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Use of undergloves to assess pathways leading to contamination on firefighters' hands

Andrea F. Wilkinson[a], M. Christina Kander[b], Alexander C. Mayer[a], I-Chen Chen[a], Richard M. Kesler[c], Farzaneh Masoud[d], Denise L. Smith[d], Gavin P. Horn[c], and Kenneth W. Fent[a]

[a]Division of Field Studies and Engineering, National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), Cincinnati, Ohio, USA; [b]Division of Science Integration, National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), Cincinnati, Ohio, USA; [c]Fire Safety Research Institute, UL Research Institutes, Columbia, Maryland, USA; [d]Illinois Fire Service Institute, University of Illinois at Urbana Champaign, Urbana-Champaign, Illinois, USA

ABSTRACT

Firefighters (FFs) are occupationally exposed to many carcinogens, including polycyclic aromatic hydrocarbons (PAHs). Previous studies have evaluated PAH contamination on FFs' personal protective equipment (PPE), including fire gloves; however, there is a need to better understand PAH contamination that may break through fire gloves during active firefighting, donning, and doffing of PPE. Researchers in this study aimed to understand the potential contamination of FFs' hands during firefighting activities. A pilot study was conducted with 23 FFs, asking them to wear up to 3 separate sets of newly opened cotton undergloves during (1) donning, (2) simulated firefighting activities conducted in a smoky environment, and (3) doffing activities (donning and firefighting were combined for some samples). Samples were taken from the palm, index finger, and thumb areas of the cotton gloves and analyzed for PAHs. Overall, it was found that fire gloves were relatively effective at minimizing PAH exposure on the hands (undergloves) during active firefighting operations, though some PAH contamination was still present. PAH contamination was highest during the doffing of PPE and was significantly higher on the thumb and finger relative to the palm (p values $<$ 0.05). PAH contamination was found in the cotton gloves during donning, even though FFs' self-contained breathing apparatuses were cleaned and the turnout gear was previously laundered, using commercial extractors. Future research could explore the potential for contaminated, decontaminated, and/or laundered gear to present contamination risks to fire personnel and investigate the use of undergloves as additional protection for FFs' skin.

KEYWORDS

Carcinogens; firefighting; personal protective equipment; polycyclic aromatic hydrocarbons

Introduction

Awareness of firefighters' (FFs') occupational exposures to carcinogens, including certain types of polycyclic aromatic hydrocarbons (PAHs), has increased through recent research (Bolstad-Johnson et al. 2000; Fent et al. 2017; Beitel et al. 2020; Mayer et al. 2023; Horn et al. 2024; Kander et al. 2024). The International Agency for Research on Cancer (IARC 2020) recently updated the classification of the occupation of firefighting as carcinogenic to humans (Group 1) based on sufficient evidence of increased risk of bladder cancer and mesothelioma in FF (Demers et al. 2022). While occupational exposures to carcinogens likely contribute to the increased risk of developing cancer, there is a need to further understand routes of exposure (Demers et al. 2022).

Depending on the use of personal protective equipment (PPE) and the ambient airborne chemicals present, FF exposure to PAHs can occur via inhalation, transdermal absorption, and/or ingestion (Sousa et al. 2022). Inhalation exposure to off-gassing compounds from PPE is a documented, legitimate concern (Rogula-Kozłowska et al. 2024), however, when following standard protective practices, inhalation of PAHs during an actual fire is likely low during initial attack due to the use of self-contained breathing apparatus (SCBA) which have a protection factor of 10,000 (Campbell et al. 1994). Ingestion of PAHs and other combustion byproducts present in fire effluent

CONTACT Andrea F Wilkinson olq2@cdc.gov Division of Field Studies and Engineering, National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), Cincinnati, Ohio.

is possible due to transmission from hands to mouth, for example, if consuming food or drink during incident-scene rehabilitation before cleansing of hands. Research has shown that transdermal absorption of certain compounds commonly present on the fireground may be an important route of entry (Fent et al. 2017; Keir et al. 2017), and some of this dermal exposure is likely to occur during donning and doffing (Kesler et al. 2021).

