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Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures

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ABSTRACT

Firefighters' skin may be exposed to chemicals via permeation/penetration of combustion byproducts through or around personal protective equipment (PPE) or from the cross-transfer of contaminants on PPE to the skin. Additionally, volatile contaminants can evaporate from PPE following a response and be inhaled by firefighters. Using polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) as respective markers for non-volatile and volatile substances, we investigated the contamination of firefighters' turnout gear and skin following controlled residential fire responses. Participants were grouped into three crews of twelve firefighters. Each crew was deployed to a fire scenario (one per day, four total) and then paired up to complete six fireground job assignments. Wipe sampling of the exterior of the turnout gear was conducted pre- and post-fire. Wipe samples were also collected from a subset of the gear after field decontamination. VOCs off-gassing from gear were also measured pre-fire, post-fire, and post-decon. Wipe sampling of the firefighters' hands and neck was conducted pre- and post-fire. Additional wipes were collected after cleaning neck skin. PAH levels on turnout gear increased after each response and were greatest for gear worn by firefighters assigned to fire attack and to search and rescue activities. Field decontamination using dish soap, water, and scrubbing was able to reduce PAH contamination on turnout jackets by a median of 85%. Off-gassing VOC levels increased post-fire and then decreased 17–36 min later regardless of whether field decontamination was performed. Median post-fire PAH levels on the neck were near or below the limit of detection ($<$ 24 micrograms per square meter [$\mu g/m^2$]) for all positions. For firefighters assigned to attack, search, and outside ventilation, the 75th percentile values on the neck were 152, 71.7, and 39.3 $\mu g/m^2$, respectively. Firefighters assigned to attack and search had higher post-fire median hand contamination (135 and 226 $\mu g/m^2$, respectively) than other positions ($<$ 10.5 $\mu g/m^2$). Cleansing wipes were able to reduce PAH contamination on neck skin by a median of 54%.

KEYWORDS
Contaminants; decontamination; evaporation; firefighters; PAHs; turnout gear

Introduction

The International Agency for Research on Cancer (IARC) classified occupational exposure as a firefighter as possibly carcinogenic to humans (Group 2B).[1] Since this determination was made in 2010, a number of epidemiology studies continue to find elevated risks of several cancers in firefighters. In the largest cohort mortality study to date (30,000 firefighters), Daniels et al.[2] found increased mortality and incidence risk for all cancers, mesothelioma, and cancers of the esophagus, intestine, lung, kidney, and oral cavity, as well as an elevated risk for prostate and bladder cancer among younger firefighters. In a follow-on study, Daniels et al.[3] found a dose-response relationship between fire-runs and leukemia mortality and fire-hours and lung cancer mortality and incidence. Other studies corroborate the elevated risk of a number of these cancers and provide evidence for the increased risk of other cancers, like melanoma and

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myeloma.[4–6] While chemical exposures encountered during firefighting are thought to contribute to the elevated risk of these cancers, the role that contamination on PPE and skin plays in this risk has not been well defined.

The materials found in modern buildings and furnishings are increasingly synthetic and can generate many toxic combustion byproducts when they burn.[7–9] Toxic substances identified in fire smoke include polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), hydrogen cyanide (HCN), and several other organic and inorganic compounds.[8,10–18] Many of these compounds are known or potential human carcinogens. A number of these compounds have been measured on firefighter PPE.[19–24] VOCs and HCN have also been measured off-gassing from turnout gear following use in live fires.[25,26] These contaminants, particularly the less volatile substances, could be transferred to fire department vehicles and firehouse living spaces.[27–29]

Skin exposure can occur during firefighting by way of permeation or penetration of contaminants through the hood, turnout jacket and trousers, in between interface regions of this ensemble (possibly aided by the bellows effect during firefighter movements), or through the cross-transfer of contaminants on gear to skin. Fent et al.[30] found significantly elevated levels of PAHs in skin wipes from firefighters' necks following controlled burns. In this and other studies, biomarkers of benzene and PAHs were identified post firefighting, even though SCBA were used, suggesting that dermal absorption contributed to firefighters' systemic levels.[30–33]

Differences in PPE and skin contamination by job assignment and firefighting tactic have not been well characterized. It is likely that exposures are not uniform among firefighting personnel. For example, the incident commander who is stationed outside is unlikely to have the same exposure as a firefighter who is operating on the interior of a smoke-filled room while advancing a charged hoseline or conducting search and rescue operations.

Laundering of firefighter turnout gear may not be routinely conducted following a fire response, but is more commonly performed only once or twice per year. In between launderings, toxic substances are likely to accumulate on the gear from each subsequent fire response and could transfer to the skin of firefighters. Likewise, field decontamination is rarely completed following a fire response. Field decontamination of firefighters' PPE is advocated by several firefighter support organizations.[34–36] Performing gross decontamination in the field following a fire event may remove a large quantity of hazardous substances from firefighters' PPE. A few departments have instituted new policies requiring field decontamination and even laundering of turnout gear following live-fire responses. Some departments now provide skin cleansing wipes for firefighters to use following a response.[34] However, we are unaware of any studies characterizing the effectiveness of field decontamination of firefighter PPE or skin cleaning measures. Efficacy data are needed to justify and support these efforts more broadly.

The purpose of this study was to characterize the contamination of a representative portion of firefighters' protective ensembles (turnout jackets and helmets) and skin (hand and neck skin) following structural firefighting activities involving realistic residential fires. Additionally, we aimed to investigate contamination levels on gear and skin by job assignment and firefighting tactic, as well as before and after decontamination measures. The effectiveness of skin wipes and three types of field decontamination methods were quantified. While contamination could consist of hundreds of compounds, for this article we focused primarily on PAH particulate (for surface and skin testing) and VOC and HCN gases and vapors (for off-gas testing).

Methods

Study population and controlled burns

This study was performed at the University of Illinois Fire Service Institute with collaboration from the National Institute for Occupational Safety and Health (NIOSH) and Underwriters Laboratories (UL) Firefighter Safety Research Institute (FSRI). IRB approval was obtained from both the University of Illinois at Urbana-Champaign and NIOSH. Forty-one firefighters (37 male, 4 female) participated in this study. All firefighters were required to wear their self-contained breathing apparatus (SCBA) and full PPE ensemble (including hood) prior to entering the burn structure. Use of SCBA outside the structure was at the discretion of the individual firefighter. Firefighters were instructed to use their own fire department protocols to determine if smoke exposure warranted SCBA usage. Each participant was provided brand new turnout jackets, trousers, hoods, and gloves at the beginning of the study. All PPE adhered to NFPA standards.

This study had a total of 12 scenarios (one per day and no more than four scenarios per person). For each scenario, a team of 12 firefighters completed a realistic firefighting response that involved a multiple-room fire (two separate bedrooms) in a 111 square meter (m^2) residential structure.[37] The bedrooms where the fires were ignited were fully furnished. Additional details on the structure are provided in the supplemental file.

Table 1. Deployment protocol, job assignments, and response times.

Apparatus	Job assignment (2 firefighters per assignment)	Specific tasks	Median time outside structure (min)	Median time inside structure (min)
Engine 1	Outside Command/Pump	Incident command and operate the pump	20	0
	Inside Attack	Pull primary attack line from engine and suppress all active fire	3	8
Truck 1	Inside Search	Forcible entry into the structure and then search for and rescue two victims (weighted manikins)	2	8
	Outside Vent	Deploy ladders to the structure and create openings at windows and roof (horizontal and vertical ventilation)	19	0
Engine 2	Overhaul/Backup	Pull a second attack line and support the first-in engine (from outside the structure) and then perform overhaul operations inside the structure after fire suppression	11	16
	Overhaul/RIT	Set up as a rapid intervention team (RIT) and then perform overhaul operations inside the building after fire suppression	11	17

The 12 firefighters on each team worked in pairs to perform six different job assignments (Table 1) that included operations ***inside*** the structure during active fire (fire attack and search & rescue), ***outside*** the structure during active fire (command, pump operator and outside ventilation), and ***overhaul*** operations after the fire had been suppressed (firefighters searched for smoldering items, removed drywall from walls/ceilings, and removed items from the structure). After ignition, the fires were allowed to grow until the rooms flashed over and became ventilation limited (typically 4–5 min) and then the firefighter participants were dispatched by apparatus in 1-min increments following the order in Table 1.

