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Firefighting Instructors' Exposures to Polycyclic Aromatic Hydrocarbons During Live Fire Training Scenarios

Katherine M. Kirk and Michael B. Logan

Research and Scientific Branch, Queensland Fire and Emergency Services, Brisbane, Queensland, Australia

Cumulative exposures of firefighting instructors to toxic contaminants generated from live-fire training potentially far exceed firefighter exposures arising from operational fires. This study measured the atmospheric concentrations of polycyclic aromatic hydrocarbons (PAHs) outside and inside the structural firefighting ensembles worn by instructors during five live fire training evolutions. In addition, the contamination of ensembles by deposition of PAHs was characterized. Concentrations of polycyclic aromatic hydrocarbons outside the instructors' structural firefighting ensembles during the training evolutions ranged from 430 $\mu g/m^3$ to 2700 $\mu g/m^3$, and inside the structural firefighting ensembles from 32 $\mu g/m^3$ to 355 $\mu g/m^3$. Naphthalene, phenanthrene and acenaphthylene dominated the PAHs generated in the live fire evolutions, but benzo[a]pyrene was the greatest contributor to the toxicity of the PAH mixture both inside and outside the structural firefighting ensembles. Deposition of PAHs onto the structural firefighting ensembles was measured at between 69 and 290 ng/cm^2, with phenanthrene, fluoranthene, pyrene, and benzo[a]anthracene detected on all samples. These findings suggest that firefighting instructor exposures to PAHs during a single live-fire training evolution are comparable with exposures occurring in industrial settings over a full shift. Further research is required to investigate the importance of various potential routes of exposure to PAHs as a result of ingress and deposition of PAHs in/on structural firefighting ensembles.

Keywords dermal exposure, firefighters, live fire training, PAHs, polycyclic aromatic hydrocarbons, protective clothing

Address correspondence to: Katherine M. Kirk, QIMR Berghofer Medical Research Institute, Locked Bag 2000, Royal Brisbane Hospital, Queensland 4029, Australia; e-mail: katherine.kirk@qimrberghofer.edu.au

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INTRODUCTION

A variety of studies have sought to quantify the exposures of urban firefighters to toxic combustion products during their operational duties[1–9] or during experiments with known fuels and conditions.[10,11] Although the live-fire training environment (one in which an unconfined open flame or device can propagate fire to the building, structure, or other combustible material)[12] is designed to simulate the operational fire environment, it differs in several ways including fuel quantity, fuel arrangement, and compartment characteristics. Cumulative instructor exposures to air contaminants from live-fire training potentially far exceed those of firefighters arising from operational fires, depending on the frequency of exposure. The behaviour and physiological responses of firefighting instructors in the training environment also differ from the operational fire environment. Firstly, they adopt an instructional or supervisory role rather than a firefighter role, which may affect factors such as duration of exposure and placement within the smoke. Secondly, the non-emergency situation of the training environment may not elicit the same work rate and physiological response.[13,14] Despite this, training-related exposures to air contaminants [11,15–20] have received less attention than operational exposures.

Chemicals of particular significance with respect to firefighter exposure include polycyclic aromatic hydrocarbons (PAHs), a large and heterogeneous group of compounds formed by the incomplete combustion of organic materials. While benzo[a]pyrene has been classified as carcinogenic to humans by the International Agency for Research on Cancer (IARC),[21] there is evidence that a number of other polycyclic aromatic hydrocarbons are probably or possibly carcinogenic to humans. Occupational exposures to PAHs are known to occur via inhalation, and through dermal absorption as a result of either direct skin contamination or via clothing and undergarments.[22] The potential for firefighter exposures through these latter routes has been demonstrated in biomonitoring studies where the use of self-contained breathing apparatus limited inhalational exposure.[11,19]

This article presents the atmospheric concentrations of a range of PAHs generated during live-fire scenarios for training of firefighting personnel. Further, it measures the deposition of the PAHs on the exterior of the structural firefighting ensembles of instructors, as well as their ingress through protective clothing. The toxicity of the PAH mixture generated in this type of training scenario is assessed by applying a Toxic Equivalence Factor model for estimation of cancer potencies. This is valuable in conducting risk assessments for occupational exposure to PAHs for firefighting instructors, and selecting appropriate methods for exposure control.

