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Exposure of Firefighters to Particulates and Polycyclic Aromatic Hydrocarbons

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Abstract

Firefighting continues to be among the most hazardous yet least studied occupations in terms of exposures and their relationship to occupational disease. Exposures are complex, involving mixtures of particles and chemicals such as polycyclic aromatic hydrocarbons (PAHs). Adverse health effects associated with these agents include elevated incidences of coronary heart disease and several cancers. PAHs have been detected at fire scenes, and in the firehouse rest area and kitchen, routinely adjoining the truck bay, and where firefighters spend a major part of each shift. An academic-community partnership was developed with the Cincinnati Fire Department with the goal of understanding active firefighters' airborne and dermal PAH exposure. PAHs were measured in air and particulates, and number and mass concentrations, respectively, of submicron (0.02–1 μm) and PM2.5 (2.5 μm diameter and less) particles during overhaul events in two firehouses and a University of Cincinnati administrative facility as a comparison location. During overhaul firefighters evaluate partially combusted materials for re-ignition after fire extinguishment and commonly remove Self-Contained Breathing Apparatus (SCBA). Face and neck wipes were also collected at a domestic fire scene. Overhaul air samples had higher mean concentrations of PM2.5 and submicron particles than those collected in the firehouse, principally in the truck bay and kitchen. Among the 17 PAHs analyzed, only naphthalene and acenaphthylene were generally detectable. Naphthalene was present in 7 out of 8 overhaul activities, in 2 out of 3 firehouse (kitchen and truck bay) samples, and in none collected from the control site. In firefighter face and neck wipes a greater number of PAHs were found, several of which have carcinogenic activity, such as benzofluoranthene, an agent also found in overhaul air samples. Although the concentration for naphthalene, and all other individual PAHs, was very low, the potential simultaneous exposure to multiple chemicals even in small quantities in combination with high ultrafine particle exposure deserves further study. It is recommended that personal respiratory and skin protection be worn throughout the overhaul process.

Introduction

Firefighters are heavily exposed during fire suppression to a wide range of chemicals and particulate matter.[(1–3)] Smoke from burning organic materials contains particles both 2.5 μm or less (PM2.5) 1 μm and less (termed submicron), and 0.1 μm and less (termed ultrafine) in diameter.[(1,4)] Both the particulate and gaseous phases of smoke have been shown to contain

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polycyclic aromatic hydrocarbons (PAHs), exposure to several of which has been associated with several toxic outcomes, including hemotoxicity and carcinogenicity.[1–6] Submicron and ultrafine particle exposures in ambient air have been associated with impairment of cardiovascular function and several other adverse health outcomes.[7,8] Toxicity of particles has been more clearly associated with number, rather than mass, concentration. Exposure to respirable particles and PAHs during overhaul, when firefighters enter the structure after the fire has been extinguished to examine areas for possible re-ignition of partially combusted materials, has previously been reported. Particle size was not characterized and no comparisons were made with other living or work environments, however.[6] Analysis of combustion products from model domestic structures and automobiles suggest that residential firefighters are exposed to high number concentrations of submicron particles during overhaul.[1,9]

During active fire suppression, firefighters wear Self Contained Breathing Apparatus (SCBA) with a full face mask, which provides skin and respiratory protection factors exceeding 10,000. SCBA is frequently removed during the overhaul stage, however, and additional exposures can result from sources such as soiled firefighter turnout gear, which is infrequently cleaned and may be inappropriately stored in firehouse living quarters. Exposure to PAHs may also result from skin contamination and resultant dermal absorption.[10] The aim of this pilot study was to develop an academic-community partnership with the Cincinnati Fire Department (CFD) and to work with it to assess firefighters' exposure to particles and PAHs during overhaul and during normal firehouse conditions.

Methods

Study Design

Protocols and questionnaires were developed first by the authors under direction of the University of Cincinnati Institutional Review Board (IRB), followed by final distribution and implementation through direct collaboration and discussion between the authors of this report and local fire chiefs and unit captains. The study population consisted of three units of professional firefighters serving at two municipal firehouses. Comparison ambient measurements were collected at the University of Cincinnati Radiation Safety Office, located within 0.5–2 miles of the fire stations. Ten healthy male participants with 10 or more years of firefighting experience each were recruited from these firehouses. All participants read and signed informed consent forms approved by the University of Cincinnati IRB.