Thirty-one firefighters participated in a total of four scenarios, nine participated in two scenarios, and one withdrew from the study. For the firefighters who completed four scenarios, they were assigned to new job assignments upon completing the first two scenarios. The Inside Attack firefighters on each team used the following tactics: (a) traditional ***interior*** attack from the "unburned side" (advancement through the front door to extinguish the fire) and (b) ***transitional*** fire attack (water applied into the bedroom fires through an exterior window prior to advancing through the front door to extinguish the fire). These tactics were alternated so that each tactic was used during the first two scenarios and again for the last two scenarios. Once firefighters completed their primary assignments, they were released to the "PPE bay" approximately 40 m from the structure to doff their gear. After doffing their gear, the firefighters promptly entered the adjacent "biological collection bay" for skin wipe sampling. Investigators began sampling from the turnout gear after they had been removed. After sampling, the turnout gear was stored on hangers in the PPE bay until subsequent decontamination and/or use. Large fans were used to dry turnout gear that had undergone wet-soap decon.

Experimental procedure

Table 2 provides a summary of our sample collection and analysis methods. The main purpose of the sampling was to assess the contamination levels on firefighter PPE and skin after a structural firefighting response. Sampling was conducted pre-fire, post-fire, and post field decontamination of PPE and post skin cleaning. The following sections provide an abbreviated version of the methods. More details are provided in the supplemental file.

Wipe sampling of firefighter skin

After cleaning his/her skin using commercial cleansing wipes (Essendant baby wipes NICA630FW), one firefighter from each scenario was randomly selected for pre-fire sampling of his/her neck (*right side*) and hands. After firefighting, wipe samples were collected from all firefighters' hands and the *right side* of their necks. Investigators then used two cleansing wipes to clean the necks of firefighters assigned to Inside Attack, Inside Search, Outside Vent, or Overhaul (3–4 per scenario). A subsequent wipe sample was then collected from the *left side* of their necks. This was done to provide a comparison of neck exposures to PAHs before and after cleaning. A fresh pair of gloves were worn for each skin cleaning and sample collection procedure.

Dermal wipe sampling involved the use of cloth wipes (TX1009, Texwipe) and corn oil as a wetting agent, which is similar to the sample technique used by Väänänen et al.[38] Experiments were conducted prior to this study to determine the collection efficiency of using corn oil as a wetting agent. These experiments found >75% recovery of the majority of PAHs from glass slides at various spiking levels (i.e., 5, 50, and 200 micrograms [µg]) (unpublished data). Lesser collection efficiency can be expected from skin due to its absorptive nature. Thus, the actual

Table 2. Summary of sampling methods.

Sampling performed	Collection periods	Sample time (min)	n	Analytes	Method
Wipe sampling of exterior surface of turnout jackets	Pre-fire Post-fire Post-decon	NA NA NA	36 63 Dry-brush: 12 Air-based: 12 Wet-soap: 12	PAHs	Individually packaged wipes containing 0.45% isopropanol and benzalkonium chloride analyzed by HPLC/UV/FL (NIOSH Method 5506)[46]
Wipe sampling of hand and neck skin	Pre-fire Post-fire Post-skin cleaning	NA NA NA	Hands: 12 Neck: 12 Hands: 142 Neck: 142 Neck: 46	PAHs	Cloth wipes with corn oil analyzed by HPLC/UV/FL (NIOSH Method 5506)[46]
Offgas sampling of turnout jackets and trousers	Pre-fire Post-fire Post-decon	15 15 15	12 12 12	VOCs and HCN	Thermal desorption tube, 150 cc/min, analyzed by GC/MS and soda lime sorbent tube, 200 cc/min, analyzed by UV/VIS

VOCs = volatile organic compounds (i.e., benzene, toluene, ethylbenzene, xylenes, and styrene); GC/MS = gas chromatography/mass spectrometry; HCN = hydrogen cyanide; HPLC/UV/FL = high performance liquid chromatography with ultraviolet and fluorescence detection; UV/VIS = ultraviolet-visible spectroscopy.

dermal dose was likely higher than the reported measurements in this article.

Dermal exposure levels of PAHs were standardized by the surface area of the skin collection site. The surface area of both hands (0.11 m^2) was based on mean dermal exposure factor data for adult males.[39] The surface area of half of the neck (0.021 m^2) was determined based on data from Lund and Browder[40] showing the neck accounts for 2% of the total body surface area, which is 2.1 m^2 for adult males 30–39 years of age.[39]

Wipe sampling of firefighter PPE

Wipe samples from turnout jackets were collected before firefighting (n = 36, upper sleeve), after firefighting (n = 36, middle sleeve) and after each of three types of field decontamination methods (n = 36, lower sleeve), with a primary focus on gear worn by Inside Attack, Inside Search, and Overhaul/Backup firefighters. This sampling regimen assumed that PAH contamination was distributed equivalently across the sleeve. Wipe samples were also collected from turnout gear that had not been decontaminated after use by firefighters assigned to each of the six jobs after two scenarios (n = 18). Gear that had not been decontaminated after use in four scenarios and last assigned to Inside Attack, Inside Search, and Overhaul/Backup firefighters were also sampled (n = 9). In addition, wipe samples were collected from 4 helmets (new at the beginning of the study) after use in four scenarios by firefighters assigned to Inside Attack, Inside Search, Outside Vent and Outside Command/Pump. Helmets were assigned to the position rather than the individual firefighter and were not decontaminated. The wipe samples were collected inside 100 cm^2 templates affixed to the PPE. The wipes (Allegro® 1001) were designed to remove contaminants from PPE; however, the collection efficiency for PAHs is unknown.

Decontamination

Field decontamination was carried out after firefighters had doffed their gear and post-fire off-gas and surface sampling had taken place. For dry-brush decon, the investigator used an industrial scrub brush to scrape debris and contaminants from the gear. For air-based decon, an air jet provided by a modified electric leaf blower was directed over the entire surface of the turnout jackets and pants to remove contaminants. For wet-soap decon, the investigator prepared a 2 gallon (7.6 liter) pump sprayer filled with a mixture of water and ~10 mL of Dawn® (Procter and Gamble) dish soap. The investigator pre-rinsed the gear with water, sprayed the gear with the soap mixture, scrubbed the gear with soap mixture using an industrial scrub brush, and then rinsed the gear with water until no more suds remained.

Off-gas sampling of firefighter turnout gear

Off-gas sampling preceded the wipe sampling of the turnout gear. Turnout jackets and trousers for each crew were split evenly by job assignment into two groups: decontaminated and non-decontaminated gear. Before and after each scenario, each group (consisting of 6 sets of gear) was hung on 1.8 m high bars inside one of two 7.1 cubic meter enclosures for testing the off-gassing of substances contaminating the gear. The enclosures were intended to represent the volume of a typical 6-seat apparatus cabin. The enclosures were lined in Tyvek (DuPont), located inside an open bay, sheltered from the sun, and kept at ambient temperature during the study, which ranged from 18–22°C.

