

Evaluation of 7 urinary metabolites of polycyclic aromatic hydrocarbons during a wildfire response as part of the Wildland Firefighter Exposure and Health Effects Study

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Abstract

The occupation of firefighting, including wildland firefighting, has been classified as a known human carcinogen by the International Agency for Research on Cancer. Wildland firefighters (WFFs) can be exposed to polycyclic aromatic hydrocarbons (PAHs) present in wildfire smoke, some of which are known or probable carcinogens. Currently, there is no approved respiratory protection for WFFs against wildfire smoke, making inhalation exposure to PAHs a health concern. Recent studies have also highlighted the risk of dermal exposure to PAHs for WFFs due to factors like elevated skin temperature, sweat, and the inability to shower or routinely conduct good skin hygiene practices during wildfire incidents. This pilot study aimed to assess PAH exposure among 19 WFFs in different job positions during a wildfire incident by determining urine concentrations of 7 PAH metabolites in samples collected before and after shifts across 3 days. Overall, we observed increases from pre- to post-shift for all 7 PAH metabolites when we combined all WFF samples across the 3 days. When we stratified by job position and by day, concentrations of the PAH metabolites significantly increased from pre- to post-shift for 88% (37/42) of the comparisons (P -values <0.05). Additionally, median post-shift creatinine-corrected concentrations of 2-hydroxynaphthalene exceeded the 95th percentile of the nonsmoking US general population in 67% (4/6) of comparisons. Post-shift concentrations of hydroxynaphthalenes also exceeded concentrations measured in structural firefighters responding to training fires. Overall, 2-hydroxynaphthalene was highest on Day 2 (median creatinine-corrected concentrations of 2-hydroxynaphthalene from pre- to post-shift increased 425% for crew member/overhead; 146% for saw team). Despite this finding, we did not observe significant differences by job position. However, future studies could evaluate how job position affects WFF exposures while also exploring how dermal and inhalation contribute to WFFs' PAH exposure burden.

Keywords: biomonitoring; naphthalene; polycyclic aromatic hydrocarbons (PAHs); wildland firefighting

What's Important About This Paper?

Using urinary measures of polycyclic aromatic hydrocarbon (PAH) exposures, this study confirmed prior work that wildland firefighters are exposed to these toxic agents. Exposures to some PAH compounds were similar to what's been measured in structural firefighters. Future studies should evaluate the relative contribution of dermal and inhalation routes to PAH exposures, as the 2 routes require distinct control strategies.

Introduction

The occupation of firefighting, including wildland firefighting, was recently classified as a Group 1 Known Human Carcinogen by the International Agency for Research on Cancer (IARC), based on sufficient evidence of mesothelioma and bladder cancer in firefighters (Demers et al. 2022). Wildland firefighters (WFFs) are routinely exposed to wildfire smoke, which contains combustion byproducts including polycyclic aromatic hydrocarbons (PAHs) (Adetona et al. 2017). Naphthalene is a PAH and has been classified by IARC as a Group 2B Possible Human Carcinogen (IARC 2002). PAHs have also been found to be associated with adverse health effects including kidney damage and lung function abnormalities (Abdel-Shafy and Mansour 2016; Patel et al. 2020).

Currently, there is no National Fire Protection Association-compliant, National Institute for Occupational Safety and Health (NIOSH)-approved respiratory protection available to WFFs (Domitrovich et al. 2017). As such, inhalation exposure to PAHs and other combustion byproducts is a concern for WFFs. Recent studies have also shown that dermal exposure may contribute to the WFFs' PAHs body burden (Cherry et al. 2021, 2023). Several factors relevant to WFFs can increase the potential for dermal absorption of PAHs, including elevated skin temperature and sweat (Luo et al. 2020; Probert et al. 2024). Biomonitoring is needed to evaluate PAH exposure for all routes including inhalation and dermal.

Indeed, previous studies have found that WFFs' post-shift urinary mono-hydroxylated PAH metabolite (OH-PAH) concentrations increase significantly relative to their pre-shift concentrations (Adetona et al. 2017; Cherry et al. 2023). A recent study found that baseline (pre-fire) WFF OH-PAH concentrations were higher than general population median concentrations (Barros et al. 2024). Studies have also found that inhalation exposures for WFFs can vary by job position, (Reinhardt and Broyles 2019; Navarro et al. 2021, 2023) and a biomonitoring evaluation may help to better understand WFFs' potential exposure to PAHs based on job position. As such, we sought to evaluate exposure to PAHs, stratified by job position, for WFFs during a wildfire incident.

