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Exposure to Perfluoroalkyl Substances in a Cohort of Women Firefighters and Office Workers in San Francisco

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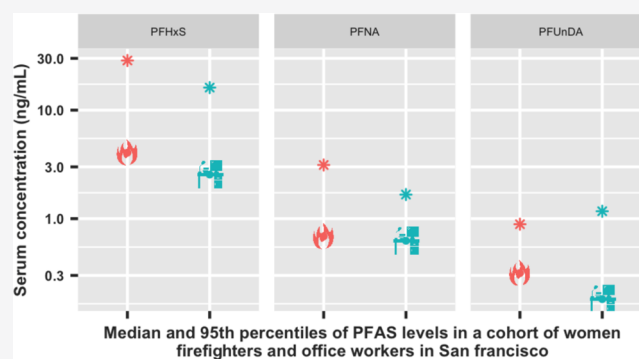


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ABSTRACT: Studies of firefighters have shown increased exposures to carcinogenic compounds and elevated rates of certain cancers compared to the general population, yet this research has focused almost exclusively on men. To address this gap, the Women Firefighters Biomonitoring Collaborative created a biological sample archive and analyzed levels of perfluoroalkyl substances (PFAS) among women firefighters ($N = 86$) and office workers ($N = 84$) in San Francisco. Serum samples were collected and analyzed using liquid chromatography–tandem mass spectrometry (LC–MS/MS) to measure and compare PFAS levels between firefighters and office workers. 7 of 12 PFAS congeners were detected in the least 70% of the study population, and 4 congeners were detected in 100% of participants. In regression models comparing PFAS levels by occupation and adjusting for potential confounders, firefighters had higher geometric mean concentrations of PFAS compared to office workers PFHxS (2.22 (95% CI = 1.55, 3.18)), PFUnDA (1.83 (95% CI = 0.97, 3.45)), and PFNA (1.26 (95% CI = 1.01, 1.58)). Among firefighters, occupational position predicted exposure—firefighters and officers had higher PFNA, PFOA, PFDA, and PFUnDA levels compared to drivers. Women firefighters are exposed to higher levels of some PFAS compared to office workers, suggesting that some of these exposures may be occupationally related.



INTRODUCTION

Firefighters have higher rates of some cancers compared to the general population. A meta-analysis of 32 studies found elevated rates of lymphoma, testicular, and prostate cancer among male firefighters.¹ Additionally, a review by the International Agency for Research on Cancer (IARC) found increased cancer rates among firefighters and designated the occupation of firefighting as “possibly carcinogenic” or “class 2b”.² More recently, a study of over 19 000 United States firefighters conducted by the National Institute for Occupational Health and Safety (NIOSH) found that total time spent at fires was associated with increased lung cancer incidence and mortality, and total number of fire responses was associated with leukemia mortality.³ Furthermore, studies in other countries have found increased rates of several cancers among male firefighters and other first responders including brain, thyroid, bladder, kidney, prostate, testicular, breast, digestive cancers, multiple myeloma, and non-Hodgkin’s lymphoma.^{4–10} Despite mounting concern about cancer among male firefighters, few studies have assessed chemical exposures or cancer risk among women firefighters, many of whom are concerned about the potential increased risk of breast cancer and other reproductive cancers. Only two studies have examined the incidence of cancer among women

firefighters. Daniels et al. found that women firefighters had higher incidence and mortality rates of breast cancer compared to the general U.S. population, though neither effect estimate was statistically significant.¹¹ A study of Florida firefighters found that women firefighters had an increase in overall cancer risk and, in particular, an increased incidence of Hodgkin’s disease and cervical and thyroid cancers compared to the general Florida population.⁹

Occupational exposures may be an important contributor to the increased risk of cancer among firefighters. Firefighters’ exposure to environmental chemicals may arise from fire suppression activities and during the salvage and overhaul phase of a fire event.^{12–16} Additionally, hazardous chemicals have been identified in fire station dust, firefighting foams, diesel emissions, contaminated fire equipment, and firefighter protective gear.^{17–21} Previous studies have shown that firefighters are occupationally exposed to polycyclic aromatic hydrocarbons,^{14,22–25} formaldehyde, dioxins, polybrominated

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diphenyl ethers (PBDEs), organophosphate flame retardants,^{26,27} and perfluoroalkyl substances (PFAS),^{20,26,28,29} among others.^{26,30,31} Many of these chemicals have been associated with adverse health outcomes including breast cancer and breast tumor development in both animal and human studies.^{32,33}

PFAS may be of particular relevance to firefighting because these compounds are used in turnout gear and are a major ingredient of some firefighting foams, such as aqueous film-forming foams (AFFF).^{20,29,34} More generally, PFAS chemicals are frequently applied to food contact paper, fabrics, and furniture to make them stain, water, and grease resistant.³⁵ PFAS have long half-lives and bioaccumulate in the environment and the human body.³⁶ Because of their widespread use and persistence, they have been detected in nearly everyone tested in large biomonitoring studies.^{37,38} Biomonitoring studies within the National Health and Nutrition Examination Survey (NHANES), a nationally representative sample of the U.S. population, have found that more than 98% of people tested had multiple congeners of PFAS detected in their bodies.³⁷

PFAS exposure has been linked to multiple adverse health outcomes including cancer, immune suppression, thyroid and sex hormone disruption, and decreased semen quality.^{39–42} Studies also indicate that exposure is associated with metabolic effects, ulcerative colitis, and adverse effects on liver and kidney function.^{43–46}

Several firefighter biomonitoring studies measured PFAS levels and found higher levels among firefighters compared to the general population.^{26,28,29} These studies, however, included few or no women. Overall, women remain under-represented in studies of firefighters, and very little is known about the extent of their chemical exposures or occupational health risks for diseases such as breast cancer.