Sampling for VOCs and HCN took place over 15 min, which was intended to be representative of the driving time for crews returning from the incident to the fire station. Afterward, half the gear was decontaminated in the field using dry brush, air-based, or wet-soap methods

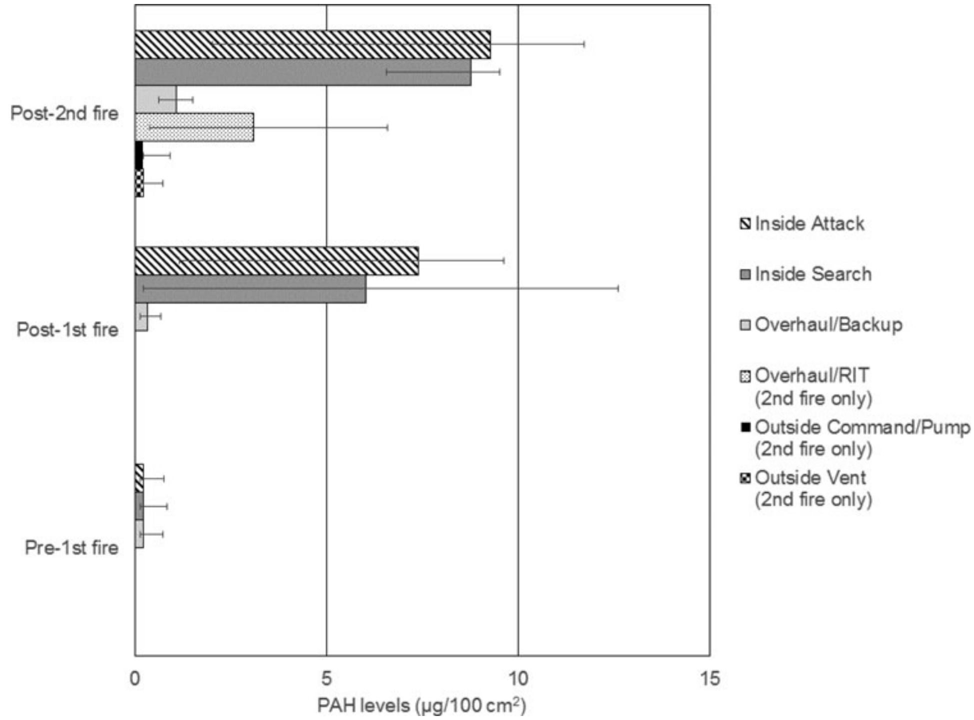

Figure 1. Median PAH levels on turnout jacket by job assignment and use in fires without field decontamination being performed ($n = 3$ for each observation, error bars represent minimum and maximum values).

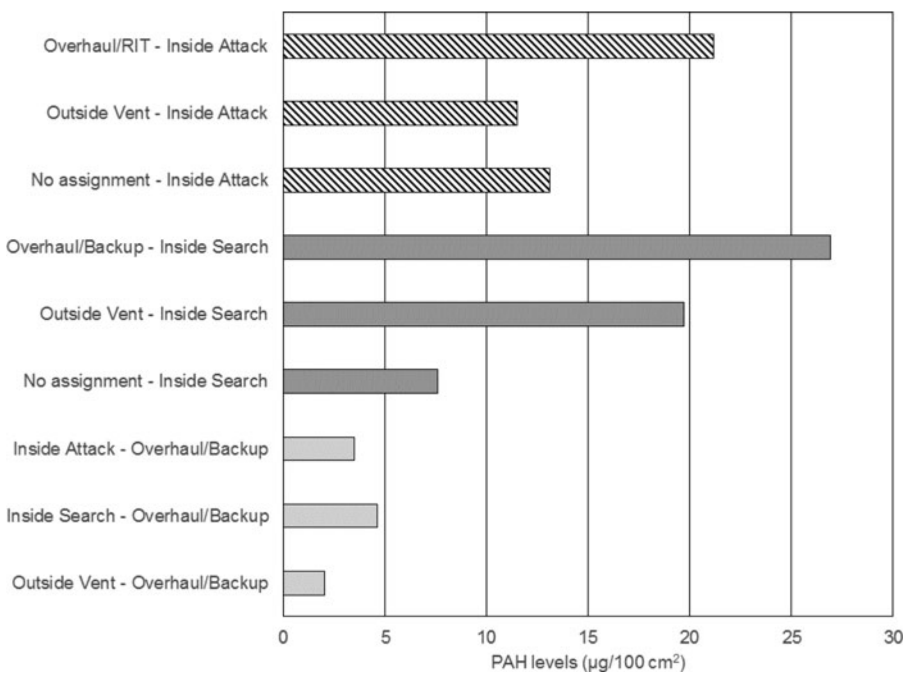

Figure 2. PAH levels on turnout jacket after use in four fires by job-assignment pairing (first assignment – last assignment).

(four scenarios each). Following field decontamination, all gear (decontaminated and non-decontaminated) were returned to their separate enclosures and tested again for off-gassing compounds.

Data analysis

Most of the descriptive comparisons for PPE surface and skin contamination were carried out using total PAHs, which was the sum of the 15 quantified PAHs. Zero was used for non-detectable concentrations in this summation. For PPE surface measurements, if all PAHs were non-detectable, the resultant zero value was imputed using the limit of detection for fluoranthene (0.2–0.3 µg/wipe) divided by the square root of 2.[41] On average, fluoranthene was the most abundant substance detected in the surface wipe samples. In presenting the levels of individual PAHs measured from turnout jackets and skin, non-detectable PAHs were assigned values by dividing the limits of detection by the square root of 2. The same imputation method was used for non-detectable VOCs off-gassing from turnout gear.

To quantify the effectiveness of the different types of decontamination methods, we calculated the percent change in PAH levels by decon type, restricting the analysis to gear that had detectable levels of PAHs post-fire. It was assumed that decontamination can only be assessed if the gear is truly contaminated. A Kruskal-Wallis test was used to test whether PAH levels remaining on turnout gear after decontamination were equivalent across the three decon-types. To quantify the effectiveness of skin cleaning using cleansing wipes, we calculated the percent change in PAH levels measured on the right neck (post-fire) vs. the left neck (post-cleaning), restricting the analysis to subjects with detectable levels of PAHs post-fire. In doing so, we assumed that (1) the PAH levels were evenly distributed across the entire neck and (2) that skin cleaning cannot be evaluated if the neck is not contaminated. A Wilcoxon signed-rank test was used to determine whether the change in PAH levels after decontamination procedures was significantly different from zero. This test was also used to assess whether PAH levels on hands were increasing on subsequent study days or differed between jobs, and whether PAH levels on turnout gear or skin differed by type of tactic. SAS 9.4 was used for carrying out the statistical analyses.

Results

Figure 1 provides a summary of the PAH contamination levels measured from non-decontaminated turnout jackets over the first two fires by job assignment. Measurements collected before the first fire (from new gear) are also provided for reference. As expected, the median PAH levels increased with successive use in fires. Samples from gear worn by firefighters assigned to Outside Command/Pump, Outside Vent, and Overhaul/RIT were only collected after the gear had been used in two fires.

Firefighters were assigned new jobs after the second fire. Figure 2 provides the PAH contamination levels measured from non-decontaminated turnout jackets after use in four fires by job-assignment pairings (first assignment – last assignment). Generally, higher contamination was found when the last job assignment was Inside Attack or Inside Search. For comparison, the PAH levels measured from helmets worn by firefighters assigned to Outside Command/Pump, Outside Vent, Inside Search, and Inside Attack (after use in 4 fires) were <0.2, 3.1, 54, and 78 micrograms per 100 square centimeters ($\mu g/100\ cm^2$) of sampled surface. Helmet contamination appeared to follow a similar trend as the turnout jackets, whereby helmets worn by inside crews (Attack and Search) were much more contaminated than helmets worn by outside crews (Vent and Command/Pump).

