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Challenges and emerging issues on firefighter's toxic chemical exposure: Smoke chemicals, contaminated PPE, and off-gassing

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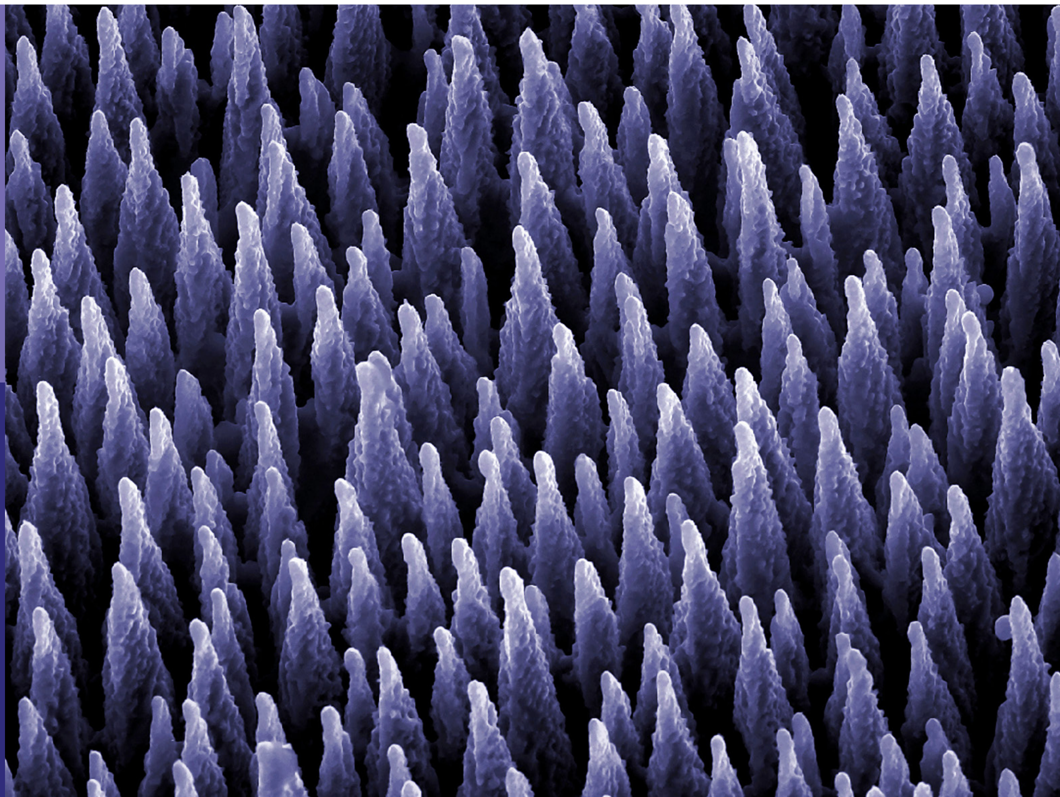
Published in
Frontiers in Materials
Frontiers in Oncology



ISSN 1664-8714
ISBN 978-2-8325-5166-0
DOI 10.3389/978-2-8325-5166-0

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Challenges and emerging issues on firefighter's toxic chemical exposure: Smoke chemicals, contaminated PPE, and off-gassing

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Citation
Song, G., Oliveira, M., Ormond, R. B., eds. (2024). *Challenges and emerging issues on firefighter's toxic chemical exposure: Smoke chemicals, contaminated PPE, and off-gassing*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-5166-0

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frontiers | Frontiers in Materials

TYPE Editorial
PUBLISHED 26 July 2024
DOI 10.3389/fmats.2024.1443259

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 03 June 2024
ACCEPTED 10 June 2024
PUBLISHED 26 July 2024

CITATION
Song G, Oliveira M and Ormond B (2024), Editorial: Challenges and emerging issues on firefighter's toxic chemical exposure: smoke chemicals, contaminated PPE, and off-gassing.
Front. Mater. 11:1443259.
doi: 10.3389/fmats.2024.1443259

Editorial: Challenges and emerging issues on firefighter's toxic chemical exposure: smoke chemicals, contaminated PPE, and off-gassing

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KEYWORDS

firefighter, contamination, PPE, toxic chemical, smoke, occupational exposure, health risks

Editorial on the Research Topic
Challenges and emerging issues on firefighter's toxic chemical exposure: smoke chemicals, contaminated PPE, and off-gassing

Introduction to the theme

This Research Topic delves into a pressing issue within the firefighting community: the exposure to toxic chemicals and its long-term health consequences for those at the forefront of firefighting emergencies. Under the theme "Challenges and Emerging Issues in Firefighters' Toxic Chemical Exposure: Smoke Chemicals, Contaminated Personal Protective Equipment (PPE), and Off-gassing," we aim to demystify the occupational dangers and advance a collaborative discourse among researchers, practitioners, and technologists to find tangible solutions. This initiative addresses the significant health hazards associated with smoke chemicals, contaminated PPE, and the off-gassing of equipment, seeking to bring clarity and actionable insights.

Context and background

Firefighters' bravery is undeniable, yet their battle against the silent enemy of toxic chemical exposure requires a thoughtful and informed response. Historically, firefighter safety has centered on immediate threats like burns and structural hazards. In 2022, the occupational activity as firefighter was classified as carcinogenic to humans by the International Agency for Research on Cancer. Yet, the chronic dangers of toxic chemical exposure, from the combustion at fire sites to contaminants on PPE, are now recognized as leading to serious health issues, such as cancer and cardio-respiratory diseases.