Hand hygiene is a widely accepted practice for infection and disease control (Boyce et al. 2002); however, the unique and austere work environment of the fireground can interfere with hygiene practices. Hand exposure has been a topic of growing interest as previous work has demonstrated that PAH levels on hands increase from pre- to post-fire (Fabian et al. 2010; Fent et al. 2017). Additional research looking at exposure hazards from dirty FF PPE in Korea found PAH's to be the highest in gloves (Choi et al. 2023).

As expected, FF PPE becomes contaminated during live-fire events (Fabian et al. 2010; Fent et al. 2015; 2017). Although FFs wear fire gloves during fire suppression, they typically do not wear gloves when donning or doffing PPE (Fent et al. 2017). Fire gloves generally need to achieve protection against thermal and chemical threats, and shield the skin from water, moisture, heat, cuts, and abrasions (NFPA 2018). The degree to which fire gloves protect hand-skin from combustion byproducts like PAHs encountered during firefighting is not fully understood. Previous research has shown that the use of undergloves decreased PAH contamination on FF trainers' hands by 80% compared to those who did not wear undergloves during a simulated exposure (Laitinen et al. 2010). Moreover, the relative contribution to hand-skin contamination from activities when gloves are usually not worn (such as donning and doffing of PPE) has not been fully studied.

The purpose of this pilot study was to evaluate potential PAH contamination breaking through fire gloves during simulated firefighting activities in a smoky environment, as well as the transfer of contamination to hand-skin during donning and doffing of PPE, with the primary hypothesis being that most hand contamination occurs during doffing. Findings from this study may help elucidate the primary pathways leading to hand-skin contamination in FFs.

Methods

This study was performed at the University of Illinois Fire Service Institute (IFSI) with collaboration from the National Institute for Occupational Safety and Health (NIOSH) and the Fire Safety Research Institute (FSRI of UL Research Institutes (ULRI)). Institutional Review Board (IRB) approval was obtained from the University of Illinois at Urbana-Champaign (Protocol #20585) with reliance out by NIOSH.

Study population

Participants were recruited through a local and multistate network of FFs. A total of 23 FFs, 21 males and 2 females, participated in a training scenario. Participants ranged in age from 18 to 42 years. FFs with any known underlying cardiac or gastrointestinal conditions, who were pregnant, or who used tobacco were excluded from the study. All FFs were required to be cleared for fire suppression operations by their department and have a valid fit test for SCBA within the past 12 months.

Fire exposure simulator (FES)

Briefly, as described in detail elsewhere (Horn et al. 2020), the fire exposure simulator (FES) is a prop designed to allow for training in a fire-simulated environment (Figure 1). The FES is a shipping container that is divided into three sections, where the middle section serves as a controlled combustion chamber with ceiling-mounted ductwork terminating into the east and west chambers to produce smoky conditions. For each scenario, three FFs performed simulated firefighting activities in the east and west chambers (six FF total). Smoke was generated by burning a residential sofa in the middle combustion chamber. Simulated firefighting activities were conducted on 2 min work/rest cycles totaling 13 min per scenario (Table 1). The activity protocol was developed to mimic a previously validated protocol that was used to investigate physiologic responses to firefighting activities, which found that firefighting scenarios often follow a pattern of 1–4 min of strenuous work followed by intermittent rest periods. (Ensari et al. 2017). Ignition occurred at 3 min, and the fire was suppressed at 9 min. The firefighting activities included (Horn et al. 2020):

1. Stair climb that was performed in an attached container with six sets of three steps (up and down). This activity took place outside of any smoke exposure to simulate stair climbing into a smoke-protected stairwell. Following the