We explored the contamination of turnout gear by type of tactic (interior attack vs. transitional attack). To account for the efficacy of the different decontamination methods and the effect of job assignment on contamination levels, our analysis was based on the percent change in the pre- to post-fire PAH levels on turnout gear worn by firefighters assigned to Inside Attack and Inside Search. According to this analysis, transitional attack resulted in similar changes in PAH contamination (median = 662%, range −35% to 6710%, n = 12) as interior attack (median = 1080%, range 136% to 8440%, n = 12) (Wilcoxon P = 0.48). This variability illustrates that the firefighters' movement and orientation during firefighting likely plays an important role in PPE contamination, possibly obscuring the effect of tactic.

Figure 3 provides a summary of the percent change in PAH levels from post-fire to post-decon by decon-type. The three decon-types differed significantly in their effectiveness (Kruskal-Wallis $P < 0.001$). Wet-soap decon was most effective in reducing PAH contamination, with a median reduction of 85%, compared to a reduction of 23% for dry brush decon and an increase of 0.5% for air-based decon. The latter finding is probably an artifact as it is unlikely that the contamination actually increased after air-based decon. In fact, if we restrict the analysis to turnout jackets worn by firefighters assigned to Inside Attack and Inside Search (and exclude the less

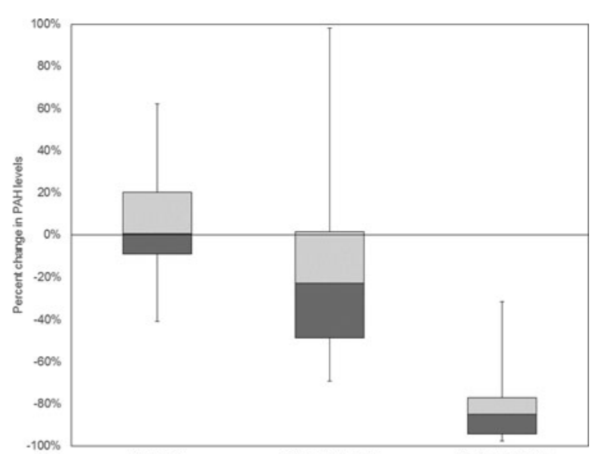

Figure 3. Box and whisker plots showing the percent difference in PAH levels measured on turnout jackets before and after decontamination. The minimum, 25th percentile, median, 75th percentile, and maximum values are provided. One sample each was excluded from air and wet-soap decon because post-fire levels were non-detectable.

contaminated Overhaul/Backup jackets), we find that the air-based decon provides a median change of −1.9% (interquartile range 12 to −30%).

Another way of testing the effectiveness of field decontamination is to compare decontaminated gear to non-decontaminated gear after both have been used in four fires. This comparison was conducted for each decon type by the firefighters' last job assignments (Inside Attack, Inside Search, and Overhaul/Backup). For example, decontaminated gear last assigned to Inside Attack was compared to non-decontaminated gear last assigned to Inside Attack. The job-assignment pairings were similar between the decontaminated and non-decontaminated groups (by design) and were unlikely to have biased the results. According to this analysis, gear that had undergone air-based, dry-brush, and wet-soap decon had 12–43%, 62–91%, and 90–95% lower contamination levels, respectively, than non-decontaminated gear (n = 3 pairs of comparisons for each decon type).

Figure 4 provides a summary of the VOCs and HCN concentrations measured off-gassing from decontaminated and non-decontaminated turnout gear. Horizontal lines are provided in the figure to denote the limits of detection. Median pre-fire levels were below the limits of detection for each analyte (and hence represent imputed values). As expected, the off-gas concentrations of these substances increased from pre-fire to post-fire and then decreased after that. The post-fire levels were well below applicable short-term exposure limits or ceiling limits; for example, the NIOSH recommended short-term exposure limit for benzene is 3,200 micrograms per cubic meter ($\mu g/m^3$), which is the lowest short-term exposure limit of all sampled compounds.[42] Post-decon levels from the decontaminated gear did not differ from the levels measured simultaneously from the non-decontaminated gear (Wilcoxon $P > 0.24$). This appeared to remain true when stratified by the different types of decontamination, although we had inadequate power to make statistical interpretations. Many of the compounds remained above the limits of detection during the post-decon testing period. For both the decontaminated and non-decontaminated gear, this testing took place an average of 24 min (ranging 17–36 min) after the culmination of the post-fire measurements.

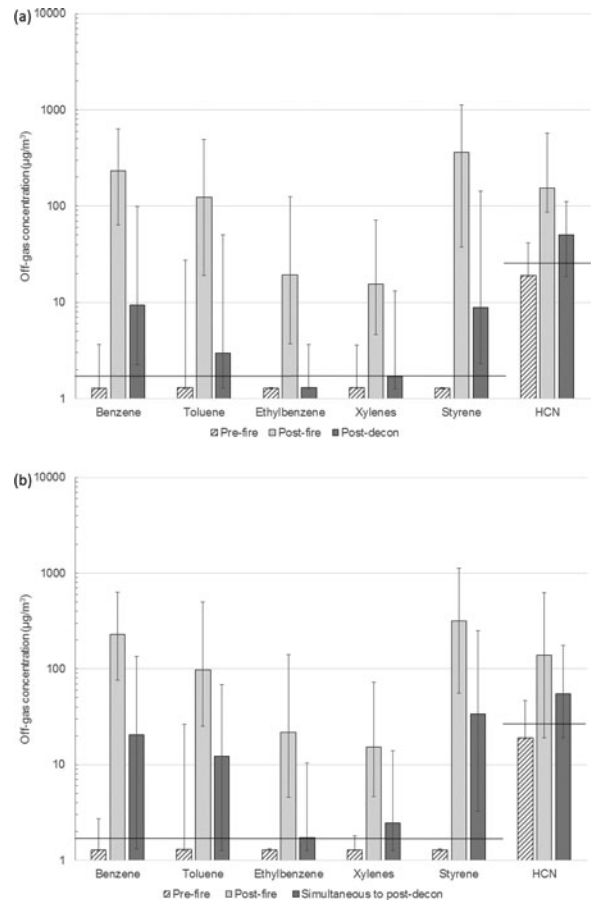

Figure 4. Median air concentrations of VOCs and HCN measured off-gassing from six sets of (a) *decontaminated* turnout gear during pre-fire, post-fire, and post-decon periods (n = 12 for each observation, except for the post-fire VOC observations in which n = 10 due to sample loss) and (b) *non-decontaminated* turnout gear during pre-fire, post-fire, and simultaneous to the post-decon periods (n = 12 for each observation). Horizontal lines represent the limits of detection for each analyte. Error bars represent the minimum and maximum values.

Table 3 summarizes the PAH dermal exposure levels measured on the firefighters' hands and neck in micrograms per square meter ($\mu g/m^2$) of sampled skin. A large percentage of the measurements were non-detectable, particularly on the neck. Note that neck samples had a higher limit of detection than hand samples due to the smaller surface area of the neck being sampled. For all job assignments other than Outside Command/Pump, the median PAH levels increased on the hands from pre- to post-fire. The percentage of detectable levels on the neck increased after firefighting, but the median levels were below detection for all job assignments. After firefighting, PAHs were detected more frequently on hands (76%) than neck (41%). For firefighters assigned to Inside Attack and Inside Search, the median post-fire PAH levels on the hands were more than four times the levels on the neck. Inside Search firefighters had significantly higher post-fire hand exposures than Inside Attack firefighters (Wilcoxon $P = 0.0248$), even though both performed inside operations during active fire. The 75th percentile post-fire levels of PAHs on the neck and hands were higher for firefighters assigned to Inside Attack and Inside Search than other positions. Outside Vent was the only job where detectable levels from the neck were

Table 3. PAH levels measured on skin before and after firefighting.