METHODS

Live-Fire Training Scenarios

Training scenarios were conducted at the Queensland Combined Emergency Services Academy's Live Fire Campus in Brisbane, Australia. Instructor exposures were measured during structural firefighting evolutions in which instructors demonstrate to students the behaviour of fire in an enclosed space (Evolution 1), and monitor the progress and safety of students making entry to a structure to conduct firefighting and search and rescue tasks (Evolutions 2 to 5).

Evolutions were conducted in adapted shipping containers with brick flooring.[23] Typical fuel consisted of five sheets of particleboard (resin-bonded wood panel product consisting of 80 to 90% wood fibers, particles, or flakes by weight) placed at the closed end of the shipping container. Movement of instructors within the training cell was determined by the requirement to demonstrate extinguishment tactics and supervise students as they conducted search, rescue, and extinguishment activities, but involved remaining below the smoke layer as much as possible. Instructor exposure durations in these evolutions ranged from 20 to 44 min (average 31 min).

Personal Protective Clothing and Equipment

Each participant donned a structural firefighting ensemble (jacket and overtrousers) (Australian Defence Apparel, Coburg, Australia) constructed of an outer shell of Nomex IIIA, a moisture barrier consisting of a breathable polyurethane membrane, and thermal barrier of Sontara E89. Additional personal protective clothing included firefighting gloves, boots, and flashhood. Self-contained breathing apparatus was worn for the duration of the test, with an assigned protection factor of 10,000.[24] To minimize contamination, personnel showered and changed all clothing (including undergarments) between evolutions, and all components of the personal protective clothing were laundered according to manufacturer's instructions prior to each evolution.

Personal air Sampling

Firefighting instructors wore active air sampling equipment attached to the outside and inside of their structural firefighting ensemble during each evolution. PAHs were sampled at flow rates of 2000 mL/min, using AirChek 2000 pumps (SKC Inc., Eighty Four, PA) and glass tubes containing 750 mg of Tenax sandwiched between two 30 mm sections of polyurethane foam. Sampling equipment inside the firefighting ensemble was attached by clip to the shoulder braces of the ensemble overtrousers at chest height, with the sampling pump carried in a pocket of the overtrousers. Sampling equipment outside the ensemble was attached to the harness of the self-contained breathing apparatus at chest height, with the sampling pump carried in a pocket of the ensemble jacket. Equal lengths of Tygon tubing were used to connect sampling media to pumps inside and outside the structural firefighting ensemble. Sample collection began at donning of personal protective equipment in a fresh air environment, and ended upon return to the fresh air environment for doffing of personal protective equipment. Samples were analyzed by Queensland Health Forensic and Scientific Services using the principles of the United States Environmental Protection Agency (USEPA) Compendium Method TO-13A,[25] with a limit of reporting for individual compounds of 50 ng per sample. The limit of reporting for samples collected during evolution 5 was 250 ng per sample due to an unplanned variation in the extraction process. When calculating total PAH concentrations, all compounds with results below reportable limits were assumed to have concentrations of zero ng per sample.

Structural Firefighting Ensemble Deposition Sampling

Deposition of PAHs on the structural firefighting ensemble was sampled by attaching a 10cm × 10 cm swatch of Nomex IIIA fabric (mass approximately 2.20 g) to the front of the ensemble. The swatch was pinned on the outside of the protective clothing on the opposite side of the torso to the polyurethane foam tube, at the same height. At the conclusion of each training evolution, the swatch was removed by the attachment pins with minimal handling, sealed individually in a polythene bag, and stored at -4°C until analysis. The samples were analyzed by Queensland Health Forensic and Scientific Services using the principles of the USEPA Compendium Method TO-13A,[25] with a limit of reporting of 500 ng/swatch for individual compounds.

Toxic Equivalency Calculations

Toxic Equivalency Factors (TEFs), where the toxicity of the reference compound is assigned a value of 1 and other compounds in the group are assigned values based on relative potency, are often used to assess the toxicity of mixtures of structurally related compounds with a common mechanism of action. In the case of PAHs, toxicity based on carcinogenic potential is compared with that of the most studied of the PAH compounds, benzo[a]pyrene. Multiple TEF models have been devised,[26] with no general consensus at present on a single ranking system.[27] One well-recognised model is that of Nisbet and LaGoy,[28] which has been previously used to assess the toxicity of PAH mixtures generated in a range of large-scale fire experiments.[27] This model has been applied here in the same manner. The TEF values for the PAHs measured in this work are shown in Table I.