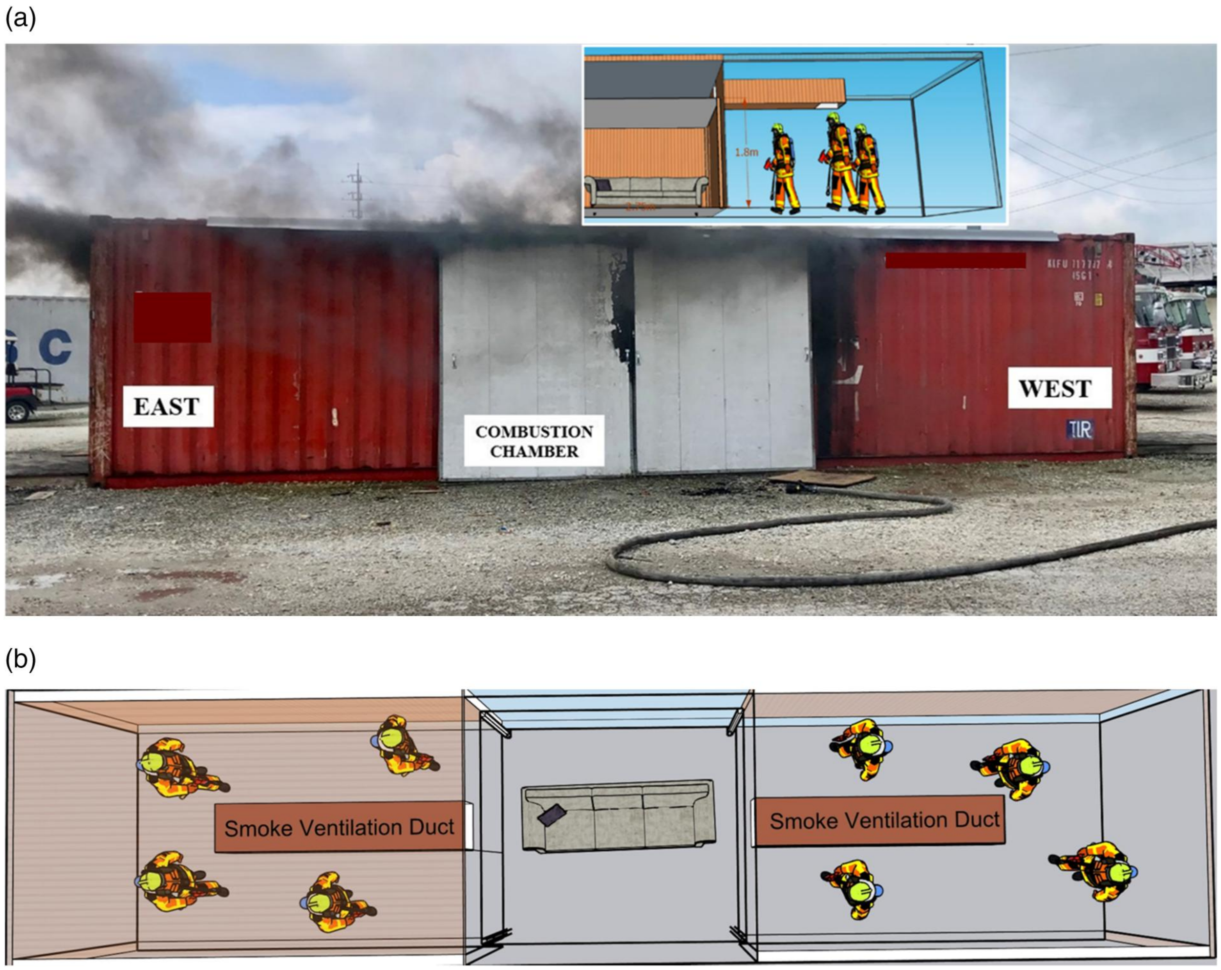

Figure 1. (a) Fire exposure Simulator based on a 12-meter (40-foot) intermodal shipping container where the Middle 10-foot section was used as a controlled combustion chamber and each directional end was used for conducting firefighting activities (search [crawling/kneeling], hose advance, and overhaul) in a smoky environment. (b) Fire exposure Simulator inside ariel view.