Job assignment	Skin site	Period	n	No. of NDs	Median (μg/m^2)[a]	Interquartile range (μg/m^2)[a]
All	Hands	Pre-fire	12	9	< 4.5	< 4.5
		Post-fire	142	34	16.3	5.2–125
	Neck	Pre-fire	12	8	< 24	< 24–31.2
		Post-fire	142	84	< 24	< 24–38.1
Inside Attack	Hands	Post-fire	24	1	135	67–190
	Neck	Post-fire	24	12	< 32[b]	< 24–152
Inside Search	Hands	Post-fire	24	0	226	144–313
	Neck	Post-fire	24	12	< 27[b]	< 24–71.7
Overhaul/Backup	Hands	Post-fire	24	8	6.5	< 4.5–16.3
	Neck	Post-fire	24	17	< 24	< 24–31.4
Overhaul/RIT	Hands	Post-fire	24	4	8.4	6.1–30.8
	Neck	Post-fire	24	15	< 24	< 24–34.5
Outside Vent	Hands	Post-fire	24	4	10.5	6.2–23.4
	Neck	Post-fire	24	10	30.5	< 24–39.3
Outside Command/Pump	Hands	Post-fire	22	17	< 4.5	< 4.5
	Neck	Post-fire	22	18	< 24	< 24

[a]Values of < 4.5 and < 24 μg/m^2 were based on the lowest limit of detection for the measured PAHs (0.5 μg) divided by the surface area of the sampled skin site (0.11 m^2 for hands and 0.021 m^2 for neck).
[b]The median was somewhere between a non-detectable and a detectable measurement; therefore, a value of less than the detectable measurement is provided.

found in more than half the subjects (58%). For firefighters assigned to Outside Vent, the median post-fire PAH levels on the neck were three times the levels on the hands.

To test whether the accumulation of contaminants on PPE was contributing to skin contamination (i.e., cross-transfer to hands), we explored the levels of PAHs on the hands of firefighters over time. The analysis was restricted to firefighters who wore gear that was not being decontaminated ($n = 18$ firefighters). We compared post-fire PAH levels on hands measured in scenario 2 to scenario 1 and those measured in scenario 4 to scenario 3. The analysis was split this way because firefighters changed job assignments after the second scenario. According to this analysis, we found no evidence that PAH levels on hands were increasing with subsequent study day (Wilcoxon $P > 0.85$) despite an increase in contamination on PPE (see Figures 1 and 2).

To test whether the tactic employed had any effect on dermal exposure, we investigated the post-fire neck and hand contamination levels for firefighters assigned to Inside Attack and Inside Search by type of tactic (Table 4). According to this analysis, hand and neck exposures did not differ significantly (Wilcoxon $P = 0.37$ and 0.28, respectively) between interior and transitional attack.

For firefighters who used cleansing wipes to clean their neck skin post-firefighting, we found a 54% median reduction in PAH levels on the neck (Interquartile range = −18% to −100%), which was statistically significant (Wilcoxon $P = 0.0043$). Again, this analysis compared levels measured from the right neck (post-fire) to the left neck (post-cleaning) and was restricted only to the 22 firefighters who had detectable post-fire PAH levels on their right neck.

The composition of PAHs measured on turnout gear and skin may be of interest as certain types of PAHs are more hazardous than others. Figure 5 provides a summary of the individual PAHs measured from turnout gear and hands of firefighters assigned to Inside Search (a higher exposure group). Overall, fluoranthene was the most abundant species identified on turnout gear and skin (constituting >25% of the total PAHs). The IARC classifications are also given in this figure. Benzo[a]pyrene is the only species that is a known human carcinogen (1) and it accounted for 5% of the PAHs measured on hands and 8% of the PAHs measured on turnout gear. Several PAHs classified as probably (2A) or possibly (2B) carcinogenic were also detected and accounted for 26% of the total levels on skin and 37% of the total levels on turnout gear. Similar PAH composition was found on jackets and hands of firefighters assigned to Inside Attack.

Discussion

This is the first study to investigate both the contamination of firefighters' PPE and skin as well as the effectiveness of field decontamination of PPE and skin.

Table 4. Post-fire PAH levels measured on the skin of firefighters assigned to interior attack and search by tactic.

Skin site	Type of tactic	n	No. of NDs	Median (μg/m^2)	Interquartile range (μg/m^2)
Hands	Interior	24	0	180	129–276
	Transitional	24	1	144	114–257
Neck	Interior	24	11	36.2	< 24–113
	Transitional	24	13	< 24	< 24–49

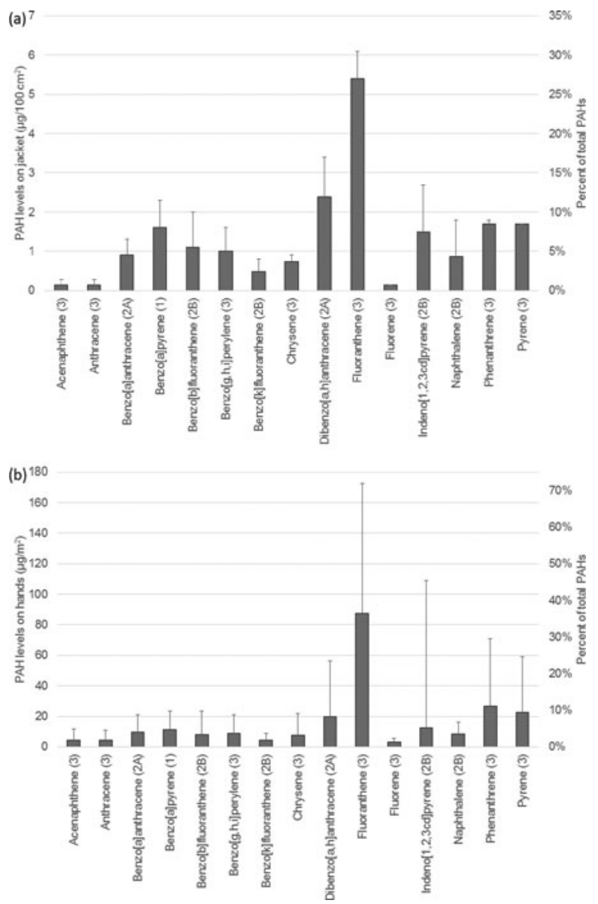

Figure 5. Median levels of specific PAHs measured on (a) *jackets* of firefighters assigned to Inside Search after use in four fires without any field decontamination (n = 3 jackets) and (b) *hands* of firefighters assigned to Inside Search after firefighting (n = 24). Also provided are the median percentage of total PAHs and IARC classification for each PAH species. Class 1 = carcinogenic to humans; 2A = probably carcinogenic to humans, 2B = possibly carcinogenic to humans, and 3 = not classifiable. Error bars represent the maximum levels measured.

This study was limited somewhat by sample size and the sensitivity of the sampling and analytical methods. In addition, the collection efficiency of the wipe sampling methods is unknown for the surfaces sampled in this study. Based on laboratory testing of these wipes (or similar wipes) at collecting PAHs from a non-porous surface, it is likely that a large percentage of PAH contamination on skin and turnout jackets (25% or more) may not have been collected. As such, our sampling results should be considered an underestimation of the actual surface loading. Despite these limitations, we were able to identify important contaminants on firefighter PPE and skin and quantify the change in contamination levels following decontamination measures. The data provide important scientific evidence of exposure risk from firefighting by job assignment and will support departments in developing and refining policies to clean their gear and skin following live-fire responses.