TABLE I. Toxic Equivalency Factors for Individual PAHs, as Recommended by Nisbet and LaGoy[(28)]

PAH	TEF
naphthalene	0.001
acenaphthylene	0.001
acenaphthene	0.001
fluorene	0.001
phenanthrene	0.001
anthracene	0.01
fluoranthene	0.001
pyrene	0.001
benzo[a]anthracene	0.1
chrysene	0.01
benzo[b]fluoranthene/benzo[k]fluoranthene	0.1
benzo[a]pyrene	1
indeno[1,2,3-cd]pyrene	0.1
dibenzo[a,h]anthracene	5^A
benzo[ghi]perylene	0.01

^{A}TEF of 5 is recommended for environmental exposures. However, a TEF of 1 is appropriate for high doses.[(28)]

RESULTS

Personal Air Sampling

Table II presents the concentrations of 16 PAHs outside and inside the instructors' ensembles during the structural firefighting training evolutions, in μg/m^3. Combined results for benzo[b]fluoranthene and benzo[k]fluoranthene are presented since the analytical technique did not permit discrimination between the two. Due to the increased limit of reporting for samples from evolution 5, fewer PAHs reached reportable concentrations. PAHs detected inside the ensemble during evolution 5 but not reaching reportable concentrations included phenanthrene, anthracene, benzo[a]anthracene, chrysene, benzo[e]pyrene, and benzo[ghi]perylene. Total PAH concentrations ranged from 430 μg/m^3 to 2700 μg/m^3 outside the instructors' firefighting ensembles, and from 32 μg/m^3 to 355 μg/m^3 inside the instructors' firefighting ensembles.

The distributions of toxicity-weighted PAHs (BaP-TEQ) are shown in Figures 1 and 2 for the samples collected outside and inside the instructors' structural firefighting ensembles, respectively. The total benzo[a]pyrene-equivalent concentration of PAHs outside the structural firefighting ensembles ranged from 4.4 μg/m^3 to 63 μg/m^3, and inside the ensembles ranged from 0.6 μg/m^3 to 17 μg/m^3.

Structural Firefighting Ensemble Deposition Sampling

Deposition concentrations of 16 PAHs on cloth swatches attached to the instructors' ensembles during the structural firefighting training evolutions are shown in Table III. Combined results for benzo[b]fluoranthene and benzo[k]fluoranthene are presented since the analytical technique did not permit discrimination between the two. Total PAH concentrations ranged from 69 ng/cm^2 to 290 ng/cm^2 across the five evolutions, with

TABLE II. Atmospheric Concentrations (μg/m^3) of Polycyclic Aromatic Hydrocarbons Outside and Inside Structural Firefighting Ensembles of Instructors During Live Fire Training

	Outside structural firefighting ensemble					Inside structural firefighting ensemble				
Compound	1	2	3	4	5	1	2	3	4	5
naphthalene	490	140	73	540	1300	13	20	79	170	210
acenaphthylene	230	83	93	390	290	3.1	2.4	8.5	18	13
acenaphthene	20	7.9	8	37	22	0.34		1.6	2.6	
fluorene	75	27	30	120	77	1.1	0.56	1.8	5.4	
phenanthrene	240	120	120	490	380	4.3	2.2	12	37	
anthracene	43	27	24	110	88	0.89	0.36	1.6	8.2	
fluoranthene	54	33	34	180	160	5.1	1.7	7.6	28	11
pyrene	54	29	33	180	160	5.3	1.9	7.8	33	14
benzo[a]anthracene	11	4.4	4.1	45	46	2.1	0.56	2.6	11	
chrysene	9.9	4	3.4	41	42	2.3	0.74	2.7	10	
benzo[b]fluoranthene/ benzo[k]fluoranthene	15	4.8	4.3	50	60	3.1	0.9	4	15	15
benzo[a]pyrene	7.3	3.3	1.8	37	47	1.7	0.4	1.7	11	13
indeno[1,2,3-cd]pyrene	2.4	1.1	0.9	16	18	1	0.28	0.9	2.6	
dibenzo[a,h]anthracene	0.54		0.2	2				0.2	0.6	
benzo[ghi]perylene	2.6	1.2	1	16	23	1	0.29	0.8	2.8	
TOTAL PAH	1250	490	430	2250	2700	44	32	133	360	280

Blanks denote results below the limit of reporting.