Although women make up 5.1% of firefighters across the United States,⁴⁷ their numbers can be higher in urban jurisdictions, including in San Francisco, which has one of the highest proportions of women firefighters (15%) of any large urban fire department in the U.S.⁴⁸ As fire departments and other first responder professions diversify and recruit more women to their ranks, it is important to characterize chemical exposures and implications for health outcomes of particular relevance to women, such as breast cancer. To address this data gap, a partnership of firefighters, environmental health scientists, and environmental health advocates created the Women Firefighters Biomonitoring Collaborative (WFBC). The WFBC is a community-based, participatory biomonitoring project that aims to better understand how women firefighters are exposed to potential breast carcinogens, while also developing a biospecimen archive of women firefighters and office workers in San Francisco. As a part of the WFBC, we conducted a cross-sectional chemical biomonitoring study to compare levels of PFAS in human serum collected from women firefighters from the San Francisco Fire Department (SFFD) and nonfirefighter women, who are office workers for the City and County of San Francisco. To our knowledge, this is the first biomonitoring study to measure environmental chemical exposures in an exclusively female cohort of firefighters and office workers.

METHODS

Recruitment. Participant recruitment and sample collection took place between June 2014 and March 2015.

Firefighter partners of the WFBC assisted with the recruitment of both firefighter and office worker participants. To recruit firefighters, members of the United Fire Service Women (UFSW), the San Francisco Firefighters Cancer Prevention Foundation (SFFCPF), and the International Association of Firefighters, Local 798 sent out announcements through their listservs and newsletters. Firefighter members of the WFBC and study staff held informational meetings at firehouses and one-on-one to describe the study to potential participants. In addition, the SFFD supported recruitment efforts by sending the material through the department listserv and publishing an article about the study in the “The Mainline”, a department newsletter written and edited by both active and retired firefighters. Similarly, office workers, who were nonfirst responder employees of the City and County of San Francisco, were recruited at city offices via public meetings led by WFBC firefighters and study staff, tabling at health fairs, and through listserv emails targeting employees of the City and County of San Francisco.

Study inclusion criteria for both firefighters and office workers included being female, over 18 years old, a full-time employee, and a nonsmoker. In addition, firefighters needed to have at least 5 years of service with the SFFD and currently be on “active duty” (i.e., assigned to a fire station) at the time of recruitment. All participants were consented into the study following protocols approved by the Institutional Review Board of the University of California, Berkeley (# 2013-07-5512).

Exposure Assessment Interview. After consent and enrollment into the WFBC study, we conducted an hour-long in-person exposure assessment interview with each participant. The interview captured demographic information, basic health information, and possible sources of PFAS exposure from occupational activities, consumer product use, and dietary factors that prior literature indicates are potential sources of PFAS exposure.^{28,49,50} Food frequency responses were converted to times per week and categorized into quartiles, tertiles, or ever/never.

Sample Collection and Processing. Blood samples were collected by a certified phlebotomist in 10 mL additive-free glass tubes and transported in a cooler with ice for processing within 3 h of collection. The serum was separated by allowing clotting at room temperature, then centrifuging at 3000 rpm for 10 min. The serum was aliquoted into 1.2 mL cryo-vial tubes and stored at $-80\text{ }^{\circ}\text{C}$ until analysis per standard protocols.⁵¹ All samples were processed and analyzed at the University of California, San Francisco.

Laboratory Analysis. 12 PFAS (perfluorobutane sulfonic acid, PFBS; perfluorohexane sulfonic acid, PFHxS; perfluoroheptanoic acid, PFHpA; perfluorooctanoic acid, PFOA; perfluorooctane sulfonic acid, PFOS; perfluorooctane sulfonamide, PFOSA; perfluorononanoic acid, PFNA; perfluorodecanoic acid, PFDA; perfluoroundecanoic acid, PFUnDA; perfluorododecanoic acid, PFDoA; perfluorobutanoic acid, PFBA; and perfluorohexanoic acid, PFHxA) were selected for the analysis. The first 10 PFAS of this list were selected because they are also monitored in the NHANES so levels in our study can be compared with those in the US general population.⁵² The final two PFAS (PFBA and PFHxA) are not currently biomonitored and were included in the study because they are produced and used in the U.S. and because their structural similarity to the other commonly detected PFAS suggests that they may have similar health effects.⁵³ Congeners

were analyzed in each serum sample (0.5 mL) using liquid chromatography–tandem mass spectrometry (LC–MS/MS). An Agilent LC1260 (Sta. Clara, CA)–AB Sciex API 5500 (Foster City, CA) platform was used in the analysis. Prior to injection into the LC–MS/MS, each sample was prepared for analysis by solid-phase extraction using a Waters Oasis HLB cartridge (10 mg, 1 cm³). Extracted aliquots of each sample (25 μ L) were run in duplicates. The 12 analytes were separated by elution gradient chromatography using the Phenomenex Kinetex C18 column (100 \times 4.6 mm², 2.6 μ) at 40 °C. An electrospray ionization source operated in the negative mode was used to ionize each analyte in the mass spectrometer.

Analytes were detected in each sample by multiple reaction monitoring using two transitions per analyte. To determine the presence of each analyte, retention time matching (within 0.15 min) along with the peak area ratio between its qualifier and quantifier ions (within 20%) was used. Quantification of each detected analyte was done by the isotope dilution method using a 10-point calibration curve (0.02–50 ng/mL) and employing two C13-labeled PFAS isotopologues. The limits of quantification for the 12 analytes range from 0.05 to 0.1 ng/mL. Analyte identification from total ion chromatograms was evaluated using the AB Sciex Analyst v2.1 software, while quantification of each analyte was processed using the AB Sciex MultiQuant v2.02 software. Analysts were blinded to firefighter and office worker status of the serum samples during the analysis. Results were reported in ng/mL for all 170 study participants.