We found that PAH contamination on PPE increased with each use in a fire. For firefighters assigned to Inside Attack, Inside Search, and Overhaul/Backup, the median levels on jackets were 7.4, 6.0, and 0.31 µg/100 cm^2 after use in a single fire and 9.3, 8.8, and 1.1 µg/100 cm^2 after use in two fires (without any decontamination), corresponding to a 1.3–3.5 fold increase. Post-fire PAH contamination on turnout jackets assigned to Inside Attack and Inside Search for the last two scenarios ranged up to 21 and 27 µg/100 cm^2, respectively. Increasing accumulation of PAHs with each fire response has been shown in other studies as well.[24,26]

In two separate studies involving live fire training using particle boards as fuel, Kirk and Logan[13,26] measured deposition of PAHs onto turnout gear of 6.9–29 µg/100 cm^2 and deposition flux of 3.3–16 nanograms per square centimeter per minute (ng/cm^2/min). The firefighting activities in these studies were most similar to those performed by Inside Attack and Inside Search in our project. Taking the median time inside the structure for Inside Attack and Inside Search of 8 min, this level of flux would result in 2.6–13 µg/100 cm^2 of PAH contamination after each fire. Because of differences in fuels, it would not be surprising if deposition flux in our study differed from Kirk and Logan,[26] but our data suggest similar levels of flux. It should be noted, however, that Kirk and Logan[13,26] used fabric swatches attached to the gear to sample PAH deposition. This would likely result in a higher collection efficiency than could be expected from our sampling methodology. Our methodology was intended to collect substances that could easily transfer to skin, while methods that extract bulk materials may also measure substances embedded in the fabric.

The PPE wipes used in our study, containing 0.45% isopropanol and benzalkonium chloride, have not been tested for their collection efficiency of PAHs. Because benzalkonium chloride is a surfactant, these wipes may be more effective at removing lipid soluble PAHs than PPE wipes containing 70% isopropanol, which, according to our unpublished data, may provide <40% collection efficiency from non-porous surfaces. Additional studies are underway to test the collection efficiency of different types of sampling wipes (wetting agents) in comparison to PAHs measured on a filter substrate affixed to turnout gear. Of note, we would expect higher wipe-sampling collection efficiency from the helmets (non-porous material), but at the same time, contamination on the helmets may be more likely to transfer to the skin during handling.

As expected, VOC and HCN levels measured off-gassing from turnout gear increased from pre-fire to post-fire. Median post-fire VOC concentrations were highest for styrene (340 μg/m^3) and benzene (230 μg/m^3). In our previous study, we measured a median of 25 μg/m^3 of benzene and 85 μg/m^3 of styrene off-gassing from a single set of gear (inside a 0.18 m^3 enclosure).[25,26] Kirk and Logan[26] reported similar off-gas concentrations of benzene and styrene from a single set of gear as our previous study. Kirk and Logan[26] also measured HCN concentrations ranging from 630–1300 μg/m^3, which were well above the post-fire levels we found in this current study (< 26–620 μg/m^3). The higher HCN concentrations may be due to the fuel package being composed primarily of engineered wood products in the Kirk and Logan[26] study.

Our current study further differs from these previous studies in that six sets of turnout gear were placed inside an enclosure representative in volume to an apparatus cabin. Hence, the VOC air concentrations we measured could be expected if six firefighters were to wear or store their turnout gear inside an enclosed apparatus cabin during a 15-min ride back to their station, provided they embarked on this trip soon after completing overhaul. While the levels we measured are well below applicable short-term exposure limits or ceiling limits, these findings indicate that firefighters could inhale a number of chemicals in the period following a fire response. Although not a major focus of this study, semi-volatile compounds would evaporate much more slowly and could pose a longer-term inhalation hazard for firefighters.

While effective at removing PAH contamination, field decontamination had no apparent effect on the VOC concentrations as decontaminated gear provided similar off-gas levels as the gear that had not been decontaminated. Our results suggest that a large proportion of the VOCs evaporated naturally from PPE that was not decontaminated (but allowed to air out on a hanger) over the time it took to decontaminate the other half of gear. Although we lacked the power to test the changes in off-gas concentrations by type of decontamination, the primary purpose of field decontamination is not to remove VOCs, but rather to remove soot and other particulate from the gear. Because soot can be composed of semi-volatile compounds or act as a sorbent for other organic substances, field decontamination could conceivably help reduce the levels of off-gassing semi-volatile compounds, and this should be investigated in future studies.

If PAH contamination was not distributed similarly across the sleeve, the decontamination findings could be biased upward or downward. However, the pre- and post-decon wipe samples were consistently collected from abutting (middle and lower) sleeve locations to minimize this bias. Of the three types of field decontamination methods investigated in this study, the wet-soap decon method was clearly the most effective at removing surface contamination, providing a median reduction in PAH levels of 85%. Soot is generally composed of lipid soluble compounds like PAHs. Surfactants, like those in dish soap, are designed to surround lipid molecules and liberate them from surfaces so that water can then take them away. Future studies should investigate how water-only decon compares with wet-soap decon. Although the dry-brush method was not as effective as the wet-soap decon method, a median PAH reduction of 23% is certainly better than doing nothing. This method would be relatively easy to implement at any department and would not take PPE out of service while drying. The air-based decon method has similar advantages to the dry-brush method, but it was not as effective in removing PAHs (∼2% reduction). We suspect that the air-velocity was able to remove "loose" particulate, but could not overcome the surface tension of much of the "sticky" soot coating the turnout gear. Airflow across the surface of the turnout gear could also facilitate the evaporation of more volatile contaminants (e.g., naphthalene), however, many of these components would evaporate naturally in a well-ventilated space. An air-based system could be effective in certain firefighting situations (e.g., when ash or dust are abundant) and this should be investigated further.

After use in four fires, gear that had undergone post-firefighting decontamination had markedly lower levels of PAHs than gear that had not undergone decontamination, with the largest effect found for wet-soap decon. This further demonstrates that field decontamination could be used routinely to manage PPE contamination. However, laundering through commercial extractors that adhere to NFPA requirements[43] would likely provide the greatest cleaning efficacy; quantifying the efficacy of extractors is currently a topic of ongoing research. How repeated laundering compares with wet-soap decon in terms of material degradation and the effects on the protective properties of the turnout gear also requires further study. Our findings indicate that PAH contamination varies by job assignment, and so departments should consider prioritizing gear for laundering based on a firefighter's assignment during the response.

For nearly all positions, 50% or more of the post-fire PAH measurements from the neck were non-detectable (i.e., <24 μg/m^2). The one exception was for firefighters assigned to Outside Vent who had 14 of 24 detectable PAH measurements from the neck after firefighting with a median level of 30.5 μg/m^2. When PAHs were detected on the neck, firefighters assigned to Inside Attack and Inside Search had higher values than other positions as evidenced by their respective 75th percentiles (152 and 71.7 μg/m^2 compared to <40 μg/m^2 for all other positions). In a previous study, we measured PAH levels on firefighters' necks ranging from <57–187 μg/m^2 and only 33% of the measurements were non-detectable.[30] In our previous study, firefighters observed the growth of a fire (involving furniture) inside a two-room structure while standing, crouching, crawling, or performing other activities to simulate firefighting tasks. These firefighters were positioned a little higher in the target rooms and had a longer smoke exposure (∼10 min) that was not as operationally relevant as the scenarios conducted here. We also collected samples across the entire neck in our previous study rather than only half the neck, which could explain the higher frequency of detectable levels.

Contaminants measured on neck skin in both studies are likely penetrating or permeating the protective Nomex® hoods worn by firefighters or infiltrating around the hood/coat or the hood/SCBA interface and therefore may be directly affected by the duration of time spent in smoke. Firefighters assigned to Inside Attack and Inside Search in our current study were operating from the crawling position, low in the smoke layer for much of the response, which would lessen their exposures. Fires were also quickly suppressed (within a few minutes after entry). Firefighters assigned to other job assignments did not enter the structure at all or entered after the fire had been suppressed. Any firefighters not wearing hoods on the fireground may have been at risk for neck exposures. In reviewing video footage, we found that several of the Outside Vent firefighters did not wear their hoods while conducting exterior operations, which could explain the higher frequency of detectable PAHs on their necks. This illustrates the importance of wearing the Nomex hood when performing exterior operations (i.e., Outside Vent). The research and development of hoods that offer additional chemical protection may be warranted especially for use in interior operations (i.e., Attack and Search).