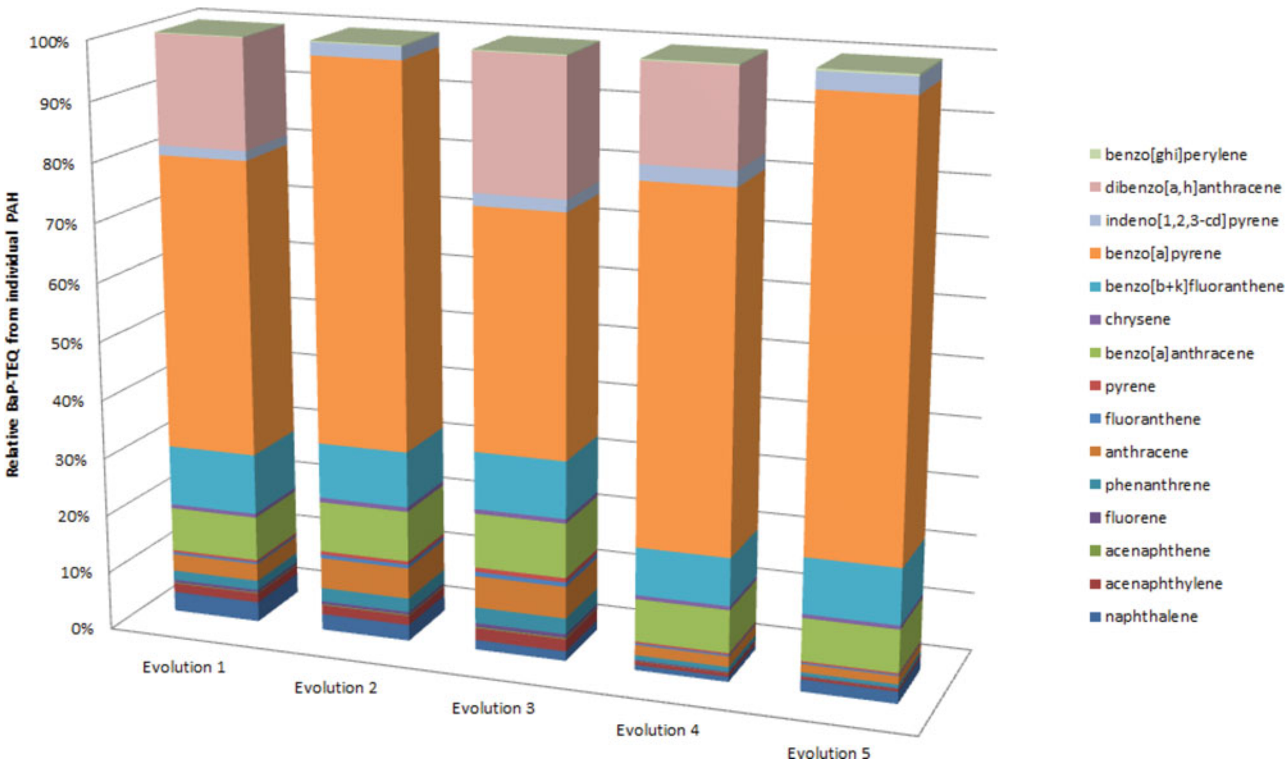

FIGURE 1. Percentage contributions of individual toxicity-weighted polycyclic aromatic hydrocarbons [BaP-TEQ] to total benzo[a]pyrene-equivalent concentration measured outside firefighting instructors' structural ensembles in live fire training scenarios.