Methods

This assessment was conducted as part of the NIOSH Wildland Firefighter Exposure and Health Effects (WFFEHE) Study (Navarro et al. 2022). This analysis evaluated PAH exposure for an Interagency Hotshot Crew (IHC) of 19 WFFs at a wildfire incident near Salmon, Idaho in 2019. A detailed description of the entire study rationale, design, and methods were reported previously (Navarro et al. 2022, 2023). Briefly, consenting WFFs on the IHC operated in 3 different roles: crew member ($N = 9$), saw team ($N = 8$), and overhead ($N = 2$). Crew members performed ground level fire management tasks such as using hand tools to dig firelines, carrying drip torches to ignite fuels, etc. WFFs on a saw team used chainsaws to fell trees and remove brush. Overhead positions directed and oversaw WFFs performing operational tasks. WFFs participating in this study were nonsmokers. To account for small sample sizes when stratifying by job position, we grouped crew members and overhead because their job activities were similar. This study was reviewed and approved by the Centers for Disease Control and Prevention (CDC)/NIOSH Institutional Review Board (See 45 C.F.R. part 46; 21 C.F.R. part 56).

Two NIOSH industrial hygienists accompanied the IHC into the field and documented environmental conditions and work activities, including the use of personal protective equipment. To assess the biological uptake of PAHs, WFFs were asked to provide pre- and post-shift urine samples on 3 consecutive days. Overall, 114 urine samples were collected. Urine samples were shipped to CDC laboratories to be analyzed for creatinine and 7 OH-PAHs in 4 PAH biomarker categories: hydroxynaphthalenes (1-hydroxynaphthalene [1-NAP] + 2-hydroxynaphthalene [2-NAP]), hydroxyfluorenes (2-hydroxyfluorene [2-FLU] + 3-hydroxyfluorene [3-FLU]), hydroxyphenanthrenes (1-hydroxyphenanthrene [1-PHE] + 2-3-hydroxyphenanthrene [2-3PHE]), and 1-hydroxypyrene (1-PYR). Creatinine was measured using a Vitros Autoanalyzer (Ortho Clinical Diagnostic, Raritan, NJ). Most creatinine concentrations fell within 30–300 mg/dL (WHO 1996), except 4 samples that were excluded from all analyses. After enzymatic hydrolysis of conjugated OH-PAHs in 100 μ L of urine,

the 7 target OH-PAHs were quantified by online solid phase extraction coupled with high performance liquid chromatography-isotope dilution tandem mass spectrometry (Wang et al. 2017). The limit of detection (LOD) ranged from 0.008 to 0.09 µg/L, depending on the OH-PAH metabolite. Replicate samples were split from 5% of the samples and analyzed separately for quality assurance, and the replicates met method performance criteria for creatinine (<10% coefficient of variation [CV]) and OH-PAHs (<15% CV).

Summary statistics are presented as geometric mean (GM), median, and range, stratified by metabolite, job position, and sampling time. Box and whisker plots with minimum, 25th percentile, median, 75th percentile, and maximum were generated by using differences of pre- and post-shift urinary concentrations, stratified by day and job position. For descriptive statistics, concentrations below the LOD were assigned values using the beta-substitution method (Ganser and Hewett 2010) conducted in R version 4.4.0 (R Core Team 2024). Only 2 samples had 1-hydroxypyrene concentrations <LOD (Table 1). All concentrations reported were creatinine-corrected.

Wilcoxon rank-sum test was carried out to determine urinary concentration differences of OH-PAH biomarkers between job positions on each day. Wilcoxon signed-rank test was used to examine whether the change in OH-PAH biomarker concentrations between pre- and post-shift by job position and day significantly differed from zero. All statistical tests were performed in SAS version 9.4 (SAS Institute, Cary, NC) and were 2-sided at the 0.05 significance level.

Results

The detailed assessment of specific job positions, sampling strategy, and personal air sampling results has been published previously (Navarro et al. 2023). Briefly, our field observations included that more smoke was present on Day 2 relative to Day 1 or Day 3. The WFFs did wear gloves and did not wear respiratory protection during their work, and soot was observed on their skin during the sampling period.