Nearly all (47 of 48) post-fire PAH measurements taken from the hands of firefighters assigned to Inside Attack and Inside Search were detectable, with interquartile ranges of 67–190 μg/m^2 for Inside Attack and 144–313 μg/m^2 for Inside Search. The respective median post-fire levels of PAHs on hand skin (135 and 226 μg/m^2) were higher than on neck skin (<32 and <27 μg/m^2). This contradicts our earlier study that found higher levels on the neck (median 52 and 63 μg/m^2) than the hands (median 16 and 24 μg/m^2).[30] For firefighters assigned to the other jobs, the median post-fire hand exposures (<4.5–10.5 μg/m^2) were similar to our earlier study. Our current findings corroborate the findings by Fernando et al. 2016[33] which found an increase in PAH and methoxyphenol contamination on firefighter skin after conducting training fires, with higher loading on the fingers than the other skin sites (back, forehead, wrist, and neck).

Hands may become contaminated during the doffing of gear. However, our analysis did not show an increasing trend in PAH levels on hands with each subsequent study day in firefighters who wore non-decontaminated gear even though the contamination levels on the jackets increased (see Figures 1 and 2). The gloves had a moisture barrier between the inner and outer materials, and as such, we do not believe the PAHs permeated the gloves. Penetration of contaminants around the gloves (likely facilitated by sweat or water on the fireground) is another possible mechanism. Inside Search firefighters in our study likely spent more time crawling than any other job assignment and as such, their gloves would have contacted contaminants and water that collected on the floor. This could explain why they had significantly higher post-fire hand exposures than the Inside Attack firefighters, even though both performed inside operations during active fire.

While this paper does not report biomarker levels of PAHs, PAHs were measured on skin and have been shown to readily absorb through skin.[44,45] Thus, it is likely that firefighters in this study, especially the interior crews, had biological uptake of PAHs. Biological absorption will be thoroughly evaluated in future manuscripts.

When executed successfully, transitional attack will knock down or substantially retard the fire from the exterior of the structure (through a window or other opening). When firefighters then enter the structure to perform final suppression and search and rescue operations, their smoke exposures should theoretically be less than if interior attack were performed. However, we did not find statistically significant differences in PPE or skin exposures by tactic for firefighters assigned to Inside Attack and Inside Search; although, median exposures were generally lower for transitional attack. Several factors can influence the magnitude of exposures during transitional attack, including exposure to smoke while outside the structure and regrowth of the fire while inside the structure. These factors may have contributed to the overall variability in PPE and skin contamination during transitional attack, thereby reducing our power to detect statistical differences. Further investigation into how tactics affect personal exposures is warranted.

One possible way of mitigating dermal contamination is by using cleansing wipes after firefighting. The median reduction in PAH levels on neck skin after using commercial cleansing wipes (i.e., baby wipes) was 54%. It is important to note that this analysis assumed equal distribution of PAHs across the neck skin. If the left side of the neck was biased to have higher exposures than the right side, our stated efficacy would be underestimated. If the opposite were to have occurred, then our stated efficacy would be overestimated. Also, by excluding firefighters who had non-detectable levels on their neck post fire, we may have introduced some bias toward higher efficacy. Despite the inherent limitations of this field experiment, we provide the first ever evidence that cleansing wipes can be effective at reducing PAH contamination from skin. Not all cleansing wipes may have equal efficacy and further investigation is warranted. The data show that some level of contamination is likely to remain on the skin after using these wipes. As such, showering, hand washing or other means of more thorough cleaning of the skin should be conducted as soon as feasible following any exposure on the fireground.

Conclusions

Personal protective equipment, neck skin, and hand skin became contaminated with PAHs during firefighting. The magnitude of contamination varied by job assignment. Firefighters assigned to Inside Attack and Inside Search generally had the most contamination on their turnout gear and skin following each response, and their hand skin was more contaminated than their neck skin. Inside Search firefighters had significantly more PAH exposure to their hands than the Inside Attack firefighters, possibly because Inside Search firefighters spent much of their time crawling on contaminated floors. Outside Vent crews had the highest frequency of detectable PAHs on their necks and this contamination was higher than the levels measured on their hands. This finding was likely due to the inconsistent use of hoods by the Outside Vent crews.

Contamination on turnout gear increased with each fire response if not decontaminated. Three types of field decontamination methods were evaluated and wet-soap decon was found to be the most effective at removing PAH contamination from turnout gear. Commercial cleansing wipes also showed some benefit at removing PAH contamination from neck skin. While turnout gear became contaminated with VOCs, off-gas levels were low (below short-term exposure limits) and a large proportion evaporated within 24 min. Overall, this study provides a greater understanding of the exposure pathways associated with firefighting and the measures that can be implemented to reduce these exposures.

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References

[1] **International Agency for Research on Cancer:** Painting, firefighting, and shiftwork. In *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Vol 98*. Lyon, France: World Health Organization, 2010.

[2] **Daniels, R.D., T.L. Kubale, J.H. Yiin, et al.**: Mortality and cancer incidence in a pooled cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950–2009). *Occup. Environ. Med. 71*(6):388–397 (2014).

[3] **Daniels, R.D., S. Bertke, M.M. Dahm, et al.**: Exposure-response relationships for select cancer and non-cancer health outcomes in a cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950–2009). *Occup. Environ. Med. 72*(10) (2015).

[4] **Tsai, R.J., S.E. Luckhaupt, P. Schumacher, R.D. Cress, D.M. Deapen, and G.M. Calvert**: Risk of cancer among firefighters in California, 1988–2007. *Am. J. Ind. Med. 58*(7):715–729 (2015).

[5] **Pukkala, E., J.I. Martinsen, E. Lynge, et al.**: Occupation and cancer – follow-up of 15 million people in five Nordic countries. *Acta Oncol. 48*(5):646–790 (2009).

[6] **Glass, D., M. Sim, S. Pircher, A. Del Monaco, C. Dimitriadis, J. Miosge**: *Final Report Australian Firefighters' Health Study*. Monash Centre for Occupational and Environmental Health. Available at http://www.coeh.monash.org/downloads/finalreport2014.pdf (accessed April 21, 2017).

[7] **Fabian, T., J. Borgerson, P. Gandhi, et al.**: Characterization of firefighter smoke exposure. *Fire Technol. 50*(4):993–1019 (2014).

[8] **Brandt-Rauf, P.W., L.F. Fallon, Jr., T. Tarantini, C. Idema, and L. Andrews**: Health hazards of fire fighters: exposure assessment. *Br, J, Ind, Med. 45*(9):606–612 (1988).