Statistical Analysis. We examined the distribution of each PFAS congener across the study population and then separately for firefighters and office workers and calculated summary statistics including geometric mean (GM), 95% confidence intervals (CI), and percentiles. As is common with environmental data, PFAS concentrations were non-normally distributed, thus we used nonparametric methods (Wilcoxon rank-sum test) to test unadjusted differences in PFAS concentrations between firefighters and office workers. We used lognormal regression analyses to assess differences in PFAS concentrations between firefighters and office workers, controlling for potential confounders. We then limited the analysis to firefighters and used lognormal regression analyses to explore the association between firefighter occupational activities and PFAS concentrations controlling for potential confounders. Congeners with at least a 70% detection frequency were included in the data analysis, and we used maximum likelihood estimation (MLE) with the NADA R package to account for left censored data (data below the limit of detection (LOD)) for all regression models.⁵⁴

Potential confounders were identified *a priori* based on the previous literature suggesting an independent relationship with PFAS levels. We assessed the relationship between each identified variable and PFAS levels in our data and tested differences between firefighters and office workers for each potential confounder. Variables were included in final regression models if there was a statistically significant association with PFAS levels in our data and if the variable demonstrated a statistically significant difference between firefighters and office workers (p -value \leq 0.05) for at least one PFAS congener.

We ran linear regression models to test the association between occupation and log-transformed PFAS concentrations controlling for age, race and ethnicity, and education (Model 1). A second model controlled for variables in Model 1 as well

as consumption frequency of fish and shellfish, red meat, poultry, fast-food or takeout food, and frozen food heated in paper or cardboard packaging (Model 2). Exponentiated β coefficients estimate the proportional change in the PFAS geometric means associated with being a firefighter compared to being an office worker and controlling for potential confounders.

We then limited our analysis to firefighters to evaluate the association between firefighter practices in the workplace with PFAS levels adjusting for age, race and ethnicity, and number of years of service with SFFD. Firefighter practices assessed included the use of self-contained breathing apparatus (SCBA) during salvage and overhaul, use of firefighting foam in the year prior to sample collection, and the participants' assigned position at the time of the questionnaire (firefighter, officer, and driver). Likewise, because airport fire stations are required to stock, test, and use PFAS-containing firefighting foam due to federal regulations, we included an indicator variable for those firefighters assigned to San Francisco Airport fire stations at the time of the study.⁵⁵ We also examined the relationship between PFAS concentrations and the frequency of hand washing during a work shift and showering after a fire event, as well as the relationship with responding to a fire within 24 h and 1 year prior to providing a biospecimen sample. Again, we exponentiated the β coefficient to obtain the proportional change in the PFAS geometric means associated with a unit change of each independent variable controlling for potential confounders.

Finally, we evaluated how PFAS levels in our study population compared with those measured in the general U.S. population and in firefighters in Southern California. Specifically, we plotted the geometric mean (GM) and 95% confidence interval from the WFBC firefighter and office worker groups and compared them to adult women from the 2013–2014 cycle of the NHANES and the Firefighter Occupational Exposure (FOX) study, in which samples were collected from a cohort of mostly male firefighters in Southern California between 2010 and 2011 ($N = 101$).^{28,52,56} WFBC firefighter and office worker levels below the LOD were replaced by the LOD reported for each congener divided by $\sqrt{2}$ to facilitate comparison of our results to the FOX and NHANES cohorts, which also used this approach (LOD/ $\sqrt{2}$).

All analyses were performed in R version 3.5.2 and R Studio 1.2.1335.^{57,58}

RESULTS

176 participants were recruited into the study. Six individuals (three firefighters and three office workers) met the study inclusion criteria and were interviewed, but did not provide a blood sample and therefore were excluded from the analysis. Our final study sample consisted of 86 firefighters and 84 office workers ($N = 170$) (Table 1).

Firefighters and office workers had similar demographic characteristics in terms of age and racial/ethnic make-up, while a significantly higher proportion of office workers was foreign-born, married, and had higher levels of educational attainment. Firefighters had an average of 17 years of service with the SFFD, while office workers had an average of 14 years of service with the City and County of San Francisco.

Occupational activities and characteristics of the firefighter group are shown in Table 2. The majority of participants were assigned to the position of the firefighter compared to officer or driver positions, and 14 firefighters were assigned to one of

Table 1. Demographic Characteristics of Firefighters and Office Workers in the Women Firefighters Biomonitoring Collaborative (2014–2015)^a

variables: mean \pm SD or N (%)	firefighters N = 86	office workers N = 84	p value ^b
age (years)	47.5 (\pm 4.6)	48.3 (\pm 10.5)	0.38
years working for SFFD or SF city and county	17.4 (\pm 4.2)	14.2 (\pm 10.1)	0.0005
U.S. born	77 (89.5%)	62 (73.8%)	0.01
race/ethnicity			
NH white	40 (46.5%)	37 (44.0%)	0.29
Latina/Hispanic	19 (22.1%)	13 (15.5%)	
NH Asian	11 (12.8%)	19 (22.6%)	
NH black	9 (10.5%)	5 (6.0%)	
NH other	7 (8.1%)	10 (11.9%)	
last grade completed			
some college or less	48 (55.8%)	15 (17.9%)	<0.0001
bachelors or higher	38 (44.2%)	69 (82.1%)	
marital status			
married	37 (43.0%)	47 (56.0%)	0.039
widowed	1 (1.2%)	2 (2.4%)	
separated/divorced	26 (30.2%)	11 (13.1%)	
never married	22 (25.6%)	24 (28.6%)	
reported yes, ever been pregnant	60 (70.6%)	52 (61.9%)	0.26
body mass index ^c			
healthy weight	33 (40.7%)	43 (52.4%)	0.13
overweight	35 (43.2%)	23 (28.0%)	
obese	13 (16.0%)	16 (19.5%)	

^aNH = non-Hispanic. ^bTo account for non-normally distributed variables, we used the Wilcoxon rank-sum test to compare continuous variables by firefighter status and the Fisher test for categorical variables. ^cCDC guidelines for BMI classification (lb/in²): healthy weight 18.5–24.9; overweight 25.0–29.9, obese > 30.

the San Francisco airport fire stations. 25 firefighters reported using firefighting foam in the year prior to the sample collection and when asked about the class of foam they used, most participants reported using class A or both class A and B foams. Over half of the participants reported rarely using their SCBA during salvage and overhaul activities after a fire. When asked about recent fires, most firefighters had not responded to a fire or participated in live-fire training in the 24 h prior to their biospecimen sample collection, while the SFFD fire history data indicated that most firefighters had 10 or more fires in the year prior to biospecimen collection.