Though there did appear to be marginal differences in PAH exposures by job position, no significant differences were found for any of the OH-PAH metabolites measured (all *P*-values > 0.05, results not shown). This was true for each individual OH-PAH metabolite (Table 1) and when grouped by their parent compound (Fig. 1). Concentrations increased from pre- to post-shift for all WFF samples combined across the 3 days.

When stratified by job position and day, we observed significant increases from pre-to post-shift for most (88% or 37/42) comparisons (Table 1). Overall, OH-PAH metabolite creatinine-corrected

concentrations were highest on Day 2. Specifically, the largest change from pre-to post-shift was observed for 2-NAP on Day 2 (median concentrations increased 425% from pre-to post-shift for crew member/overhead; median concentrations increased 146% from pre-to post-shift for saw team; Table 1).

Additionally, post-shift median creatinine-corrected concentrations of 1-NAP (once), 2-NAP (4 times), and 1-PYR (twice) exceeded the 95th percentile from the 2015 to 2016 National Health and Nutrition Examination Survey (NHANES) for nonsmokers on at least 1 day (Table 1). Post-shift median creatinine-corrected concentrations for the other OH-PAH metabolites never exceeded the NHANES nonsmokers 95th percentiles. However, maximum post-shift concentrations (across all sample days) exceeded this percentile for every OH-PAH metabolite measured. 1-PYR also has a biological exposure index (BEI) of 2.5 µg/L (not corrected for creatinine; ACGIH 2024). No 1-PYR urine concentrations from this study were above 2.5 µg/L. ACGIH recommends the BEI for 1-PYR be adjusted for benzo(a)pyrene but we did not characterize benzo(a)pyrene exposure in this evaluation.

Discussion

Among WFFs during a wildfire incident, we observed significant increases in OH-PAH metabolite urinary concentrations from pre-to post-shift across 3 days. Results from this study suggest that WFFs can experience higher exposure to PAHs during their work shifts than the general population, regardless of their job position.

Navarro et al. (2023) reported that on Day 2, the IHC conducted a firing operation, which included crewmembers igniting fuels (unburned vegetation) to create a break in fuel between the main fire and the control lines. Day 2 was also when the most smoke was observed where WFFs were working. Navarro et al. (2023) also characterized personal air concentrations of naphthalene and found they were not elevated on Day 2 relative to Day 1 or Day 3 (Navarro et al. 2023). By contrast, our urinary results suggest that exposure to PAHs (in particular 2-NAP) was highest on Day 2. Considering the relatively low air concentrations of naphthalene and the fact that soot was observed on WFFs' skin (including on their hands and arms), it is likely that dermal absorption contributed to the WFFs' exposures, possibly during activities like mop up (removing partially burnt materials/extinguishing smoldering vegetation by covering with dirt). Previous studies show that naphthalene is the most prevalent PAH detected on skin wipes collected from WFFs (Cherry et al. 2023; Broznitsky et al. 2024).

Table 1. Pre- and post-shift urinary concentrations ($\mu\text{g/g}$ creatinine) of OH-PAH metabolites collected from WFFs, stratified by position and sampling day.