[9] **Kerber, S.**: Analysis of changing residential fire dynamics and its implications on firefighter operational timeframes. *Fire Technol. 48*(4):865–891 (2012).
[10] **Austin, C.C., D. Wang, D.J. Ecobichon, and G. Dussault**: Characterization of volatile organic compounds in smoke at municipal structural fires. *J. Toxicol. Environ. Health A 63*(6):437–458 (2001).
[11] **Bolstad-Johnson, D.M., J.L. Burgess, C.D. Crutchfield, S. Storment, R. Gerkin, and J.R. Wilson**: Characterization of firefighter exposures during fire overhaul. *AIHA J. 61*(5):636–641 (2000).
[12] **Edelman, P., J. Osterloh, J. Pirkle, et al.**: Biomonitoring of chemical exposure among New York City firefighters responding to the World Trade Center fire and collapse. *Environ. Health Perspect. 111*(16):1906–1911 (2003).
[13] **Kirk, K.M., and M.B. Logan**: Firefighting instructors' exposures to polycyclic aromatic hydrocarbons during live fire training scenarios. *J. Occup. Environ. Hyg. 12*(4):227–234 (2015).
[14] **Evans, D.E., and K.W. Fent**: Ultrafine and respirable particle exposure during vehicle fire suppression. *Environ. Sci. Process. Impacts 17*:1749–1759 (2015).
[15] **National Institute for Occupational Safety and Health**: *Evaluation of Chemical and Particle Exposures during Vehicle Fire Suppression Training*, by Fent, K.W., D.E. Evans J. Couch (Report #HETA 2008-0241-3113). U.S. Department of Health and Human Services, 2010.
[16] **National Institute for Occupational Safety and Health**: *Evaluation of Dermal Exposure to Polycyclic Aromatic Hydrocarbons in Fire Fighters*, by Fent, K.W., J. Eisenberg, D.C. Evans, et al. (Report #2010-0156-3196). U.S. Department of Health and Human Services, 2013.
[17] **Fent, K.W., and D.E. Evans**: Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. *J. Environ. Monit. 13*(3):536–543 (2011).
[18] **Horn, G.P., S. Kerber, K.W. Fent, B. Fernhall, and D. Smith**: *Cardiovascular & Chemical Exposure Risks in Modern Firefighting: Interim Report, 2016*. Illinois Fire Service Institute. Available at https://www.fsi.illinois.edu/documents/research/CardioChemRisksModernFF_InterimReport2016.pdf (accessed April 21, 2017).
[19] **Alexander, B.M., and C.S. Baxter**: Plasticizer contamination of firefighter personal protective clothing – a potential factor in increased health risks in firefighters. *J. Occup. Environ. Hyg. 11*(5):D43–D8 (2014).
[20] **Alexander, B.M., and C.S. Baxter**: Flame retardant contamination of firefighter personal protective clothing – a potential health risk for firefighters. *J. Occup. Environ. Hyg.* 1–26 (2016).
[21] **Stull, J.O., C.R. Dodgen, M.B. Connor, and R.T. McCarthy**: Evaluating the effectiveness of different laundering approaches for decontaminating structural fire fighting protective clothing. In *Performance of Protective Clothing: Fifth Volume*, J.S. Johnson and S.Z. Mansdorf, (eds.). American Society for Testing and Materials, 1996.
[22] **Baxter, C.S., J.D. Hoffman, M.J. Knipp, T. Reponen, and E.N. Haynes**: Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. *J. Occup. Environ. Hyg. 11*(7):D85–D91 (2014).
[23] **Baxter, C.S., C.S. Ross, T. Fabian, et al.**: Ultrafine particle exposure during fire suppression – is it an important contributory factor for coronary heart disease in firefighters? *J. Occup. Environ. Med. 52*(8):791–796 (2010).
[24] **Easter, E., D. Lander, and T. Huston**: Risk assessment of soils identified on firefighter turnout gear. *J Occup. Environ. Hyg. 13*(9):647–657 (2016).
[25] **Fent, K.W., D.E. Evans, D. Booher, et al.**: Volatile organic compounds off-gassing from firefighters' personal protective equipment ensembles after use. *J. Occup. Environ. Hyg. 12*(6):404–414 (2015).
[26] **Kirk, K.M., and M.B. Logan**: Structural fire fighting ensembles: accumulation and off-gassing of combustion products. *J. Occup. Environ. Hyg. 12*(6):376–383 (2015).
[27] **Brown, F.R., T.P. Whitehead, J.S. Park, C. Metayer, and M. X. Petreas**: Levels of non-polybrominated diphenyl ether brominated flame retardants in residential house dust samples and fire station dust samples in California. *Environ. Res. 135*:9–14 (2014).
[28] **Park, J.S., R.W. Voss, S. McNeel, et al.**: High exposure of California firefighters to polybrominated diphenyl ethers. *Environ. Sci. Technol. 49*(5):2948–2958 (2015).
[29] **Shen, B., T.P. Whitehead, S. McNeel, et al.**: High levels of polybrominated diphenyl ethers in vacuum cleaner dust from California fire stations. *Environ. Sci. Technol. 49*(8):4988–4994 (2015).
[30] **Fent, K.W., J. Eisenberg, J. Snawder, et al.**: Systemic exposure to PAHs and benzene in firefighters suppressing controlled structure fires. *Ann. Occup. Hyg. 58*(7):830–845 (2014).
[31] **Laitinen, J., M. Makela, J. Mikkola, and I. Huttu**: Fire fighting trainers' exposure to carcinogenic agents in smoke diving simulators. *Toxicol. Lett. 192*(1):61–65 (2010).
[32] **Laitinen, J., M. Makela, J. Mikkola, and I. Huttu**: Firefighters' multiple exposure assessments in practice. *Toxicol. Lett. 213*(1):129–133 (2012).
[33] **Fernando, S., L. Shaw, D. Shaw, et al.**: Evaluation of firefighter exposure to wood smoke during training exercises at burn houses. *Environ. Sci. Technol. 50*(3):1536–1543 (2016).
[34] **Fire Fighter Cancer Support Network**: "Taking Action against Cancer in the Fire Service." Available at http://firefightercancersupport.org/wp-content/uploads/2013/08/Taking-Action-against-Cancer-in-the-Fire-Service.pdf (accessed April 21, 2017).
[35] **International Firefighter Cancer Foundation**: "Firefighter Decontamination Shower." Available at http://iwww.ffcancer.org/ndex.cfm (accessed April 21, 2017).
[36] **InterAgency Board**: "Evaluation of hazards in the post-fire environment." Available at https://iab.gov/Uploads/evaluation_of_hazards_in_the_post-fire_environment.pdf (accessed April 21, 2017).
[37] **Horn, G.P., R.M. Kesler, S. Kerber, et al.**: Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic. *Ergonomics*. 1–16 (2017).
[38] **Vaananen, V., M. Hameila, P. Kalliokoski, E. Nykyri, and P. Heikkila**: Dermal exposure to polycyclic aromatic hydrocarbons among road pavers. *Ann. Occup. Hyg. 49*(2):167–178 (2005).
[39] **U.S. Environmental Protection Agency**: *Exposure Factors Handbook: 2011 Ed.*, (Report #EPA/600/R-09/052F). National Center for Environmental Assessment, 2011.

[40] **Lund, C.C., and N.C. Browder**: The estimation of areas of burns. *Surg. Gynecol. Obstet. 79*:352–358 (1944).
[41] **Hornung, R.W., and L.D. Reed**: Estimation of average concentration in the presence of non-detectable values. *Appl. Occup. Environ. Hyg. 5*(1):46–51 (1990).
[42] **National Institute for Occupational Safety and Health**: "Pocket Guide to Chemical Hazards." Available at http://www.cdc.gov/niosh/npg/ (accessed April 21, 2017).
[43] **National Fire Protection Association (NFPA)**: *1851: Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting. [Standard]*. Quincy, MA: NFPA, 2014.
[44] **VanRooij, J.G., M.M. Bodelier-Bade, and F.J. Jongeneelen**: Estimation of individual dermal and respiratory uptake of polycyclic aromatic hydrocarbons in 12 coke oven workers. *Br. J. Ind. Med. 50*(7):623–632 (1993).
[45] **VanRooij, J.G., J.H. De Roos, M.M. Bodelier-Bade, and F.J. Jongeneelen**: Absorption of polycyclic aromatic hydrocarbons through human skin: differences between anatomical sites and individuals. *J. Toxicol. Environ. Health 38*(4):355–368 (1993).
[46] **National Institute for Occupational Safety and Health**: *Manual of Analytical Methods* 4th ed. Publication No. 94–113 (August 1994); 1st Supplement Publication 96–135, 2nd Supplement Publication 98–119, 3rd Supplement Publication 2003–154. P.C. Schlecht, P.F. O'Connor (eds). Cincinnati, OH: U.S. Department of Health and Human Services, 2013.