Given the random nature of timing for fire events, firefighters were trained in use of sampling equipment and data collection. All participating firefighters were trained on the proper use of all equipment needed to sample at the live overhaul events. A toolbox was assembled, containing all necessary equipment to collect two each of PM2.5 and PAH samples, and one real time stationary measurement using the P-Trak. The toolbox contained four SKC air sampling pumps, one P-Trak submicron particle counter, two PM2.5 assembled sampling trains, two PAH assembled sampling trains, one tripod, sampling information cards, and detailed “setup” and “take-down” instructions. The PM2.5 sampling trains were pre-assembled and sealed at both ends with Parafilm and the PAH sampling trains were pre-assembled and sealed at one end with Parafilm and at the other with a 37-mm cassette cap. The air sampling pumps located in the firefighter toolbox were replaced with newly charged and calibrated pumps every 3 days. During stationary sampling, the samplers and P-Trak were attached to a tripod at the height of breathing zone.

Air monitoring was conducted in three different environments: metropolitan fire stations (two, designated A and B), overhaul scenes at live fire events (five), and the University of Cincinnati Radiation Safety Office. At both fire stations resting areas contained a kitchen that adjoined a truck bay and was connected to it by a door that was frequently open. This arrangement was prevalent among stations in the Cincinnati Fire Service. Air monitoring was conducted in the fire truck bay and equipment storage area, the kitchen/common area, and the sleeping quarters. Samples were collected over an 8hr period on a single day. Stationary PM2.5 and PAH samples were collected in each of these three locations. The number concentration of submicron particles was also simultaneously measured with P-Trak direct reading.

During overhaul activities both personal and stationary samples were collected, each using two separate sampling trains that collected PAHs and PM2.5. Submicron particle numbers were concurrently measured using a P-Trak counter. Firefighters were able to choose if the samples would be personal or stationary to avoid being burdened with air monitoring equipment. This also allowed for flexibility to ensure samples from the overhaul atmosphere were collected, regardless of the situation.

When a live overhaul event occurred, the firefighters completed all monitoring procedures and an information card was filled out, including date, address, time of overhaul event, and start and stop times for each pump. Sampling was carried out for the majority of the overhaul period, and the sampling time varied from 15 to 29 min. After sampling was completed, each PM2.5 and PAH sampling train was detached from its respective pump and sealed in a plastic bag which was then stored in the fire station's refrigerator. To assess dermal PAH contamination and absorption firefighters wiped, with unsoiled hands, their face and neck, anatomic areas that have high relative absorption abilities for this type of agent, following a fire event.

The air monitoring at the control site was performed in the business office and break room at the University of Cincinnati Radiation Safety Office. In both locations, PAHs and PM2.5 samples were collected, and a P-Trak counter was also utilized in each location to measure the number concentration of submicron particles. This monitoring was conducted over an 8 hr period on one day.

Sampling and Analysis Methods

Two measures of particle concentration were used: mass concentration of PM2.5, and number concentration of sub-micron particles in the 0.02–1 μm size range. PM2.5 samples were collected using PMI-samplers (Personal Modular Impactor, SKC Inc., Eighty Four, Pa.) equipped with 37-mm diameter Teflon filters (2 μm pore size; SKC Inc.). The pumps (Universal 44XR; SKC Inc.) were calibrated to 3.0 ± 0.1 liters per minute. The filters were weighed before and after the sampling by a commercial laboratory (RTI International, Research Triangle Park, N.C.). Number concentrations of submicron particles were assessed with a TSI P-Trak submicron particle counter, which records real time particle number concentrations in the size range of 0.02–1 μm with a 1-min resolution. Although the P-Trak upper size limit of 1000 nm extends beyond the defined "ultrafine" size range (<100 nm), samples from this counter have been found to represent the ultrafine range well.[11]