Metabolite	Job position	Sampling day	N (N below the limit of detection [LOD])	GM	Median	Range	General population 95th Percentile (nonsmokers) ^A	P-value ^B (pre vs post for each day)
1-NAP	All WFFs	Pre (All days)	57 (0)	1.87	1.97	0.09–40.27	9.85	NC
		Post (All days) ^C	52 (0)	5.41	5.05	0.74–27.05		
	Crew member/overhead	Pre Day 1	11 (0)	0.81	0.85	0.09–14.02	19.7	Reference
		Post Day 1	11 (0)	3.18	2.99	0.74–15.71		0.0020
		Pre Day 2	11 (0)	1.82	2.20	0.57–4.08		Reference
		Post Day 2 ^C	9 (0)	6.96	5.06	3.03–27.05		0.0039
		Pre Day 3	11 (0)	1.90	2.14	0.78–3.90		Reference
		Post Day 3	9 (0)	3.62	3.62	1.47–17.82		0.0078
	Saw team	Pre Day 1	8 (0)	1.55	1.07	0.22–40.27		Reference
		Post Day 1	8 (0)	9.64	10.58	6.20–13.38		0.4609
		Pre Day 2	8 (0)	4.48	5.02	1.81–6.85		Reference
		Post Day 2	8 (0)	9.73	9.09	4.98–16.96		0.0156
		Pre Day 3	8 (0)	3.00	3.21	1.08–6.55		Reference
		Post Day 3	7 (0)	4.00	4.22	2.63–5.96		0.8125
2-NAP	All WFFs	Pre (All Days)	57 (0)	8.88	8.70	0.57–85.21	19.7	NC
		Post (All Days) ^C	52 (0)	23.88	21.55	4.57–171.5		
	Crew member/overhead	Pre Day 1	11 (0)	7.04	8.00	0.57–31.51	0.695	Reference
		Post Day 1	11 (0)	23.69	24.22	4.57–171.5		0.0049
		Pre Day 2	11 (0)	10.92	8.87	4.05–85.21		Reference
		Post Day 2 ^C	9 (0)	31.76	46.61	9.15–148.7		0.0039
		Pre Day 3	11 (0)	8.75	7.20	2.11–28.8		Reference
		Post Day 3	9 (0)	15.98	14.41	5.45–59.41		0.0078
	Saw team	Pre Day 1	8 (0)	7.15	11.10	1.21–24.76		Reference
		Post Day 1	8 (0)	27.73	20.11	13.63–69.26		0.0078
		Pre Day 2	8 (0)	11.57	10.31	5.24–37.02		Reference
		Post Day 2	8 (0)	28.71	25.37	11.98–79.58		0.0156
		Pre Day 3	8 (0)	8.91	8.06	2.02–33.99		Reference
		Post Day 3	7 (0)	19.21	17.83	10.8–53.18		0.0781
2-FLU	All WFFs	Pre (All Days) ^C	56 (0)	0.16	0.17	0.02–0.47	0.695	NC
		Post (All Days)	53 (0)	0.41	0.4	0.14–1.43		
	Crew member/overhead	Pre Day 1	11 (0)	0.12	0.15	0.02–0.28	0.695	Reference
		Post Day 1	11 (0)	0.28	0.25	0.14–0.98		0.0049
		Pre Day 2	11 (0)	0.15	0.17	0.07–0.33		Reference
		Post Day 2	10 (0)	0.48	0.42	0.28–1.43		0.0039
		Pre Day 3 ^C	10 (0)	0.18	0.19	0.07–0.47		Reference
		Post Day 3	9 (0)	0.35	0.35	0.16–0.76		0.0156

Table 1. Continued

Metabolite	Job position	Sampling day	N (N below the limit of detection [LOD])	GM	Median	Range	General population 95th Percentile (nonsmokers) ^A	P-value ^B (pre vs post for each day)
3-FLU	Saw team	Pre Day 1	8 (0)	0.13	0.15	0.04–0.37	0.331	Reference
		Post Day 1	8 (0)	0.47	0.47	0.20–0.83		0.0078
		Pre Day 2	8 (0)	0.26	0.28	0.17–0.36		Reference
		Post Day 2	8 (0)	0.59	0.53	0.34–1.11		0.0078
		Pre Day 3	8 (0)	0.21	0.27	0.07–0.38		Reference
		Post Day 3	7 (0)	0.46	0.40	0.33–0.67		0.0313
	All WFFs	Pre (All Days) ^C	56 (0)	0.10	0.11	0.01–0.39	0.331	NC
		Post (All Days) ^C	52 (0)	0.23	0.22	0.05–0.58		
	Crew member/overhead	Pre Day 1	11 (0)	0.06	0.07	0.01–0.21	0.307	Reference
		Post Day 1	11 (0)	0.14	0.15	0.05–0.56		0.0049
		Pre Day 2	11 (0)	0.09	0.11	0.03–0.23		Reference
		Post Day 2	10 (0)	0.27	0.26	0.16–0.58		0.0020
		Pre Day 3 ^C	10 (0)	0.14	0.15	0.06–0.39		Reference
		Post Day 3 ^C	8 (0)	0.25	0.25	0.13–0.51		0.0234
1-PHE	Saw team	Pre Day 1	8 (0)	0.07	0.06	0.02–0.33	0.307	Reference
		Post Day 1	8 (0)	0.21	0.23	0.10–0.38		0.0391
		Pre Day 2	8 (0)	0.15	0.14	0.10–0.30		Reference
		Post Day 2	8 (0)	0.29	0.31	0.18–0.53		0.0078
		Pre Day 3	8 (0)	0.14	0.17	0.05–0.25		Reference
		Post Day 3	7 (0)	0.27	0.27	0.16–0.40		0.0313
	All WFFs	Pre (All Days)	57 (0)	0.10	0.12	0.01–0.4	0.307	NC
		Post (All Days)	53 (0)	0.21	0.21	0.06–0.91		
	Crew member/overhead	Pre Day 1	11 (0)	0.07	0.10	0.01–0.26	0.374	Reference
		Post Day 1	11 (0)	0.15	0.11	0.06–0.67		0.0186
		Pre Day 2	11 (0)	0.10	0.11	0.04–0.18		Reference
		Post Day 2	10 (0)	0.21	0.18	0.11–0.64		0.0059
		Pre Day 3	11 (0)	0.10	0.12	0.04–0.31		Reference
		Post Day 3	9 (0)	0.19	0.21	0.10–0.35		0.0039
	Saw Team	Pre Day 1	8 (0)	0.08	0.10	0.02–0.35	0.374	Reference
		Post Day 1	8 (0)	0.26	0.27	0.11–0.61		0.0391
		Pre Day 2	8 (0)	0.17	0.16	0.11–0.34		Reference
		Post Day 2	8 (0)	0.26	0.24	0.11–0.91		0.0781
		Pre Day 3	8 (0)	0.12	0.14	0.03–0.40		Reference
		Post Day 3	7 (0)	0.26	0.23	0.20–0.50		0.0313
2-3PHE	All WFFs	Pre (All Days)	57 (0)	0.12	0.12	0.01–0.4	0.374	NC
		Post (All Days)	53 (0)	0.30	0.30	0.08–1.08		
	Crew member/overhead	Pre Day 1	11 (0)	0.08	0.09	0.01–0.22	0.374	Reference
		Post Day 1	11 (0)	0.20	0.18	0.08–0.70		0.0020