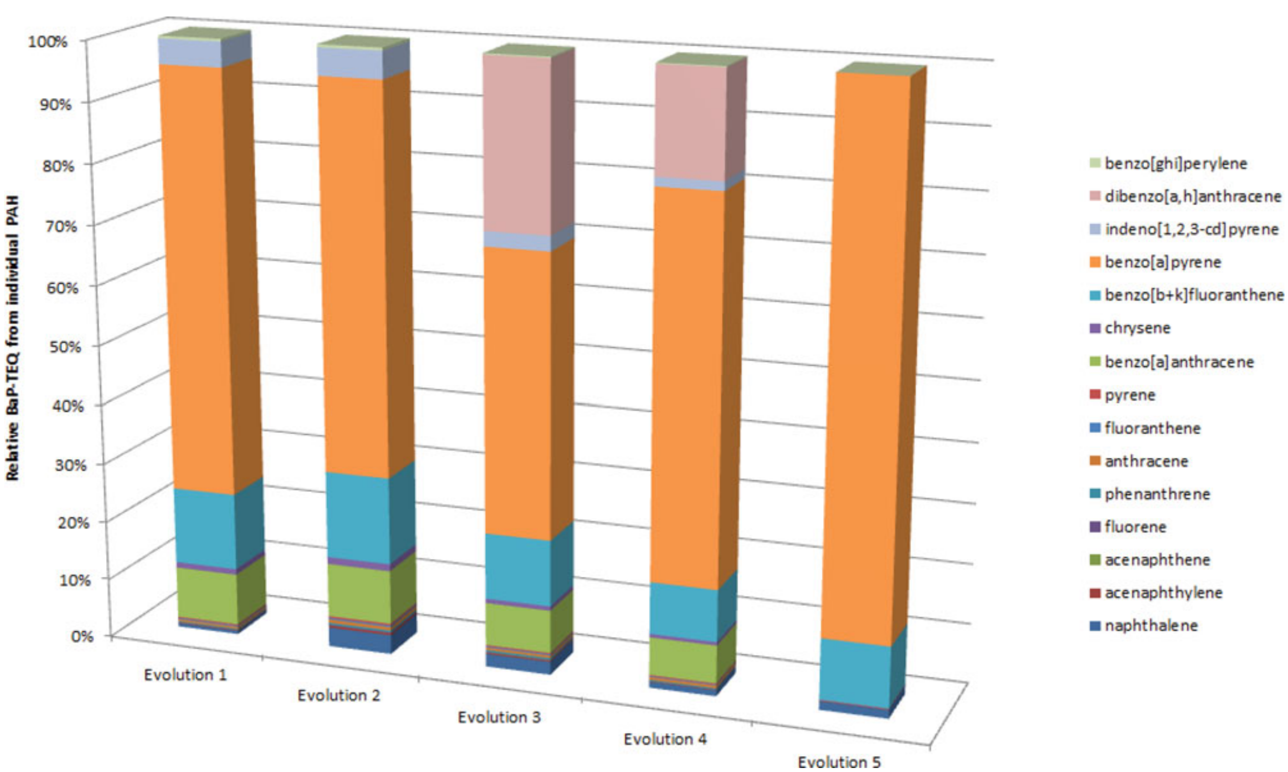

FIGURE 2. Percentage contributions of individual toxicity-weighted polycyclic aromatic hydrocarbons [BaP-TEQ] to total benzo[a]pyrene-equivalent concentration measured inside firefighting instructors' structural ensembles in live fire training scenarios.

only four compounds (phenanthrene, fluoranthene, pyrene, and benzo[a]anthracene) detected on all swatches.

The distribution of toxicity-weighted PAHs (BaP-TEQ) for these deposition samples is presented in Figure 3. The total benzo[a]pyrene-equivalent concentration of PAHs deposited on the swatches ranged from 0.6 ng/cm^2 to 31 ng/cm^2.

DISCUSSION

The current findings show that PAHs are generated in substantial quantities in live-fire training scenarios, with quantifiable deposition onto and ingress into structural firefighting ensembles during a single training evolution. Measurements of atmospheric concentrations, dermal deposition, and personal protective clothing contamination cannot be easily related to levels of human uptake, due to the variety of interacting factors which contribute to the production of an internal dose.[29] However, they are useful in identifying potential exposure pathways. Potential routes of PAH exposure for firefighting instructors wearing self-contained breathing apparatus during training sessions include: post-training inhalation of resuspended and/or off-gassed PAH from structural firefighting ensembles; transfer from structural firefighting ensemble to skin; and direct deposition to skin from the microenvironment inside the structural firefighting ensemble.