Table 1. Timeline for participants conducting firefighting activities in the fireground exposure simulator (FES).

Time (min)	Firefighter activities	FES conditions
0:00	Stairs (in adjacent training facility)	Background–All FES doors open
1:00		
2:00	Transition to FES & rest	
3:00	Rest	Close east and west chamber doors, ignition of sofa, close middle burn chamber
4:00	Search	
5:00		
6:00	Rest	
7:00		
8:00	Hose advance	
9:00		Crack burn chamber, suppression (∼15 s)
10:00	Rest	Fully open middle burn chamber
11:00		
12:00	Overhaul	Open east and west chamber doors to vent
13:00		
14:00	Leave chamber and walk upwind	
15:00	Enter data collection tent for sample collection and doffing	
16:00		
17:00		
18:00		
19:00		

completion of the stair climb, FFs walked a short distance to the exposure chamber.

2. Search that was simulated by FFs crawling around the exterior wall of the chamber as the sofa was ignited and smoke began to fill the FES structure. FFs searched in a clockwise direction for 1 min, then counterclockwise for 2 min.
3. Hose advance that was simulated using a pulley mounted to the chamber wall. Note: The burning sofa in the combustion chamber was suppressed by a staff member to end the combustion process. This allowed steam to flow into the exposure chambers.
4. Overhaul that was simulated with FFs standing and grasping a pike pole, performing motions of pulling down a ceiling. During this time, the doors on each end of the exposure chambers were opened, and smoke naturally vented out of the structure, as is common during the overhaul process.

After completing the training activities, FFs were promptly escorted to the sampling area upwind of the fire. Because the simulated firefighting activities were conducted without flowing water, the training environment where FFs operated remained dry.

Firefighting PPE and undergloves

FFs were fitted for assigned PPE and base layer clothing and completed uniform simulated firefighting activities in the FES (Table 1). PPE and base layer clothing were new at the start of the study. All FFs were properly sized for NFPA 1971 compliant structural fire gloves and donned the same size and model throughout the study. The turnout gear and fire gloves were laundered between each training scenario using commercial extractors. FFs were provided with new base layers for each scenario. The base layers included cotton gloves to act as surrogate skin to capture contamination that may be present on the hands. These cotton gloves will be referred to as "undergloves" throughout the paper. In one group of FFs ($n = 12$), three sets of cotton gloves were utilized; one pair to evaluate effect of donning PPE (when FFs would typically be bare handed), a second pair was worn under traditional fire gloves during active firefighting (i.e., undergloves), and one pair to evaluate effect of doffing PPE (when FFs would typically be bare handed). In this group, FFs put on two sets of undergloves before donning their PPE (Figure 2). After FFs donned their PPE, attached the regulator to their facepiece, and turned on the SCBA cylinder to supply air to the regulator, a researcher removed the outermost underglove and placed it in a Ziploc bag, helped the FFs put on a new outermost underglove, and then assisted the FFs with putting on their fire gloves. Once the fire gloves were on, the FFs engaged in simulated firefighting activities in the FES.

In another group of FFs ($n = 11$), two sets of cotton undergloves were utilized; one pair to evaluate both PPE donning and active firefighting, and a second pair for PPE doffing. In this group, FFs also put on two sets of undergloves before donning their gear, but researchers did not collect any undergloves until after they completed simulated firefighting activities in the FES.