Table 1. Continued

Metabolite	Job position	Sampling day	N (N below the limit of detection [LOD])	GM	Median	Range	General population 95th Percentile (nonsmokers) ^A	P-value ^B (pre vs post for each day)
1-PYR	Saw team	Pre Day 2	11 (0)	0.12	0.12	0.04–0.22	0.420	Reference
		Post Day 2	10 (0)	0.36	0.29	0.2–1.08		0.0020
		Pre Day 3	11 (0)	0.14	0.14	0.07–0.40		Reference
		Post Day 3	9 (0)	0.32	0.30	0.21–0.58		0.0039
		Pre Day 1	8 (0)	0.07	0.09	0.02–0.19		Reference
		Post Day 1	8 (0)	0.29	0.35	0.09–0.53		0.0156
		Pre Day 2	8 (0)	0.18	0.18	0.09–0.29		Reference
		Post Day 2	8 (0)	0.38	0.36	0.21–0.78		0.0078
		Pre Day 3	8 (0)	0.15	0.15	0.05–0.40		Reference
		Post Day 3	7 (0)	0.35	0.38	0.21–0.68		0.0313
	All WFFs	Pre (All Days)	57 (2)	0.16	0.16	0.02–0.61		NC
		Post (All Days)	53 (0)	0.36	0.35	0.11–0.97		
	Crew member/ overhead	Pre Day 1	11 (1)	0.11	0.15	0.02–0.41	0.420	Reference
		Post Day 1	11 (0)	0.27	0.30	0.11–0.97		0.0049
		Pre Day 2	11 (0)	0.17	0.17	0.06–0.45		Reference
		Post Day 2	10 (0)	0.34	0.28	0.19–0.95		0.0098
		Pre Day 3	11 (0)	0.17	0.17	0.08–0.47		Reference
		Post Day 3	9 (0)	0.33	0.32	0.16–0.94		0.0039
	Saw team	Pre Day 1	8 (1)	0.09	0.10	0.03–0.16		Reference
		Post Day 1	8 (0)	0.42	0.46	0.19–0.82		0.0078
		Pre Day 2	8 (0)	0.27	0.27	0.16–0.61		Reference
		Post Day 2	8 (0)	0.46	0.51	0.26–0.93		0.0547
		Pre Day 3	8 (0)	0.24	0.25	0.10–0.44		Reference
		Post Day 3	7 (0)	0.40	0.37	0.24–0.66		0.0469

Abbreviations: NC = Not calculated, µg/g creatinine = micrograms per gram creatinine, OH-PAH = mono-hydroxylated polycyclic aromatic hydrocarbon metabolite, N = Number of samples, GM = Geometric mean, 1-NAP = 1-Hydroxynaphthalene, 2-NAP = 2-Hydroxynaphthalene, 2-FLU = 2-Hydroxyfluorene, 3-FLU = 3-Hydroxyfluorene, 1-PHE = 1-Hydroxyphenanthrene, 2-3PHE = 2-3-Hydroxyphenanthrene, 1-PYR = 1-Hydroxypyrene.