Comparison of PAH distributions and toxicity-weighted PAH distributions from the air samples taken outside the structural firefighting ensembles of the instructors during live-fire training evolutions demonstrates strong similarity with the results from large-scale room fire experiments.[27] Naphthalene, phenanthrene, and acenaphthylene dominated the PAHs generated (as a function of mass), but benzo[a]pyrene, dibenzo[a,h]anthracene, benzo[a]anthracene, and benzo[b]fluoranthene/benzo[k]fluoranthene were the major contributors to the toxicity of the PAH mixture. The range of total PAH concentrations measured outside the structural firefighting ensembles during the training evolutions (short-term time-weighted averages (TWAs) over 20 – 44 min) were within the range detected in a previous study of PAHs in personal air samples during live-fire training[11] and exceeded the range of 8-hour TWA exposures for all industrial sites considered by Unwin et al.[30] in their cross-occupational hygiene survey. If only benzo[a]pyrene concentrations are considered, short-term TWA concentrations ranged from 1.8 μg/m^3 to 47 μg/m^3, which again exceed the range of 8-hour TWA exposures investigated by Unwin et al.[30]

Van Rooij et al.[31] concluded in their study of coke oven workers that up to 95% of the total absorbed amount of PAH enters through the skin. For firefighters (including instructors) wearing protective clothing and self-contained breathing apparatus, the potential for dermal uptake from the microenvironment inside the protective clothing has greater relevance for exposure considerations than the external environment. The lower concentrations of PAHs inside the structural firefighting ensembles than outside indicate that the clothing confers substantial, but not complete, protection, with observed reductions

TABLE III. Deposition Concentration (ng/cm^2) of Polycyclic Aromatic Hydrocarbons on Structural Firefighting Ensembles of Instructors During Live Fire Training

	Deposition concentration (ng/cm^2)				
Compound	**1**	**2**	**3**	**4**	**5**
naphthalene					
acenaphthylene				20	
acenaphthene					
fluorene				14	
phenanthrene	15	16	20	145	29
anthracene		5.3		27	
fluoranthene	31	22	32	32	68
pyrene	36	21	34	31	78
benzo[a]anthracene	12	5	17	6.5	30
chrysene	9.6		16	5.4	
benzo[b]fluoranthene/ benzo[k]fluoranthene	11		11	7	31
perylene	5.6				
benzo[a]pyrene	8.6		6.6	5.5	24
benzo[e]pyrene					11
indeno[1,2,3-cd]pyrene					11
dibenzo[a,h]anthracene					
benzo[ghi]perylene					10
TOTAL PAH	129	69	137	293	292

Note: Blanks denote results below the limit of reporting.

in total PAH concentration of 69 to 96%. Relative concentrations of the various PAHs inside the structural ensembles in this study differed from those observed outside the structural ensemble. In particular, the relative concentration by mass of naphthalene was higher, while acenaphthylene, phenanthrene, and anthracene were comparatively underrepresented. These results suggest better attenuation by the structural ensembles for higher molecular-weight PAHs, which exist primarily as solid-phase particulates.

The relative toxicity-weighted concentrations outside and inside the structural ensembles were similar, reflecting the low Toxic Equivalency Factors assigned by Nisbet and LaGoy[28] to those compounds whose relative concentrations varied the most. Both total PAH concentrations and benzo[a]pyrene concentrations inside the structural firefighting ensembles were comparable to the highest eight-hour TWA occupational exposure values found by Unwin et al.[30] for the industries investigated. However, the concentrations in the present study were measured over short time periods (20–44 min). Eight-hour TWAs for firefighting instructors would be substantially lower, depending on the number of training evolutions conducted per day. Also, unlike many other occupations, the inhalation exposure route is generally well protected for firefighters wearing self-contained breathing apparatus.