For both groups, after firefighting ended, the FFs were transported to an outdoor canopy-protected area to shield FFs from environmental conditions while removing their fire gloves without touching the outside of the contaminated fire gloves. A researcher wearing clean nitrile gloves then collected the outermost undergloves and immediately placed them in Ziploc bags. The remaining underglove was then worn during doffing of PPE. After PPE had been fully doffed, researchers wearing clean nitrile gloves collected the remaining underglove.

Figure 2. Cotton undergloves before and after firefighting operations.

Sample processing and analysis

Undergloves were processed in an environmentally controlled laboratory at IFSI. Researchers wearing clean nitrile gloves cut samples (5 cm x 5 cm) from the fingers, thumb, and palm of each underglove, collected the samples in individual Ziploc bags, and stored them in a −20 °C freezer until they were shipped on ice for analysis (see Figure 3). Bulk fabric samples were analyzed for PAHs using a modified version of NIOSH Method 5506 (Kander et al. 2024). To yield a quality control recovery limit, laboratory control spikes for all studied PAHs were applied to each fabric blank. Sample quantities are displayed in Table 2; 19 samples were excluded from analysis due to evidence of microbial contamination during storage.

Data analysis

The descriptive comparisons for underglove contamination were conducted using the sum of the six most dominant PAH concentrations (Σ6PAH, μg/g). This was done because measures for the other PAHs were very low or non-detectable, and to include them in the summation would introduce an upward bias. Non-detectable concentrations for the six PAHs below the limit of detection (LOD) were imputed using the β-substitution method (Ganser and Hewett 2010). Descriptive statistics are presented as geometric mean (Corbally et al. 2021), median, and range for the Σ6PAHs, stratified by sampling site (finger, palm, thumb) and collection period relative to smoke exposure (doffing, donning/firefighting (which includes both donning and firefighting sample results when collected separately)). GM and median concentrations are also provided for the most dominant individual PAHs.

For statistical testing, a marginal model incorporating an exchangeable working correlation structure was used to account for the statistical correlation among repeated glove samples from the same FF (Chen et al. 2024). The model was employed to determine if Σ6PAH levels significantly differed among sampling sites during the doffing phase. Analyses were also conducted to test whether Σ6PAH or individual PAH levels of the most dominant analytes significantly differed between doffing and donning/firefighting at each sampling site. All statistical tests were performed in R version 4.4.0 (Team 2024) and were two-sided at the 0.05 significance level.

Figure 3. Cotton underglove sample preparation. Samples cut from the index finger, thumb, and palm.

Table 2. Sample counts for sampling sites and collection periods.

Sampling site from cotton undergloves	Sample collection period from undergloves relative to firefighting	Frequency	Notes	How the samples were categorized for most analyses
Index Finger	Doffing	23	1 sample per participant	Doffing
	Firefighting	12	1 sample per participant	Donning/Firefighting
	Donning	12	1 sample per participant	Donning/Firefighting
	Donning/firefighting	11	1 sample per participant	Donning/Firefighting
Palm	Doffing	18	5 samples excluded from analysis	Doffing
	Firefighting	9	3 samples excluded from analysis	Donning/Firefighting
	Donning	8	4 samples excluded from analysis	Donning/Firefighting
	Donning/Firefighting	11	1 sample per participant	Donning/Firefighting
Thumb	Doffing	18	5 samples excluded from analysis	Doffing
	Firefighting	9	3 samples excluded from analysis	Donning/Firefighting
	Donning	8	4 samples excluded from analysis	Donning/Firefighting
	Donning/Firefighting	11	1 sample per participant	Donning/Firefighting