Perfluoroalkyl Substance Exposures. Table 3 shows the LOD, detection frequency, GM (95% CI), and percentiles of each PFAS compound analyzed. Of the 12 PFAS we measured in participants' serum, 4 congeners were not detected in any of the study participants (PFBA, PFHxA, PFHpA, and PFOSA). 8 PFAS had measurable levels, 7 of which were detected in at least 70% of study participants and 4 were detected in 100% of study participants (PFHxS, PFNA, PFOA, and PFOS). We excluded PFDoA from further analyses since it was detected in fewer than 25% of study participants. Distributional comparisons of PFAS levels between WFBC firefighters and office workers for those compounds with detection frequencies of at least 70% are shown in Figure S1. Levels of PFNA, PFHxS, and PFUnDA were statistically significantly higher among the firefighter group compared to office workers.

Table 4 shows the results from multiple linear regression models assessing the relationship between log-transformed PFAS concentrations and occupation, comparing firefighters to

Table 2. Occupational Characteristics for WFBC Firefighters 2014–15 (N = 86)

variables	mean (\pm SD) or N (%)
frequency of hand washing while at work (times/shift)	18.8 (\pm 12.5)
frequency of hand washing while not at work (times/day)	10.3 (\pm 5.3)
reported using firefighting foam in the past year	25 (29.1%)
class of firefighting foam used (ever) ^a	
class A only	39 (45.3%)
class B only	6 (7.0%)
class A and B	28 (32.6%)
assigned to airport fire station	14 (16.3%)
response to fire in last 24 h ^b	15 (17.4%)
number of fires responded to in year prior to sample collection (N = 66) ^c	
\leq 9	17 (25.8%)
10–15	17 (25.8%)
16–19	15 (22.7%)
\geq 20	17 (25.8%)
assignment in the SFFD	
driver	21 (24.4%)
officer	25 (29.1%)
firefighter	40 (46.5%)
used self-contained breathing apparatus (SCBA) during salvage/overhaul ^d	
always/often	12 (15.0%)
sometimes	14 (17.5%)
rarely/never	54 (67.5%)

^aMissing data on the class of foam used for 13 firefighters. ^bIncludes fire response and training involving live fires. ^cIncludes firefighters, who consented to give access to SFFD fire history records (N = 66). ^dSix firefighters reported "do not participate" in salvage/overhaul.

office workers (referent) controlling for potential confounders (Tables S1 and S2). Multiple regression models found higher serum levels of PFHxS, PFUnDA, and PFNA among firefighters compared to office workers in both unadjusted and adjusted models. PFHxS levels were 2.22 (95% CI = 1.55, 3.18) times higher, PFUnDA levels were 1.83 (95% CI = 0.97, 3.45) times higher, and PFNA levels were 1.26 (95% CI = 1.01, 1.58) times higher in firefighters compared to office workers after adjusting for age, race and ethnicity, and education, as well as the frequency of consumption of fish/shellfish, red meat, poultry, fast-food, food heated in packaging.

When limiting our analysis to firefighters, we found that assigned firefighter position was associated with higher levels of 5 of the 7 PFAS (Table 5). Having the occupational position of firefighter or officer (versus driver) was associated with higher average serum levels of PFNA, PFOA, PFOS, PFDA, and PFUnDA, and lower levels of PFBS. Firefighters assigned to the airport had higher levels of PFNA than those assigned to other stations in the fire department. Likewise, firefighters who reported using firefighting foam in the year prior to the sample collection had elevated levels of several PFAS compared to those who reported not using foam in the past year.

Surprisingly, using SCBA, washing hands during a work shift and showering after a fire incident were associated with increased levels of some PFAS. Average PFNA, PFDA, and PFUnDA concentrations were higher among participants, who said that they sometimes used their SCBA during salvage/overhaul versus rarely or never. Similarly, average PFHxS levels were higher among participants, who said that they washed their hands more frequently or who responded that they always showered after a fire event compared to those who washed

Table 3. Geometric Mean (GM) and 95% Confidence Interval (CI), Detection Frequency (DF), Level of Detection (LOD) (ng/mL), and Percentiles^a for Each PFAS Analyzed in the WFBC Cohort^a

compound name	abbr.	DF %	LOD	GM (95% CI)	Min	Max	percentiles			
							25th	50th	75th	95th
perfluorohexane sulfonic acid	PFHxS	100	0.02	3.79 (3.24, 4.43)	0.22	90.57	1.87	3.04	6.79	22.28
perfluorooctanoic acid	PFOA	100	0.02	1.15 (1.05, 1.25)	0.29	5.18	0.83	1.11	1.56	3.22
perfluorooctane sulfonic acid	PFOS	100	0.02	4.11 (3.68, 4.59)	0.54	81.02	2.56	4.14	6.53	12.61
perfluorononanoic acid	PFNA	100	0.05	0.67 (0.61, 0.74)	0.15	4.49	0.42	0.64	1.03	2.2
perfluorodecanoic acid	PFDA	98	0.02	0.25 (0.23, 0.28)	<LOD	3.69	0.17	0.24	0.36	0.83
perfluoroundecanoic acid	PFUnDA	80	0.02	0.18 (0.14, 0.22)	<LOD	10.85	0.11	0.26	0.48	1.11
perfluorobutane sulfonic acid	PFBS	73	0.02	0.13 (0.10, 0.16)	<LOD	1.45	<LOD	0.23	0.34	0.84
perfluorododecanoic acid	PBDaA	24	0.02	^b	<LOD	1.73	<LOD	<LOD	<LOD	0.3
perfluorobutanoic acid	PFBA	0	0.05	^b	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
perfluorohexanoic acid	PFHxA	0	0.02	^b	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
perfluoroheptanoic acid	PFHpA	0	0.02	^b	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
perfluorooctane sulfonamide	PFOSA	0	0.02	^b	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD

^aPercentiles and summary statistics calculated using LOD/sqrt(2) for those with less than 100% detection frequency. ^bGM and 95% CI not calculated for PFAS with less than 70% DF.