Air sampling for PAHs was conducted following NIOSH method 5515. The sampling train included a personal pump (Universal 44XR; SKC Inc.) with a flow rate of 2.0 ± 0.1 liters per min, a filter cassette equipped with a 37-mm diameter Teflon filter (2 μm, SKC Inc.) followed by an XAD-2 sorbent tube (XAD-2, 8 × 110 mm size, 2-section, 50/100 mg sorbent, with GS ends, WWW separators; SKC Inc.). The lower limit of quantification for PAHs was 0.1 ppm per sample, which corresponds to an air concentration of 0.5 $\mu g/m^3$ if sampling time is 30 min. Flow rates of both pumps were checked after sampling to confirm that the flow rate was within ±5% of the target flow rate.

To assess Dermal PAH absorption firefighters wiped their face and neck with a Wet-nap (Magid Co. Chicago, Ill.). The wipes were then placed in a 50 ML tube and mailed to the laboratory. Air and wipe samples were analyzed by Research Triangle Institute following NIOSH method 5515.

Results

Air Samples

The greatest mean concentrations of submicron particles and PM2.5 were found at overhaul events, although the mean concentrations of submicron particles in the kitchens of the firehouses were only a little smaller than those found at overhaul events (Tables I and II). All peaks in the real time particle number concentration in the kitchen of Firehouse B corresponded with the cooking of meals (Figure 1). During lunch preparation the submicron particle concentration in the kitchen peaked at 500,000 particles/cm^3, the highest that could be measured. Concentrations in truck bays were also relatively high (25–57% of values in the kitchen of the same firehouse), but those in firehouse sleeping quarters and control site rooms were considerably smaller. The highest PM2.5 particle mass concentration measured in Firehouse A was in the truck bay and was more than 10 times that in the control site. The highest PM2.5 mass concentration in Firehouse B was in the kitchen and was over 30 times higher than that at the control site. The highest mass concentration measured at the live overhaul events was over 3000 times that measured at the control site (Tables I and II). Very similar trends were observed in Firehouse A (data not shown). The highest particle mean number concentrations recorded from the live overhaul events was more than 15 times higher than those in the break room at the control site. A 24-hr time-weighted average (TWA) for PM2.5 of 143 $\mu g/m^3$ could be calculated from an average PM2.5 mass concentration over all the overhaul events (5178 $\mu g/m^3$, Table II) and an assumption that firefighters in Firehouse B spent approximately one-third of their 24 hr shift each in the kitchen, truck bay and sleeping quarters, together with 33.5 min in overhaul (an observed average value). This calculation showed that firefighters' exposure during a 24-hr work shift can exceed the EPA NAAQS 24-hr average of 35 $\mu g/m^3$, although exposure over any individual shift will be highly variable.

Of the16 PAHs, only naphthalene was detected in samples collected at one of the firehouses (A, in the kitchen and truck bay). Only naphthalene, acenaphthylene, and benzofluoranthene (measured as a mixture of b-, j-, and k- isomers) were detected in the samples collected during overhaul events. Naphthalene was detected more frequently than acenaphthylene. All detectable PAH concentrations measured during overhaul events were higher than those collected at firehouses (Table II).

The real time particle number concentrations from three independent overhaul events showed considerable consistency (Figure 2). When comparing the number concentrations measured at Firehouse B with those collected at the live overhaul events (Tables I and II), all *mean* number concentrations measured at the firehouse were lower than those measured at the live overhaul events. The *peak* number concentrations measured in both the kitchen and truck bay were unexpectedly high, however. The peak number concentration value recorded in the kitchen of Firehouse B was the highest recorded in this study, and the peak recorded in the truck bay was only 5% lower than the highest peak recorded during the live overhaul event.

Wipe Samples

A total of 20 skin wipes were collected from 10 firefighters following 5 fire events. The compound that was consistently (65% of samples) detected on wipes was benzo[b,j,k] fluoranthene (mixture of three isomers). Pyrene was detected in 6 (30%) of the wipes. Some other compounds that were detected were benz[a]anthracene, chrysene, fluoranthene, phenanthrene, benzo[a]pyrene, and benzo[e]pyrene. Benzo [b,j,k] fluoranthene was found in all wipes where any PAH was found above the limit of detection.