Results

The analysis of specific PAH compounds measured from all doffing period samples revealed that the underglove contamination was dominated by 6 species (Table 3). By focusing comparisons among the sum of these 6 species, there was identification of several statistically significant differences (p-values < 0.05) in contamination levels between collection periods and sample sites (Table 4). Significant differences in Σ6PAHs were found in the finger and thumb sites between the collection periods (i.e., doffing > donning/firefighting) (p-values $= 0.0001$ and 0.0007). Significant differences in Σ6PAHs were also observed in the doffing period between the sample sites (i.e., finger, thumb > palm) (p-values < 0.0001). Table 5 provides summary data (Σ6PAH concentrations) for the group of FFs where there were three distinct collection periods (donning, firefighting, and doffing). The doffing period samples accounted for 62.8% of the Σ6PAH GM contamination measured from the undergloves, followed by the donning period samples at 19.3%, and the firefighting period samples at 17.9%. For the individual PAHs, statistically significant differences were also found between collection periods (i.e., doffing > donning/firefighting samples) for the finger and thumb sample sites (Table 6).

Discussion

To the best of the authors' knowledge, this is the first study to examine FF surrogate hand contamination using cotton undergloves during distinct periods in the FFs' emergency response work cycle on the fireground. These methods allowed researchers to examine not only the type and magnitude of PAH contamination FFs are exposed to, but also the periods when exposures occurred. These data improve overall understanding of exposures associated with PPE donning, firefighting activities, and PPE doffing and cross-contamination, leading to hand-skin exposure. The results can support ongoing efforts to educate workers and inform mitigation strategies.

In this study, the turnout gear and fire gloves were laundered between each fire, and the SCBAs were initially hand-washed with cleaning solution, water, and a scrub brush, and then scoured with degreaser wipes. It is reasonable to assume that donning of properly cleaned PPE would result in minimal transfer of

Table 3. GM and median PAH concentrations (μg/g) for the six most dominate analytes measured in samples collected after the doffing period ($N = 59$).

Analyte	Non-detection Rate (%)	GM	Percentage of total GM	Median	Percentage of total median
Benzo(a)anthracene	83.1	0.008	4.5	0.003	4.2
Benzo(a)pyrene	71.2	0.011	6.2	0.004	5.6
Benzo(b)fluoranthene	64.4	0.016	9.4	0.008	11.3
Benzo(g,h,i)perylene	76.3	0.011	6.4	0.005	7.0
Dibenzo(a,h)anthracene	57.6	0.093	54.2	0.042	59.2
Indeno(1,2,3-cd)pyrene	76.3	0.032	18.5	0.008	11.3
All others	93.2	0.001	0.8	0.001	1.4

Table 4. GM and median Σ6PAHs (μg/g) on undergloves by sampling site and collection period.

Sampling Site	Collection period relative to smoke exposure	$N^{\#}$	N of Non-Detects	GM	Median	Range	*P*-Value (Doffing vs Donning/ Firefighting at each sampling site)	*P*-Value (Comparison of sampling sites for the doffing phase)	
Glove, Finger	Donning/Firefighting*	35	31	0.07	0.05	0.04–1.25	Reference		
($N = 58$)	Doffing	23	10	0.39	0.66	0.05–8.20	0.0001	Reference	
Glove, Palm	Donning/Firefighting*	28	27	0.01	0.01	0.01–0.35	Reference		
($N = 46$)	Doffing	18	16	0.02	0.01	0.01–2.48	0.1465	<.0001	Reference
Glove, Thumb	Donning/Firefighting*	28	26	0.08	0.07	0.04–3.05	Reference		
($N = 46$)	Doffing	18	6	0.51	0.69	0.06–13.83	0.0007	0.0199	<.0001

*Inclusion of glove samples from donning, burn, and combined donning and Firefighting samples.
#N: Number of samples.

Table 5. GM and median Σ6PAHs (μg/g) on glove samples (all sites) by collection time point (where we had three distinct samples).

Time point	N	N of non-detects	GM Σ6PAHs	Percentage of total GM	Median Σ6PAHs	Percentage of total median
Doffing	59	32	0.179	62.8	0.072	40.7
Donning	28	25	0.055	19.3	0.053	29.9
Firefighting	30	27	0.051	17.9	0.052	29.4

Table 6. Individual GM PAH levels (μg/g) measured from doffing and donning/firefighting period samples by sample site.