Table 4. Unadjusted and Adjusted^{a,b} Proportional Change in Geometric Mean (95% Confidence Interval) of PFAS Concentrations by Firefighter Status (Office Worker as Referent), from Maximum Likelihood Estimation (MLE) Models

model	β Coef	exp β (95% CI)	p value
Perfluorononanoic Acid PFNA			
unadjusted	0.23	1.25 (1.03, 1.53)	0.0245
model 1 ^a	0.22	1.25 (1.01, 1.54)	0.0369
model 2 ^b	0.23	1.26 (1.01, 1.58)	0.0399
Perfluorooctanoic Acid PFOA			
unadjusted	-0.04	0.96 (0.81, 1.13)	0.6070
model 1 ^a	-0.02	0.98 (0.83, 1.18)	0.8666
model 2 ^b	0.07	1.07 (0.89, 1.30)	0.4730
Perfluorooctanoic Sulfonate PFOS			
unadjusted	0.09	1.10 (0.88, 1.36)	0.4097
model 1 ^a	0.15	1.16 (0.93, 1.45)	0.1887
model 2 ^b	0.10	1.10 (0.87, 1.40)	0.4334
Perfluorohexane Sulfonate PFHxS			
unadjusted	0.43	1.54 (1.14, 2.07)	0.0051
model 1 ^a	0.57	1.77 (1.29, 2.43)	0.0004
model 2 ^b	0.80	2.22 (1.55, 3.18)	0.0000
Perfluorodecanoic Acid PFDA			
unadjusted	0.13	1.14 (0.92, 1.43)	0.2324
model 1 ^a	0.09	1.10 (0.87, 1.39)	0.4420
model 2 ^b	0.14	1.15 (0.89, 1.49)	0.2947
Perfluorobutane Sulfonate PFBS			
unadjusted	0.17	1.19 (0.65, 2.18)	0.5731
model 1 ^a	0.30	1.35 (0.70, 2.59)	0.3710
model 2 ^b	0.36	1.43 (0.71, 2.91)	0.3192
Perfluoroundecanoic Acid PFUnDA			
unadjusted	0.55	1.74 (1.00, 3.02)	0.0496
model 1 ^a	0.48	1.61 (0.88, 2.97)	0.1236
model 2 ^b	0.60	1.83 (0.97, 3.45)	0.0623

^aModel 1 adjusted for: age, race/ethnicity, and education. ^bModel 2 adjusted for covariates in model 1 and consumption of: fish/shellfish, red meat, poultry, fast-food or takeout food, frozen food heated in paper or cardboard package. The office worker is the referent group.

hands or showered after a fire event the least often. Those who washed their hands 16–20 times during a work shift had 2.90 (95% CI = 1.61, 5.23) times higher concentration of PFHxS

compared to those who reported washing their hands 10 times or less per shift. Those who reported always showering after a fire event had 2.08 (95% CI = 1.04, 4.05) times higher PFHxS levels compared to those who reported that they sometimes showered.

Figure 1 compares PFAS levels measured in our WFBC participants with other cohorts, including adult women from the 2013–2014 NHANES⁵² and the predominantly male 2010–2011 FOX study.⁵⁶ WFBC firefighters and office workers had higher serum levels of PFHxS and a higher detection frequency for PFBS than both NHANES and FOX; while PFBS had low detection frequencies in both the FOX and NHANES studies (DF: 6.9 and 0.7%, respectively), the WFBC had a PFBS detection frequency of 74% for firefighters and 70% for office workers. WFBC firefighters also had higher levels of PFNA, PFDA, and PFUnDA levels compared to NHANES, whereas office workers had similar levels to NHANES for PFOS and PFNA. Both WFBC firefighter and office worker groups had lower levels of PFOA compared to NHANES and lower levels of PFOS, PFOA, PFNA, PFDA, and PFUnDA than those measured in the FOX study.

DISCUSSION

This biomonitoring study is the first to assess levels of PFAS compounds in an all-female cohort of firefighters and office workers. Of the 12 PFAS we measured, detection frequencies ranged from 0 to 100% and all participants had at least 4 PFAS congeners (PFHxS, PFOA, PFOS, and PFNA) detected in their serum samples. Widespread use of PFAS in consumer products, contamination of food and water sources, and their environmental persistence may contribute to the high background levels of these compounds in both firefighters and office workers. Indeed PFAS are ubiquitous in the environment and have been found in dust, food, and humans worldwide.^{35,59} In addition, the widespread use of PFAS-containing products on clothing, furniture fabrics, carpets, and paper food packaging also contributes to levels found in people.^{49,60} Drinking water contamination is considered an important source of PFAS exposure in many communities,^{49,61,62} and people with contaminated drinking water have elevated PFAS in their blood.⁶³ However, local San Francisco Bay Area water systems are not likely to be a significant source of PFAS exposure for WFBC study

Table 5. Adjusted Proportional Change in Geometric Mean (GM) of Covariates (95% CI) and Serum PFAS Concentration among Firefighters from Maximum Likelihood Regression (MLE) Models^a