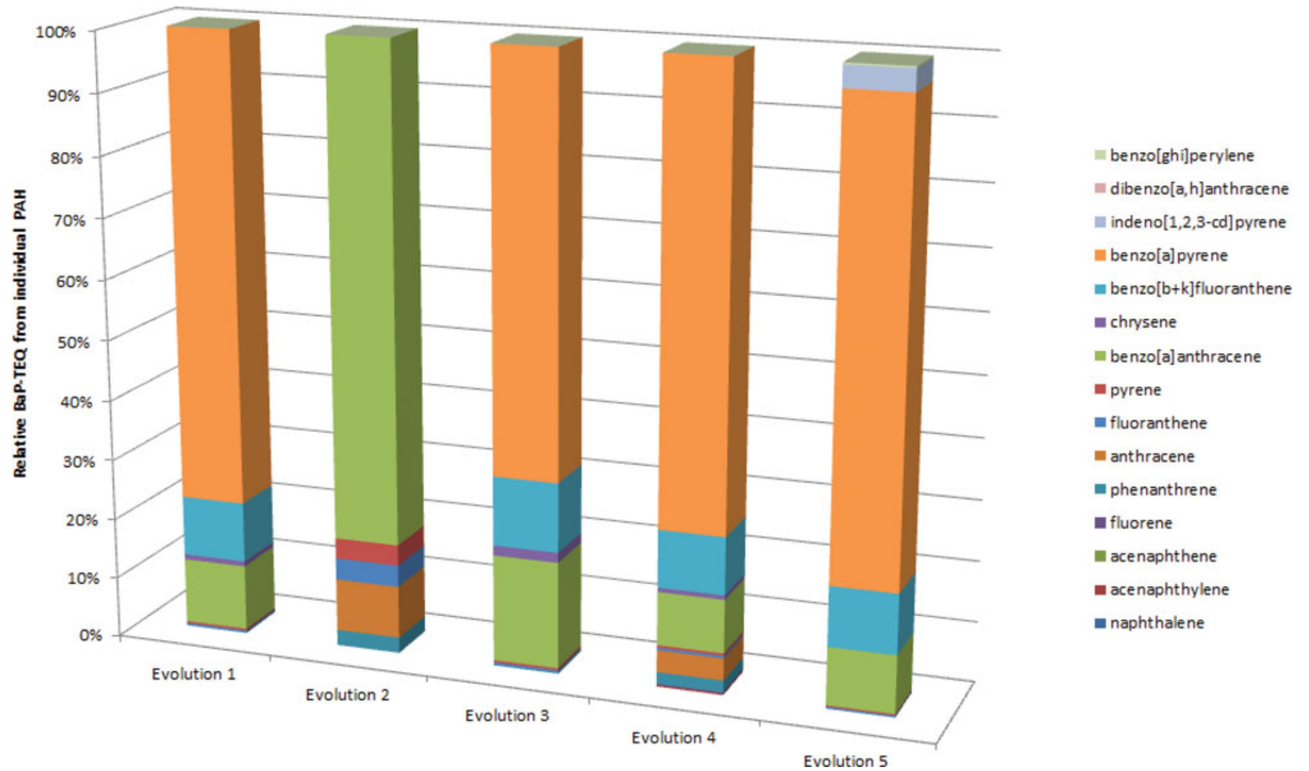

FIGURE 3. Percentage contributions of individual toxicity-weighted polycyclic aromatic hydrocarbons [BaP-TEQ] to total benzo[a]pyrene-equivalent deposition concentration on firefighting instructors' structural ensembles in live fire training scenarios.

This study is unable to differentiate the relative contributions of permeation (chemical movement through the material on a molecular basis) and penetration (chemical movement through closures and imperfections)[32] to the ingress of PAHs inside the structural firefighting ensembles worn by the instructors. In addition, the possibility exists that air sampling within the ensemble may have drawn in air contaminants.[11] The volume of air sampled over the duration of the training evolutions (approximately 60 liters) may be substantially larger than the volume of air inside an ensemble when it is worn. Even allowing for air exchange inside the ensemble due to the bellows effect, the results of this study likely represent an overestimate of the amount of PAHs that permeate/penetrate the structural firefighting ensembles.