Discussion

In this study we found highest mean PM2.5 mass and submicron particle number concentrations during overhaul events. Peak values for submicron particle number concentrations in at least one kitchen of the firehouses were comparable to those measured during live overhaul, however, and higher than in any other area of either firehouse. It is possible that the high temperatures generated during live overhaul caused values obtained during this activity to be underestimated; however, since the operating temperature range for the P-Trak counter is 0–38°C and temperatures during overhaul frequently exceed this value by a large margin. Higher temperatures would not allow proper condensation of alcohol onto the submicron particles in the condensation nucleus counter resulting in all particles not being counted. High concentrations of fine and submicron particles have previously been found to result from cooking of various foods,[11–19] and in exhaust emitted by diesel trucks.[16] The mean particle number concentrations collected at both firehouses in the kitchen and truck bay were considerably higher than those collected in the sleeping quarters of the firehouses or at the control sites as expected (Table III).

Our findings suggest that firefighters can be exposed to large numbers of submicron particles during overhaul, but also in firehouses where rest areas contain a kitchen. In the majority of firehouses this usually adjoins and shares a doorway with a truck bay, an additional source of these particles. Our measurements from Firehouse B and overhaul events suggested that firefighters could be exposed during a 24-hr work shift to a level that can exceed the EPA NAAQS 24-hr average,[20] though comparison of concentrations in this study to occupational or environmental standards or guidelines is difficult due to the irregular nature of firefighter activities and exposures, both at fire scenes and in the firehouse.

Highest PM2.5 mass concentrations measured at the live overhaul events were two orders of magnitude greater than peak concentrations found at the firehouses. This result shows an increased risk of PM2.5 exposure firefighters face during overhaul compared to that during time spent at the firehouse. The mass concentrations collected in our study were comparable to those reported previously[6] though the particles collected in that study were larger than 2.5 um. All particle mass concentrations found at the firehouses or at the live overhaul events were much higher than those at the control site. The concentrations in the sleeping quarters, truck bay, and during overhaul were one, one and four orders of magnitude, respectively, greater than those at the control site. These results therefore suggest that firefighters are exposed to higher levels of fine PM2.5 particles compared to the concentrations observed at the control site. Due to the highly variable nature of firefighting, it is difficult to compare exposure levels to occupational exposure limits (OELs), especially since these limits do not exist for PM2.5 particles. Air PAH concentrations were very low even for the two compounds measured at levels above the limit of detection. Reasons for this may be that the monitoring time at the live overhaul events was too brief, the longest being 27 min and the low flow rate prescribed by NIOSH method 5515. Our results are consistent with results from a previous study that characterized firefighter exposure during overhaul,[6] however. In the present study, all mean concentrations were below 1 $\mu g/m^3$. The highest concentrations were found for naphthalene, acenaphthylene, and benzofluoranthene, although the latter was only present above the level of detection in samples from overhaul. In both studies these compounds were the only PAHs with detectable concentrations. Of the three PAHs detected in air samples in this study (acenaphthylene, naphthalene, and benzofluoranthene), only naphthalene has any criteria values such as OELs. The concentration of naphthalene was a fraction of the recommended short-term exposure limit (STEL) of 75 mg/m^3. [21,22] Although the concentration for naphthalene, and all other individual PAHs, was very low, the potential simultaneous exposure to multiple chemicals even in small quantities in combination with high ultrafine particle exposure deserves further study.

In firefighter skin and neck wipes PAH concentrations were also low, but many more PAHs were detected in this manner than in the air. The only compounds found in both overhaul air and skin wipe samples were benzofluoranthene isomers.

Conclusion

This study showed that firefighters are exposed to elevated levels of fine PM2.5 and submicron particles during overhaul activities, but also in areas of the firehouse where they spend a large proportion of each shift. Trace amounts of the PAHs naphthalene, benzofluoranthene, and acenaphthylene were detected in most of the overhaul samples, but none was detected in samples collected from a control site not involved with the fire service.