variable	N	PFNA	PFOA	PFOA	PFOA	PFOA	PFOA	PFOA	PFOA	PFOA	PFHxS	PFDA	PFBS	PFUnDA
frequency of SCBA use during salvage/overhaul														
rarely/never	54	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
sometimes	14	1.90 (1.25, 2.87) [†]	1.19 (0.86, 1.64)	1.29 (0.88, 1.89)	0.75 (0.39, 1.47)	1.44 (1.02, 2.04) [†]	0.83 (0.25, 2.79)	reference	reference	reference	reference	reference	reference	3.64 (1.41, 9.39) [†]
often/always	12	1.47 (0.99, 2.18) [*]	0.99 (0.73, 1.35)	0.88 (0.61, 1.27)	0.59 (0.31, 1.12)	1.17 (0.84, 1.63)	0.46 (0.15, 1.48)	reference	reference	reference	reference	reference	reference	1.12 (0.45, 2.79)
used firefighting foam in the last year														
no	50	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
yes	25	1.29 (0.94, 1.79)	1.10 (0.86, 1.39)	1.19 (0.92, 1.54)	1.26 (0.79, 2.00)	1.08 (0.82, 1.41)	1.64 (0.64, 4.18)	reference	reference	reference	reference	reference	reference	1.23 (0.59, 2.56)
position in the fire department														
driver	21	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
officer	25	1.61 (1.13, 2.29) [†]	1.42 (1.07, 1.90) [†]	1.25 (0.90, 1.74)	0.98 (0.53, 1.79)	1.45 (1.05, 2.00) [†]	0.27 (0.09, 0.78) [†]	reference	reference	reference	reference	reference	reference	3.18 (1.34, 7.51) [†]
firefighter	40	2.12 (1.54, 2.93) [*]	1.42 (1.09, 1.85) [†]	1.26 (0.93, 1.70)	0.91 (0.53, 1.58)	1.47 (1.10, 1.97) [†]	0.54 (0.21, 1.41)	reference	reference	reference	reference	reference	reference	1.99 (0.91, 4.36) [†]
frequency of hand washing during a 24 h work shift (times/shift)														
≤10	21	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
11–15	24	0.92 (0.62, 1.36)	0.90 (0.66, 1.22)	0.87 (0.63, 1.20)	1.83 (1.03, 3.23) [†]	1.08 (0.77, 1.51)	0.81 (0.27, 2.43)	reference	reference	reference	reference	reference	reference	0.50 (0.20, 1.22)
16–20	20	1.02 (0.68, 1.53)	0.99 (0.72, 1.36)	1.20 (0.86, 1.67)	2.90 (1.61, 5.23) [†]	0.90 (0.63, 1.27)	0.77 (0.25, 2.40)	reference	reference	reference	reference	reference	reference	0.65 (0.26, 1.64)
>20	21	0.70 (0.46, 1.06) [*]	0.95 (0.69, 1.30)	0.74 (0.53, 1.03) [*]	1.42 (0.78, 2.58)	0.76 (0.53, 1.07)	2.13 (0.68, 6.62)	reference	reference	reference	reference	reference	reference	0.59 (0.23, 1.50)
frequency of washing and/or showering after an incident														
sometimes	11	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
always	75	0.79 (0.50, 1.26)	0.98 (0.69, 1.40)	0.91 (0.62, 1.35)	2.08 (1.04, 4.15) [†]	1.01 (0.68, 1.49)	0.52 (0.15, 1.83)	reference	reference	reference	reference	reference	reference	0.89 (0.32, 2.52)
assigned to the airport														
no	72	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
yes	14	2.26 (1.61, 3.19) [*]	1.00 (0.75, 1.35)	1.03 (0.74, 1.42)	0.61 (0.34, 1.08) [*]	1.05 (0.75, 1.45)	1.05 (0.75, 1.45)	reference	reference	reference	reference	reference	reference	2.04 (0.88, 4.73)
any fire in 24 h prior to sample collection														
no	71	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
yes	15	0.94 (0.64, 1.37)	0.95 (0.71, 1.27)	1.14 (0.83, 1.56)	1.48 (0.84, 2.63)	0.84 (0.61, 1.16)	1.68 (0.60, 4.74)	reference	reference	reference	reference	reference	reference	0.94 (0.40, 2.20)
number of fires in the year prior to the sample collection ^b														
≤9	17	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference	reference
10–15	17	0.80 (0.54, 1.19)	0.84 (0.60, 1.18)	0.98 (0.66, 1.44)	0.98 (0.50, 1.95)	1.04 (0.70, 1.54)	1.04 (0.70, 1.54)	reference	reference	reference	reference	reference	reference	0.50 (0.18, 1.40)
16–19	15	0.90 (0.60, 1.36)	1.04 (0.73, 1.48)	1.01 (0.67, 1.53)	1.32 (0.64, 2.69)	1.02 (0.68, 1.54)	1.02 (0.68, 1.54)	reference	reference	reference	reference	reference	reference	0.70 (0.24, 2.02)
≥20	17	0.64 (0.43, 0.97)	0.74 (0.52, 1.05)	0.72 (0.48, 1.08)	0.84 (0.41, 1.72)	0.78 (0.51, 1.18)	0.78 (0.51, 1.18)	reference	reference	reference	reference	reference	reference	0.72 (0.25, 2.09)

^aModels adjusted for race/ethnicity, age, and years of service with SFFD. ^bData from participants, who consented to grant access to their fire history from SFFD; *p value ≤ 0.1; [†]p value ≤ 0.05; [‡]p value ≤ 0.001.