A. The NHANES 95th percentiles are determined from the 2015 to 2016 NHANES cycle for people aged 18–49 years for nonsmokers.

B. Wilcoxon signed-rank tests were used to examine whether the change in PAH concentrations between pre- and post-shift by job position and day significantly differs from zero. Significant results are bolded.

C. An interfering substance was present in one sample. That sample was removed from analyses.

Adetona et al. (2017) characterized urinary concentrations of several OH-PAH metabolites before and after conducting wildland firefighting activity on prescribed burns (intentionally set fires for resource management). Our study found higher post-shift GM concentrations compared to Adetona et al. (2017) for 2-NAP (Adetona GM = 12.1 µg/g creatinine) and lower GMs for the other OH-PAH metabolites including 1-NAP (Adetona GM = 8.82 µg/g creatinine), 2-FLU (Adetona GM = 1.49 µg/g creatinine), 3-FLU (Adetona GM = 0.426 µg/g creatinine), 1-PHE (Adetona GM

= 0.557 µg/g creatinine), and 1-PYR (Adetona GM = 0.576 µg/g creatinine).

Post-shift urinary concentrations of hydroxynaphthalenes in this study also exceeded median concentrations when compared to structural firefighters after they performed firefighting activities in a live-fire training environment (Mayer et al. 2023). Fent et al. (2020) also evaluated other OH-PAH metabolites in structural firefighters and reported that they had post-fire median concentrations of hydroxyfluorenes, hydroxyphenanthrenes, and 1-PYR above those found