Sampling Site	Collection period relative to smoke exposure	Benzo(a) anthracene	Benzo(a) pyrene	Benzo(b) fluoranthene	Benzo(g,h,i) perylene	Dibenzo(a,h) anthracene	Indeno (1,2,3-cd)pyrene
Glove, Index Finger	Doffing (referent)	0.006	0.032	0.034	0.009	0.244	0.025
($N=58$)	Donning/Firefighting	0.002**	0.005***	0.005***	0.003**	0.047***	0.007**
Glove, Palm	Doffing (referent)	NA	0.002	0.002	0.007	0.009	NA
($N=46$)	Donning/Firefighting	NA	0.001	0.001	0.005	0.006	NA
Glove, Thumb	Doffing (referent)	0.012	0.015	0.051	0.021	0.281	0.042
($N=46$)	Donning/Firefighting	0.004*	0.004*	0.009**	0.006*	0.044***	0.014*

*P-value < 0.05, **P-value < 0.01, and ***P-value < 0.001.

contaminants to hands, and this can be expected even though donning of PPE is usually performed without any hand protection. However, when broken down into three collection periods, an estimated 20% of the GM Σ6PAH contamination was found during the donning phase.

Previous studies have found that certain contaminants, including PAHs, can remain on or embedded in turnout gear even after laundering or preliminary exposure reduction (Mayer et al. 2019; 2020; Krzemińska and Szewczyńska 2022; Girase et al. 2022; Wilkinson et al. 2023). Moreover, FFs may not always launder turnout gear and fire gloves or clean their SCBA in between firefighting responses. Hence, real-world cross-contamination during donning of the gear could be even more pronounced than indicated by these data.

When evaluating the three distinct collection periods, the firefighting period samples had the lowest amount of PAHs (16% of total GM Σ6PAHs collected). Although the fire gloves were laundered before use, the inside of the gloves may have contained some residual contamination. Otherwise, small amounts of PAH contamination in the fire environment may have managed to penetrate or permeate the fire gloves. Overall, these data indicated that fire gloves provide relatively high protection from PAHs and likely other combustion byproducts during firefighting operations. However, as previously noted, the exposure conditions in this study did not include contributions from contaminated water that may allow penetration of PAHs around the glove and through the glove/jacket interface. This mechanism has been proposed as a possible source of hand contamination when FFs might be crawling in environments with standing suppression water that would likely contain these contaminants (Fent et al. 2017).

Perhaps not surprisingly, the doffing period samples accounted for the majority (64%) of the GM Σ6PAH contamination collected on the undergloves. The FFs in this study were able to remove their fire gloves without touching the outside due to assistance from the research team, similar to EMS glove removal, but otherwise handled their contaminated PPE during doffing as most FFs typically do. Considering fire gloves have been found to be the PPE element that has among the highest contamination levels (Fent et al. 2020; Choi et al. 2023), fire gloves that are removed with less care could result in higher levels of contamination than what we found during the doffing period. Although doffing techniques exist that incorporate the use of latex or nitrile gloves or partner-assisted removal of items to help minimize the transfer of contamination to hand-skin, these techniques were not employed as they do not represent standard practice on the fireground. Regardless of the doffing technique, the results highlight the importance of hand hygiene following the removal of PPE. The hypothesis that exposure is likely coming from doffing and not from fire effluent breaking through the gloves during fire activities is further supported by the higher amounts of contamination on the finger and thumb compared to the palm. Contamination on the digits (compared to the palm) is also more likely to be ingested or transferred to other areas of the body during post-fire activities, depending on hand hygiene practices.