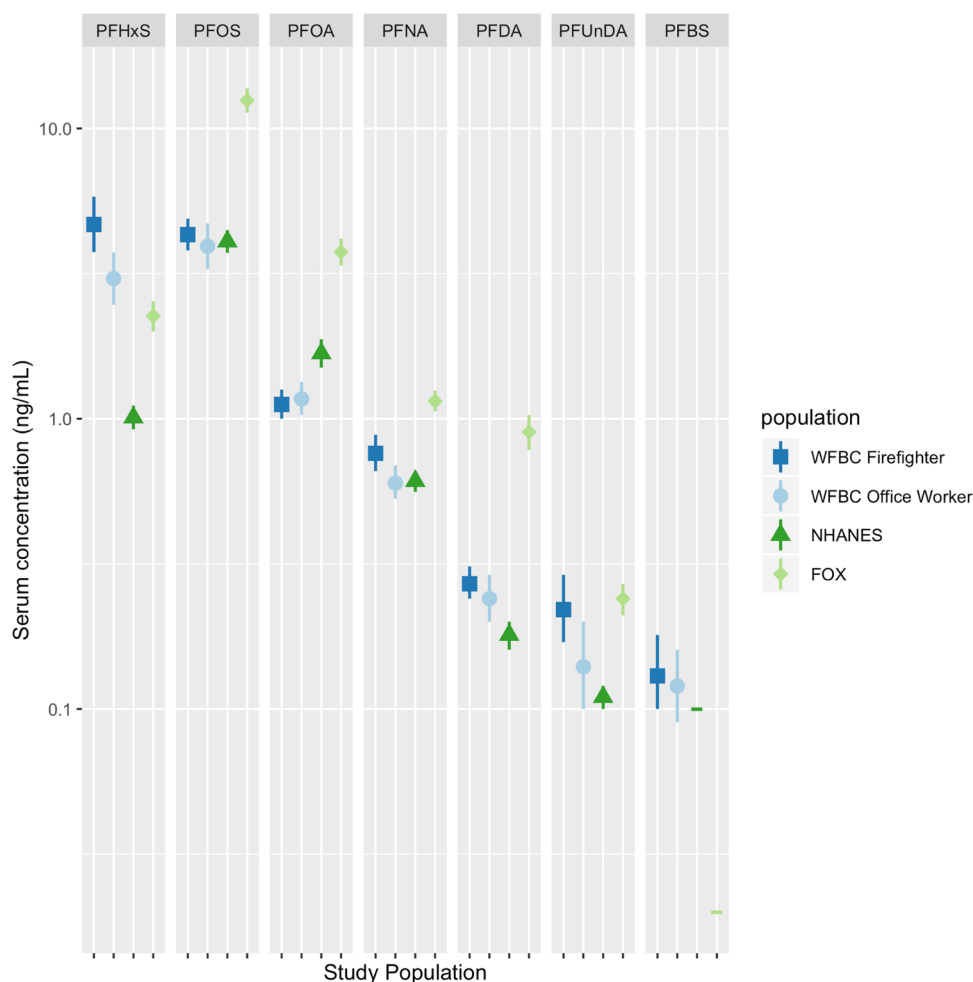


Figure 1. Comparison of geometric mean (GM) and 95% confidence intervals (CI) of PFAS levels measured in WFBC firefighters and office workers (2014–15) with adult women in NHANES (2013–14) and male firefighters in the FOX study (2010–11). Figure footnote: The figure shows GM and 95% CI for those PFAS with detection frequencies of at least 70% among WFBC participants. PFBS had low DF for FOX (6.9%) and NHANES (0.7%); therefore, we plotted the LOD, represented by horizontal green lines, in lieu of GM and 95% CI. We replaced levels below the LOD with $\text{LOD}/\sqrt{2}$ and applied the LOD respective to each study population. Tests of statistical significance for differences between WFBC groups are shown in Table 4.

participants. Municipal water systems in the locations where most study participants live were tested for PFAS under the Environmental Protection Agency's Unregulated Contaminant Monitoring Rule in 2016; tests of San Francisco Public Utilities Commission (SFPUC) water sources between 2012 and 2018 did not find measurable levels of PFBS, PFHxS, PFHPA, PFNA, PFOA, or PFOS in San Francisco or surrounding community municipal water systems.^{64,65}

Multivariate models showed that PFHxS, PFUnDA, and PFNA exposure was higher in firefighters compared to office workers after controlling for age, race and ethnicity, and education. When we additionally controlled for the frequency of eating certain foods, the association remained higher in firefighters compared to office workers and the strength of association increased or remained the same after adjustment for potential confounders. When we limited the analysis to firefighters, we found that several occupational activities were associated with higher PFAS levels. Firefighters' assigned position was the most strongly associated with higher PFAS levels, with those assigned as firefighters or officers having higher levels of PFNA, PFOA, PFDA, and PFUnDA compared to drivers. Compared to drivers, PFOS was higher among

those assigned to the firefighter position; however, PFBS was higher among drivers compared to officers. Differential PFAS exposures by position may be explained by different roles at fire events. Engine drivers typically remain with the apparatus because they supply water for initial interior fire suppression work, as well as set the ladders for ventilation procedures. In addition, drivers in the SFFD do not typically perform overhaul procedures after a fire is extinguished, and thus may avoid a critical source of exposure.⁶⁶ We did not find an association between PFAS levels and fighting a fire in the previous 24 h or with the number of fires in the year prior to sample collection.

Firefighting foams may be another important source of PFAS exposure. Aqueous film-forming foams (AFFFs) are known to contain PFAS surfactants, including PFOS, PFOA, and PFHxS.^{20,67} Our data suggest that firefighters who reported using firefighting foam in the past year had higher levels of several PFAS than those who reported not using firefighting foams in the past year. Among airport firefighters, we found that PFNA levels were 2 times higher compared to firefighters assigned to other stations in San Francisco. Although PFNA is not considered a main ingredient in

AFFF, a study in Finland found that firefighters using AFFF in training activities had increased levels of PFNA after the training activities.²⁰

Unexpectedly, procedures that generally are intended to reduce contaminant exposures were associated with increased exposures for some PFAS. Washing hands more frequently during the work shift and always showering after a fire event were associated with increased PFHxS levels, while sometimes using SCBA during salvage overhaul was associated with increased PFNA, PFDA, and PFUnDA. One explanation is that firefighters may differentially report hand washing, showering frequency, and SCBA use; those firefighters involved in more fire suppression activities could possibly report these activities more than those who respond to fewer fire calls because washing and SCBA use are expected occupational hygiene practices. Self-reporting bias in terms of occupational safety and health procedures, which has been shown in other studies,^{68,69} may have also affected our results. Similarly, duration of SCBA use during fire events may also be an important factor to examine in future studies, as it is possible that although firefighters may wear SCBA frequently, they may remove it after extinguishing a fire and during salvage and overhaul operations because gear is heavy, conditions are hot, and the location appears to be free of smoke.^{15,66} In addition, there may be unknown and unmeasured occupational sources of PFAS exposure in firefighting that could help explain observed associations.