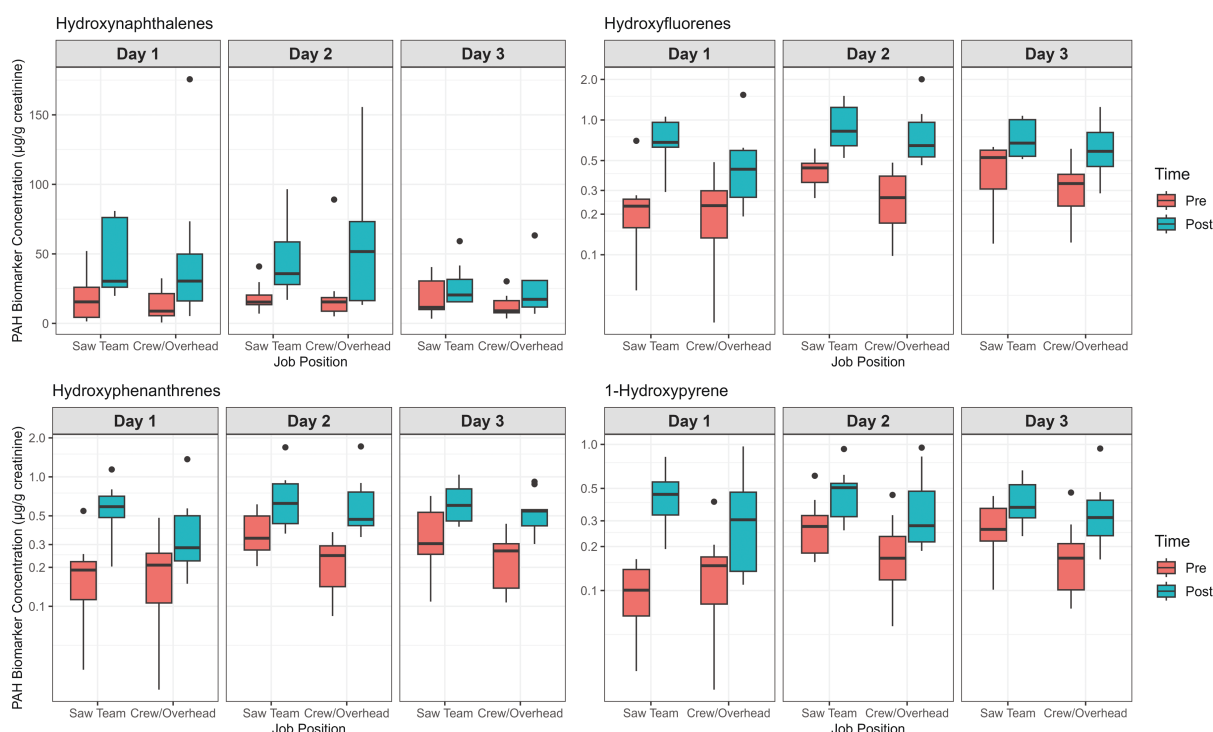


Fig. 1. Pre- and post-shift creatinine-corrected urinary concentrations of hydroxynaphthalenes (1-NAP + 2-NAP), hydroxyfluorenes (2-FLU + 3-FLU), hydroxyphenanthrenes (1-PHE + 2-3PHE), and 1-hydroxypyrene (1-PYR) for each sampling day, stratified by job position. The box represents the interquartile range (IQR) and the line in each box represents the median. The upper whisker represents the far upper fence 1.5 IQR above the 75th percentile, the lower whisker represents the lower fence 1.5 IQR below the 25th percentile, and the dots represent outliers.

in the current study. This could be an artifact of the difference in fuels for wildland fires and structural fires. It is important to note that structural firefighters in all of these other studies wore self-contained breathing apparatus; the WFFs in the present study did not wear any respiratory protection. Dermal exposures were not evaluated in the WFFs from the current study, but soot was observed on their skin on all 3 days. Overall these findings, along with the results from [Adetona et al. \(2017\)](#), suggest that 2-NAP levels in the current study were elevated relative to what has previously been characterized in the literature for other USA WFFs and even structural firefighters.

A potential limitation of this study is that we did not characterize the biological absorption (ie urinary concentrations) of volatile organic compounds, including toluene, ethylbenzene, and xylenes, that were measured in the air during this wildfire event ([Navarro et al. 2023](#)). We began sampling in the middle of the wildland season, so pre-shift samples on Day 1 could have been impacted by previous exposures from the season or from dietary intake (eg char-grilled foods).

We grouped crew and overhead firefighters together even though their exposures may vary. We also did not evaluate dermal exposure to PAHs. Future studies could characterize VOC exposures for WFFs, evaluate dermal exposure to PAHs, and further assess how job position affects exposure to better understand WFFs' overall exposure burden.

Conclusions

WFFs come into contact with and absorb PAHs while performing their duties resulting in PAH biomarker concentrations that can exceed those in the general population. No significant differences were observed by job position. The current study reveals a significant increase in urinary concentrations of 7 PAH metabolites among WFFs from pre- to post-shift. Together, these findings suggest that, in addition to inhalation, dermal absorption may contribute to WFFs' exposures to PAHs. WFFs could prioritize skin decontamination efforts (eg decontamination wipes after mop up) to reduce exposures.

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Disclaimer

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

References

Abdel-Shafy H, Mansour M. 2016. A review on polycyclic aromatic hydrocarbons: source, environmental impact, effect on human health and remediation. *Egypt J Pet.* 25:107–123. <https://doi.org/10.1016/j.ejpe.2015.03.011>

American Conference of Governmental Industrial Hygienists (ACGIH). 2024. Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices; American Conference of Governmental Industrial Hygienists: Cincinnati, OH, USA.

Adetona OS, et al. 2017. Hydroxylated polycyclic aromatic hydrocarbons as biomarkers of exposure to wood smoke in wildland firefighters. *J Expo Sci Environ Epidemiol.* 27:78–83. <https://doi.org/10.1038/jes.2015.75>

Barros B, et al. 2024. Baseline data and associations between urinary biomarkers of polycyclic aromatic hydrocarbons, blood pressure, hemogram, and lifestyle among wildland firefighters. *Front Public Health.* 12:1338435. <https://doi.org/10.3389/fpubh.2024.1338435>

Broznitsky N, et al. 2024. A field investigation of 3 masks proposed as respiratory protection for wildland firefighters: a randomized controlled trial in British Columbia, Canada. *Ann Work Expo Health.* 68:906–918. <https://doi.org/10.1093/annweh/wxae073>

