohorts. Other limitations of the study include uncertainties in EFs and fuel load estimates. The EFs and structural and building loads are relatively outdated; however, most buildings in NYC, built before 1990, were comparable to the conditions used to generate EFs. In our analyses, we used the median surface area for buildings, but national estimates of property loss may not be representative of individual fires in the five boroughs of NYC. It most likely overestimated smoke aerosols released for the low-intensity first-alarm 'food-on-stove-events' that accounted for 39% of fire incidents but only 0.4% of smoke exposures. More precise estimates may be obtained in the future by geospatially overlapping incident and land-use data to determine building characteristics and home insurance records. Information on time spent at fires was largely incomplete, however, even in the presence of complete data, this would be challenging to measure. It has been suggested that firefighters' responses are relatively shorter in duration than in the past with some estimates as little as 20 hours/year, so the potential for exposure misclassification is plausible.[20 32 33] Evidence regarding individual use of personal protective equipment was also lacking.

All FDNY firefighters wore the same self-contained breathing apparatus (SCBA) and thermal protective ensemble ('bunker gear') during this study period. Compliance with wearing this ensemble was 100%, but there is great variability with SCBA use when at a fire scene while waiting to be deployed, but not actually engaged in a response.[20 34] Counterintuitive as it may be, this is more likely to occur during the third-fifth alarm incidents. Of note, the incidents included in this study cohort may not be fully representative of incidents for the active-duty FDNY workforce that had not retired during this study period. Another limitation is that data used to estimate particle concentrations were only available within 11 years prior to retirement, and thus, are skewed towards firefighters assigned to senior crew positions. Nevertheless, we were still able to identify differences in activity patterns and refine JEM through the highly/minimally exposed classification scheme. Finally, this study lacks external validity to direct particle emission monitoring methods that are inherently challenging to obtain during firefighting; however, this warrants future investigation.

In summary, this study presented a refined JEM for occupational exposures to firefighting smoke with the overall goal of characterising exposures to structural and non-structural particles of firefighters, so that future studies can more accurately examine their effect on health outcomes such as longitudinal pulmonary function, cardiopulmonary disease and cancer. Broadly, the utilisation of this tool can help better understand burden of exposure for other cohorts, cumulative dose–response relationships for many health outcomes and, inform exposure prevention and planning.

Acknowledgements We thank Rajiv Aggarwal and Wes Fang of the Bureau of Technology Development & Systems at the Fire Department of the City of New York (FDNY BTDS) for their assistance in obtaining incident and response data.

Contributors Conceptualisation: DGG. Methodology: DGG, DJP and IK. Data management: DGG. Validation: YL TS. Formal analyses: DGG. Interpretation of analyses: DGG, DJP, IK. Writing—original draft preparation: DGG, DJP, IGK. Writing—review and editing: all authors. DGG was the project lead/guarantor and accepts full responsibility for the finished work, had access to the data, and controlled the decision to publish. All authors have read and agreed to the published version of the manuscript.

Funding This research was funded by National Institute of Occupational Safety and Health (NIOSH) contracts 200-2017-93326 and 200-2017-93426.

Competing interests None declared.

Patient consent for publication Consent obtained directly from patient(s)

Ethics approval This study involves human participants and was approved by City University of New York Graduate School of Public Health and Health Policy Institutional Review Board Protocol number: 2020-0957 Albert Einstein College of Medicine Institutional Review Board Protocol number:07-09-320. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Data that support the findings of the study may be obtained upon reasonable request from RZO and/or DJP. These include de-identified aggregate data from 2010 through 2021 related to fire incidents and responses in the study cohort (i.e. Fire Department of the City of New York [FDNY] firefighters enrolled in the World Trade Center Health Program). All other data included in the manuscript are publicly available and are described in the text.

ORCID iDs
David G Goldfarb http://orcid.org/0000-0003-2682-7543
Rachel Zeig-Owens http://orcid.org/0000-0002-8679-2306

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