We compared the levels of PFAS congeners in WFBC participants with levels from two other exposure studies: A cohort of mostly male firefighters in Southern California (FOX) and a nationally representative sample of adult women (NHANES). In general, WFBC firefighters and office workers had lower PFAS levels than those measured in the FOX study, except for PFHxS, which was significantly higher in both WFBC firefighters and office workers. In particular, the lower levels of PFOA and PFOS in the WFBC participants compared to NHANES and FOX may reflect the temporal trends associated with the phase-out of these compounds in consumer products and firefighting equipment. The FOX study samples were collected between 2010 and 2011, 3 years before the start of the WFBC study and during the phase-out period of PFOA and PFOS.⁷⁰ Studies have shown that PFAS levels have changed over time with many PFAS that have been phased out decreasing and their replacements increasing.^{37,38,71,72} Interestingly, we did see overall higher levels of PFHxS in both groups of WFBC participants collected in 2013–2014 relative to the 2010–2011 FOX cohort. The increased levels in WFBC participants may be due to PFHxS' long half-life (8.5 years) compared to PFOS (5.4 years) or PFOA (3.8 years).⁷³ In addition, there may be other sources of PFHxS exposures that continue to affect California residents overall.⁷¹ The elevated PFHxS levels among WFBC firefighters in relation to FOX participants may be due, in part, to its use as a replacement for PFOA and PFOS in firefighting foams.⁶⁷ Additionally, the lower levels of most PFAS among WFBC participants compared to the mostly male cohort of FOX participants may be further explained by excretion pathway differences between men and women, where women may have lower levels due to the binding affinity of PFAS with fatty acid-binding proteins of the blood thus increased excretion during menstruation.^{74,75}

WFBC and NHANES data were collected at around the same time (2013–14 for NHANES and 2014–15 for the

WFBC) and levels between WFBC and adult women of NHANES were more similar to each other than with the FOX study, where the FOX study had higher PFAS levels except for PFHxS and PFUnDA. However, PFHxS, PFDA, and PFBS levels were higher in WFBC firefighters and office workers compared to NHANES adult women. While we compared WFBC chemical levels to adult women in NHANES, due to our small sample size we did not consider other comparisons by factors such as occupation or race/ethnicity. The lower PFAS levels among WFBC and NHANES compared to FOX may be due in part to the aforementioned increased excretion of PFAS among women. The increased levels of PFBS among WFBC firefighters and office workers may indicate its use as a replacement of PFAS, while its relatively short half-life of approximately 25 days may indicate other common and occupational exposures to this compound.⁷⁶

Health effects observed in people exposed to PFOA include high cholesterol, ulcerative colitis, thyroid disease, testicular and kidney cancers, and pregnancy-induced hypertension.⁷⁷ PFOS exposure has also been associated with immunotoxicity, as indicated by a decreased response to vaccines in children,⁷⁸ and other studies of people exposed to PFAS show effects on liver and decreased birth weight.⁷⁹ In animal studies, PFAS have been shown to have a variety of similar toxicological effects including liver toxicity, suppressed immune function, altered mammary gland development, obesity, and cancer.^{80,81} The concordance between endpoints identified in animal studies and human studies, most notably effects on the liver, kidney, fetal growth, and development, and suppression of the immune system, add confidence to the findings.^{82,83} Based on these studies in humans and animals, some government agencies have established limits on allowable levels of PFOA and PFOS in drinking water.^{82,84} For PFOA, these benchmarks are designed to prevent people from having blood serum levels above 14 ng/mL.⁸⁵ The maximum value in this study was 5 ng/mL. However, PFOA has been shown to alter mammary gland development in mice following in utero exposure at even lower levels, and estimates of target serum levels to protect against those effects are less than 1 ng/mL.⁸⁵ The health effects of the other PFAS found in elevated levels in firefighters have not been well-studied and target serum concentrations that are expected to protect against adverse effects are not available for PFNA, PFBS, PFHxS, PFUnDA, so it is difficult to compare measured levels in firefighters with benchmarks intended to protect against health effects. Allowable daily intake amounts intended to protect against adverse health effects are in the same range as PFOA for PFNA, while for PFHxS they are about 10 times higher and for PFBS they are 100 times higher.⁸⁶ However, the higher allowable daily intakes for PFBS and PFHxS do not necessarily correspond to higher allowable serum levels for these chemicals. Instead, they reflect differences in the relationship between intake and serum concentration for each of the chemicals.

Our study has several limitations. There may still be unmeasured confounders and unknown sources of PFAS for which data was not possible to obtain. For example, while we were able to ask participants about their use of AFFF, we do not know the formulations of foam stocked and used in the SFFD. We also do not have information on the extent to which formulations have changed since PFOS and PFOA have been phased out or if existing stocks of AFFF in SFFD have been replaced with newer formulations. It was also difficult to assess the relationship between fire events and exposures. Since we

did not time the sample collection with fire events, very few firefighters had responded to a fire event in the 24 h prior to the sample collection. We were able to access historical fire event data from the fire department through the Human Resources Management System (HRMS) database, which allowed us to estimate the number of fires each firefighter had attended in the year prior to sample collection. However, this information was limited to participants who consented to giving us access to their HRMS ($N = 66$), which diminished statistical power to assess the relationship between fire events and chemical exposure levels. In addition, the HRMS data does not provide details about the intensity of the fire or the participant's assigned role at the fire event (e.g., whether the firefighter was involved in direct fire suppression activities or providing back up and support).

We used a community-based participatory research design that entailed the active involvement of firefighters to develop study protocols and recruit participants (both firefighters and office workers) into the study. By including office workers from the City and County of San Francisco, we were able to compare firefighter exposures to a working population of women who were not involved in firefighting activities, but who live and work in the same geographical region allowing us to examine which PFAS chemicals are most strongly associated with firefighting. Understanding the extent to which PFAS exposures differ between firefighters and office workers can elucidate which compounds are likely to have occupational sources, highlight opportunities for prevention strategies, and assess the effectiveness of workplace exposure reduction efforts.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.9b05490>.

Average (mean \pm SD) food consumption in times per week, and the percentage of study participants who ate that food item for firefighters and office workers (Table S1); mean PFAS concentration (ng/mL) for each category of food consumption for foods potentially associated with exposure (Table S2); distribution of PFAS with detection frequencies $>70\%$ among WFBC firefighters ($N = 86$) and office workers ($N = 84$) (Figure S1) (PDF)

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Notes

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