In the firefighting ensemble deposition samples, the most predominant PAHs (by mass) were phenanthrene, fluoranthene, and pyrene. The primary contributors to the toxicity of the mixture of PAHs deposited onto the structural firefighting ensembles in the current study were benzo[a]pyrene, benzo[a]anthracene, and benzo[b]fluoranthene/benzo[k] fluoranthene. The predominant PAHs are in line with findings of previous studies of occupationally soiled protective clothing donated by metropolitan fire services.[29,33] Stull et al.[33] found benzo[a]anthracene, chrysene, fluoranthene, phenanthrene, and pyrene as contaminants of structural firefighting jackets, with pyrene deposition concentrations of up to 75 mg/cm^2. This concentration is several orders of magnitude higher than the pyrene deposition concentrations on the swatches from the training evolutions in the current study (21–78 ng/cm^2).

However, the deposition concentrations of individual PAHs (expressed in μg/g sample) in the current study are similar to those found by Alexander and Baxter[29] on firefighting gloves, jacket cuffs, and hoods. The deposition results from the current experiment are from a single training evolution with no prior sample contamination, whereas the results of the previous studies are from occupationally soiled firefighting ensembles with unknown, potentially extensive usage and laundering histories. In particular, the study by Stull et al.[33] sampled from the areas of greatest apparent soiling from the three coats of a group of 12 which appeared most visually soiled, and therefore may represent a near-maximal contamination load. The U.S. National Institute for Occupational Safety and Health (NIOSH)[34] used wipe sampling to measure PAH deposition on the pants of a single, previously laundered structural firefighting ensemble worn in a live-fire training evolution. Though the sampling collected 27 μg of PAH, this result cannot be directly compared with deposition concentration values since no sampling surface area information was provided.

The lowest molecular weight PAH in this study, naphthalene, was measured in significant quantities both outside and inside the structural firefighting ensembles. However, it was noticeably absent in the deposition samples. This may be due to one or more factors, including (i) low propensity for deposition, (ii) higher permeability through the fabric, and/or (iii) off-gassing from the samples prior to analysis. Although naphthalene exists primarily in the gas phase, it could adsorb onto carbonaceous particles deposited onto structural firefighting ensembles. Alexander and Baxter[29] found naphthalene among the contaminants in occupationally soiled firefighting clothing, indicating that medium- to long-term contamination of structural firefighting ensembles with this compound is possible.

CONCLUSION

Multiple studies have investigated the concentrations of air contaminants to which firefighters are exposed during operational duties or training. However, the potential difference between the ambient concentrations in the operational or training firefighting environment and those of the microenvironment within the firefighter's or instructor's structural firefighting ensemble, from which the majority of dermal uptake would occur, has received little if any attention. The current study found that PAH concentrations outside the structural firefighting ensembles exceeded those found in industries with the highest PAH levels. Concentrations inside the ensembles were significantly lower, demonstrating a protective effect that results in lower dermal exposures than would be expected from the ambient PAH concentrations. However, the microenvironments within the structural firefighting ensembles still included measurable levels of known and suspected carcinogens, with PAH concentrations from a single training evolution comparable to the highest eight-hour TWA PAH concentrations identified in industry.

Since firefighting can encompass a wide range of fire incident types (residential, vehicle, industrial, petrochemical), further attention to the types and quantities of air contaminants generated in various types of fire scenarios is warranted. Investigation into the ingress of toxic combustion products through protective clothing and the impact of work practice variation (for example, placement and activity within the fire environment) may identify opportunities for reducing firefighter and instructor exposures to PAHs during firefighting. The potential for dermal deposition and subsequent dermal uptake of PAHs during various types of fire scenarios also needs additional investigation to develop appropriate post-fire decontamination guidelines.

Retention of PAHs in occupationally soiled firefighting protective clothing has been previously studied, but the amount of PAHs deposited during individual live-fire training evolutions has not been considered. This study has found deposition concentrations of PAHs from single training evolutions comparable with those extracted from protective clothing with a history of being used operationally. Further research is required to characterize the accumulation of PAH deposits on structural firefighting ensembles across multiple exposures, and investigate the potential for exposure to PAH from off-gassing and/or resuspension following the removal of contaminated ensembles.

RECOMMENDATIONS

This study demonstrates that structural firefighting ensembles afford some protection against dermal exposure to PAHs. However, it is recommended that firefighters shower promptly after exposures incurred during live-fire training and operational firefighting. Changing and laundering of both personal protective clothing elements and garments worn under the protective clothing are also potentially important components of occupational hygiene that should be considered as methods of PAH exposure control.

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