Benzofluoranthene and several additional types of PAH with reported carcinogenic activity[23] were detectable as firefighter skin contaminants, suggesting skin absorption as a potential route of exposure for these agents. Firefighter activities and exposures, both at fire scenes and in the firehouse are routinely highly irregular, therefore comparison in any study of this occupation of measured exposures to occupational or environmental standards or guidelines such as occupational exposure limits (OELs) will be difficult, especially since these limits do not exist for PM2.5 particles and are limited for the PAHs detected.

In the present study measurements were also made on a single day, and future studies to investigate variation over time are warranted. Overall firefighter exposures to fine particles and toxic agents were considerably greater than those of the population at the control site studied. We therefore recommend, in agreement with others, that firefighters attempt to reduce exposure through the use of personal protective equipment (PPE), and especially wear SCBA throughout overhaul events. Avoidance and prompt removal of skin contamination is also recommended. Measures should also be taken to reduce firefighter exposures in the firehouse since there is potential at several locations for additional and comparable exposure to particulate matter and organic chemicals of the same types as those found during overhaul activities.

Recommendations

The findings of this study indicate that firefighter exposure to particulates and toxic chemicals should be reduced. During overhaul PPE and SCBA should be worn continuously to avoid respiratory and skin exposure, and firehouse exposure reduced by, prompt skin decontamination after fire events and use of appropriate ventilation design.

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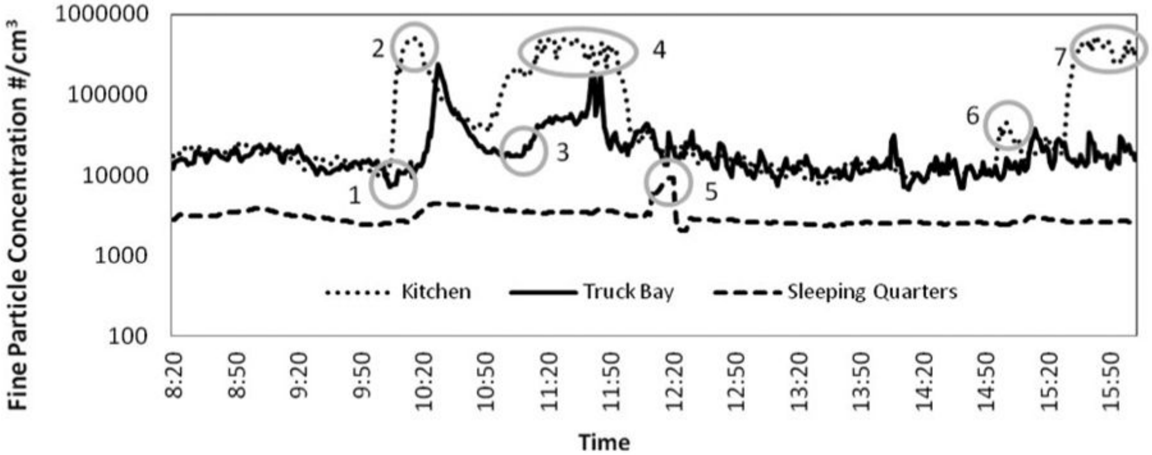

Figure 1.
Number concentration of submicron particles measured with the P-Trak at three different areas at Firehouse B. Peak values are numbered in order of their chronological appearance.

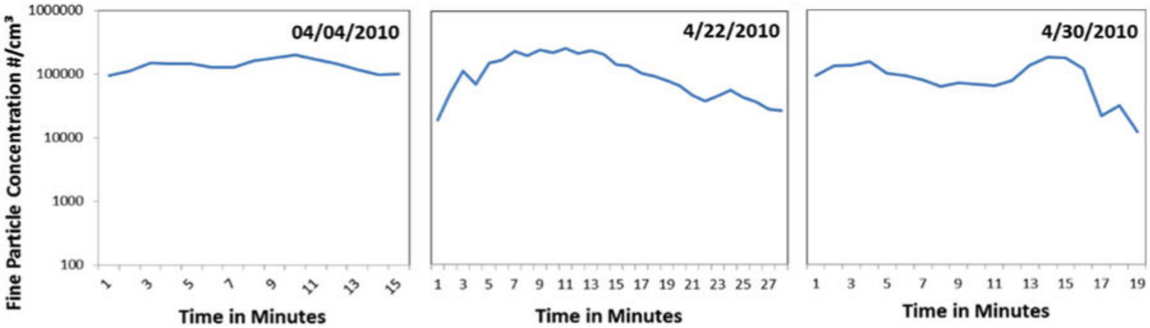

Figure 2.