Cherry N, et al. 2021. Exposure and absorption of PAHs in wildland firefighters: a field study with pilot interventions. *Ann Work Expo Health.* 65:148–161. <https://doi.org/10.1093/annweh/wxaa064>

Cherry N, et al. 2023. Exposures to polycyclic aromatic hydrocarbons and their mitigation in wildland firefighters in two Canadian provinces. *Ann Work Expo Health.* 67:354–365. <https://doi.org/10.1093/annweh/wxac085>

Demers PA, et al. 2022. Carcinogenicity of occupational exposure as a firefighter. *Lancet Oncol.* 23:985–986. [https://doi.org/10.1016/S1470-2045\(22\)00390-4](https://doi.org/10.1016/S1470-2045(22)00390-4)

Domitrovich J et al. 2017. Final report: wildland fire smoke health effects on wildland firefighters and the public. Book final report: wildland fire smoke health effects on wildland firefighters and the public. J. F. S. Program. Boise, ID. https://www.firescience.gov/projects/13-1-02-14/project/13-1-02-14_final_report.pdf

Fent KW, et al. 2020. Firefighters' absorption of PAHs and VOCs during controlled residential fires by job assignment and fire attack tactic. *J Expo Sci Environ Epidemiol.* 30:338–349. <https://doi.org/10.1038/s41370-019-0145-2>

Ganser G, Hewett P. 2010. An accurate substitution method for analyzing censored data. *J Occup Environ Hyg.* 7:233–244. <https://doi.org/10.1080/15459621003609713>

International Agency for Research on Cancer (IARC). 2002. International Agency for Research on Cancer (IARC) monographs volume 82: naphthalene. Lyon, France.

Luo K, et al. 2020. Dermal bioaccessibility and absorption of polycyclic aromatic hydrocarbons (PAHs) in indoor dust and its implication in risk assessment. *Environ Pollut.* 264:114829. <https://doi.org/10.1016/j.envpol.2020.114829>

Mayer A, et al. 2023. Evaluating exposure to VOCs and naphthalene for firefighters wearing different PPE configurations through measures in air, exhaled breath, and urine. *Int J Environ Res Public Health.* 20:12. <https://doi.org/10.3390/ijerph20126057>

Navarro K, et al. 2022. The Wildland Firefighter Exposure and Health Effect (WFFEHE) study: rationale, design, and methods of a repeated-measures study. *Ann. Work Expo. Health.* 66:714. <https://doi.org/10.1093/annweh/wxab117>

Navarro K, et al. 2023. Characterization of inhalation exposures at a wildfire incident during the Wildland Firefighter Exposure and Health Effects (WFFEHE) Study. *Ann. Work Expo. Health.* 67:1011–1017. <https://doi.org/10.1093/annweh/wxad046>

Navarro K, et al. 2021. Exposure to particulate matter and estimation of volatile organic compounds across wildland firefighter job tasks. *Environ Sci Technol.* 55:11795. <https://doi.org/10.1021/acs.est.1c00847>

- Patel A, Shaikh S, Jain K, Desai C, Madamwar D. 2020. Polycyclic aromatic hydrocarbons: sources, toxicity, and remediation approaches. *Front Microbiol.* 11:562813. <https://doi.org/10.3389/fmicb.2020.562813>
- Probert C, Nixon E, Ormond R, Baynes R. 2024. Percutaneous absorption of fireground contaminants: naphthalene, phenanthrene, and benzo[a]pyrene in porcine skin in an artificial sweat vehicle. *Toxics.* 12:588. <https://doi.org/10.3390/toxics12080588>
- R Core Team. 2024. R: A language and environment for statistical computing; R foundation for statistical computing. Vienna, Austria. <https://www.R-project.org/>
- Reinhardt T, Broyles G. 2019. Factors affecting smoke and crystalline silica exposure among wildland firefighters. *J Occup Environ Hyg.* 16:151–164. <https://doi.org/10.1080/15459624.2018.1540873>
- Wang Y, et al. 2017. Quantification of urinary mono-hydroxylated metabolites of polycyclic aromatic hydrocarbons by on-line solid phase extraction-high performance liquid chromatography-tandem mass spectrometry. *Anal Bioanal Chem.* 409:931–937. <https://doi.org/10.1007/s00216-016-9933-x>
- World Health Organization (WHO). 1996. Biological monitoring of chemical exposure in the workplace. World Health Organization.