In terms of the composition of PAH contamination found under the gloves, the majority (54% of the GM Σ6PAHs) was comprised by dibenzo(a,h)anthracene, which has been classified as a Group 2 A probable human carcinogen by IARC (Demers et al. 2022). Previous studies have found that dibenzo(a,h)anthracene is one of the most predominant PAH contaminants collected via wipe sampling from the exterior of FFs' PPE following smoke exposure (Wilkinson et al. 2023). Using wipe sampling, researchers previously measured a median of 16.3 μg/m^2 (interquartile range 5.2–125 μg/m^2) of total PAHs from FFs' hands after firefighting and doffing gear (Fent et al. 2017). Accounting for the surface area and average mass of the bulk samples (0.0025 m^2, 0.56 g) in the present study, the median Σ6PAH mass/area concentrations for the doffing-period finger, palm, and thumb samples were 148, 2.2, and 156 μg/m^2, respectively. The higher levels were measured from the finger and thumb compared to the palm (and previous hand wipe sampling results), highlighting the spatial distribution in hand contamination (as well as the different sampling techniques). While the focus of this evaluation was on PAHs, many other hazardous substances have been measured on contaminated FFs' PPE, including persistent organic pollutants (Fent et al. 2017; Mayer et al. 2023). Hence, the mixture of contaminants that could be transferred to hand-skin is more complex than just PAHs.

Limitations

This pilot study did have some limitations. The FFs in the study were exposed to fire effluent for only 11 min, which may be a shorter duration compared to real emergency response fire scenarios. The exposure conditions in this study do not account for potential contributions from water-assisted penetration of PAHs around the glove body. While the subjects in this project simulated firefighting activities, it is probable that FFs in real-world emergency operations, particularly those involved in search and rescue operations, may use their hands in a different manner than incorporated in this study. Consequently, there is a possibility that the data has not fully captured the extent of exposure during firefighting operations.

Because two pairs of undergloves were worn during firefighting, the innermost pair (analyzed as the doffing period sample) could have become contaminated during the live fire operations. However, this alone would not explain the higher levels of PAH contamination found in the undergloves for the doffing period versus the firefighting period. The data indicated that the doffing period undergloves accumulated most of the PAH contamination during firefighters' removal of gear and equipment.

It is also important to note that this study's methods were focused on measuring particulate-phase PAH contamination. Previous research has shown that naphthalene, a type of PAH that is mainly present in vapor form, is the primary PAH emitted during fires (Mayer et al. 2023; Kander et al. 2024; Teixeira et al. 2024). The pathways leading to naphthalene hand contamination could be different than what we found for the particulate-phase PAHs.

Conclusion

The results of this pilot study suggest that fire gloves are effective at minimizing PAH exposure to the hands during simulated firefighting operations in smoke-filled environments. However, cautious removal of gloves and other PPE may be encouraged as the surface of these items can carry harmful contaminants that can be transferred to hand-skin and then be absorbed transdermally or inadvertently ingested. Ideally, as a best practice to minimize hand contamination, FFs can doff PPE without contacting the firefighting glove exterior or with a partner who can remove their gloves, followed by donning nitrile or latex gloves before doffing the rest of their PPE and equipment. Proper hand hygiene may now follow. The aforementioned process is aligned with recommendations from the National Fire Protection Association's NFPA 1001 Standard for Fire Fighter Professional Qualifications, which details job performance requirements for field reduction of contaminants (NFPA 2019). It is also important to note that there are many aspects of firefighting work where gloves are not routinely worn; for example, when handling a hoseline during cleanup. This could be another source of hand contamination following the doffing of PPE that could contribute to overall dermal exposure.

Future research could evaluate the potential for laundered or decontaminated gear to continue to present cross-contamination potential. While undergloves in this study were used as surrogates for hand-skin, undergloves may potentially be used to increase the level of PPE protection. The cotton undergloves absorbed the measured PAH contamination, preventing it from reaching the FFs' skin. Future research could explore the application of undergloves as a means of increasing skin protection for FFs, while also carefully considering the impact on dexterity, work function, and burn risk (Everaert et al. 2023).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

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