Number concentration of submicron particles measured with the P-Trak during three overhaul events at stated dates. (color figure available online)

Table I

Result of Air Monitoring at Two Firehouses and in Control Environment (All samples were stationary.)

	Submicron particles (number/cm^3)					PAH(μg/m^3)	
Location	**Mean**	**Median**	**St. Dev.**	**Peak**	**PM2.5 (μg/m^3)**	**Naphthalene**^{A}	**Acenaphthylene**^{A}
Firehouse A							
Kitchen	69,289	24,510	74,214	254,133	23	9.22	BLQ
Truck Bay	39,149	41,436	17,957	81,795	55	9.24	BLQ
Sleeping Quarters	4,668	2,619	2,490	7,909	20	BLQ	BLQ
Firehouse B							
Kitchen	93,689	19,167	144,474	500,000	155	BLQ	BLQ
Truck Bay	23,265	16,018	25,488	241,911	18	BLQ	BLQ
Sleeping Quarters	3,034	2,720	898	9,223	28	BLQ	BLQ
Radiation Safety Office							
Break Room	9,280	10,328	6,370	87,421	5	BLQ	BLQ
Office	6,372	6,623	3,753	46,310	*B*	BLQ	BLQ

^{A}Only analytes with detectable levels.

^{B}Data unavailable due to sampling equipment failure.

BLQ = Below Limit of Quantification.

Table II

Result of Air Monitoring During Five Overhaul Events (All samples were stationary unless otherwise specified.)

Event Date	Submicron particle number/cm^3				PM 2.5 ($\mu g/m^3$)	PAH ($\mu g/m^3$)		
	Mean	Median	Std. dev	Peak		Naphthalene[A]	Acenapthylene[A]	Benzofluoranthene[A]
4/4	139,406	144,883	30,692	198,850	2,686[B]	56.72[B]	BLQ[B]	23.06[B]
					17,530	59.33	BLQ	23.30
4/9	*C*	*C*	*C*	*C*	3560	89.91	8.04	7.3
	C	*C*	*C*	*C*	253	BLQ	BLQ	BLQ
4/19	*C*	*C*	*C*	*C*	10,740	80.64	1.32	BLQ
	C	*C*	*C*	*C*	2,604	2.44	BLQ	BLQ
4/22	119,495	99,456	79,936	255,915	857[B]	26.23[B]	3.63[B]	13.06[B]
					3,192	18.02	BLQ	13.08
4/30	95,684	93,152	49,064	180,383	*C*		*C*	
					C		*C*	

[A]Only analytes with detectable levels.

[B]Personal samples.

[C]Data unavailable due to sampling equipment failure.

BLQ: Below limit of quantification.

Table III
PAHs Detected in Firefighter Face Wipes Following a Fire Event

PAH	N (%)[A]	Mean mass per wipe (μg) (SD[B])
Benz[a]anthracene	3 (15%)	0.11 (0.023)
Benzo{b,j,k] fluoranthene	13 (65%)	0.16 (0.049)
Benzo[a]pyrene	2 (10%)	0.09 (0.04)
Benzo[e]pyrene	1 (5%)	0.11
Chrysene	1 (5%)	0.10
7,12-Dimethylbenz[a]anthracene	1 (5%)	0.05
Fluoranthene	3 (15%)	0.08 (0.03)
Indeno[1,2,3,-c,d]pyrene	1 (5%)	0.06
Phenanthrene	1 (5%)	0.15
Pyrene	6 (30%)	0.12 (0.02)

[A] number of skin wipes (percentage of total) in which the PAH was detected.

[B] standard deviation.