Firefighting personnel are routinely exposed to a complex array of harmful substances released during fires, including training exercises, and brought inside fire stations on contaminated PPE and firefighting tools and vehicles. The increased use of synthetic materials has escalated the risk, producing more dangerous particulates and chemicals like semi-volatile organic compounds (SVOCs) and volatile organic compounds (VOCs). This focus on smoke chemicals is crucial, as they represent a widespread danger.

The risk persists beyond the flames. PPE, intended for protection, can harbor fine toxic particles that compromise firefighter health during and after the incident. Such contamination highlights the urgency for stringent decontamination protocols.

The array of chemical hazards, including BETXs (benzene, ethylbenzene, toluene, and xylene), formaldehyde, and heavy metals, demonstrate the complexity of exposure and health risks. Furthermore, the scrutiny on per- and polyfluoroalkyl substances (PFAS) used in fire-resistant PPE and foams has unveiled significant health threats, emphasizing a systemic hazard that extends into the environment.

Overview of scholarly contributions

This Research Topic presents a series of nine meticulously researched articles that collectively enhance our understanding of the various health risks associated with firefighters' exposure to toxic chemicals. The contributions are thematically diverse yet interconnected, providing a holistic view of the topic. To facilitate a coherent synthesis, the articles are categorized into related research domains for a consolidated overview.

Cancer risks and biochemical pathways

Sweeney et al. An in-depth review focusing on the aryl hydrocarbon receptor (AhR) pathway reveals the complex role of environmental toxins in breast cancer, highlighting AhR as a pivotal element in cancer biology and offering insights into the environmental injustice of toxin exposure.

Lee et al. A meta-analysis that synthesizes data on cancer incidence and mortality, unearthing a correlation between firefighting and an elevated risk for certain cancers, advocating for improved cancer surveillance and longitudinal studies within the profession.

Mazumder et al. A critical examination of PFAS, their presence in firefighting gear and foams, and the consequential cancer risks, underpinning the urgent need for revisiting exposure risks and protective measures for firefighters.

Mental health and psychosocial dynamics

Cheng et al. Original research utilizing network analysis to dissect the relationship between PTSD and depression in Chinese firefighters, offering groundbreaking insights that could inform more nuanced mental health interventions.

Protective equipment and decontamination

Girase et al. An investigation into various cleaning methods, including liquid CO2, highlighting their effectiveness in removing contaminants while preserving the functional integrity of turnout gear.

Hossain et al. Research evaluating the efficacy of surfactants and charcoal-based cleaners in decontaminating PAHs from gear, challenging existing protocols and suggesting improvements for enhanced safety.

McQuerry et al. A study addressing the sizing and fit challenges in PPC for female firefighters, underscoring how inadequate protective gear can increase exposure risks and impact operational performance.

Epidemiological studies and environmental assessments

Koru-Sengul et al. An epidemiological analysis revealing that firefighters have a higher 5-year lung cancer survival rate compared to other groups, possibly due to healthier lifestyles and better medical treatment adherence.

Williams et al. An exploratory study detecting PAHs within fire stations, implying that PPE could inadvertently introduce harmful substances into firefighters' working environments, suggesting a reevaluation of decontamination practices.

Collective insights and future directions

Together, these articles present a compelling body of evidence that underscores the multifaceted nature of toxic chemical exposure risks in firefighting. From individual health vulnerabilities and mental wellbeing to broader epidemiological trends and systemic risks associated with equipment and environments, the research spans a wide spectrum. The collective insights advocate for enhanced protective measures, rigorous cleaning protocols, and tailored approaches to address gender-specific needs in PPE. This work also calls for an overarching strategy that includes proactive health screening, improved decontamination procedures, and continued research into the long-term impacts of toxic exposures in the firefighting community.

Author contributions

GS: Conceptualization, Writing–original draft. MO: Writing–review and editing. BO: Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

frontiers | Frontiers in Pharmacology

TYPE Review
PUBLISHED 15 December 2022
DOI 10.3389/fphar.2022.1095289

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Pharmacology of Anti-Cancer Drugs, a section of the journal Frontiers in Pharmacology

RECEIVED 11 November 2022
ACCEPTED 05 December 2022
PUBLISHED 15 December 2022

CITATION
Sweeney C, Lazennec G and Vogel CFA (2022), Environmental exposure and the role of AhR in the tumor microenvironment of breast cancer.
Front. Pharmacol. 13:1095289.
doi: 10.3389/fphar.2022.1095289

Environmental exposure and the role of AhR in the tumor microenvironment of breast cancer

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Activation of the aryl hydrocarbon receptor (AhR) through environmental exposure to chemicals including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated dibenzo-p-dioxins (PCDDs) can lead to severe adverse health effects and increase the risk of breast cancer. This review considers several mechanisms which link the tumor promoting effects of environmental pollutants with the AhR signaling pathway, contributing to the development and progression of breast cancer. We explore AhR's function in shaping the tumor microenvironment, modifying immune tolerance, and regulating cancer stemness, driving breast cancer chemoresistance and metastasis. The complexity of AhR, with evidence for both oncogenic and tumor suppressor roles is discussed. We propose that AhR functions as a "molecular bridge", linking disproportionate toxin exposure and policies which underlie environmental injustice with tumor cell behaviors which drive poor patient outcomes.

KEYWORDS

AhR, breast cancer, air pollution, particulate matter, environmental injustice, macrophages, tumor microenvironment, tumor promotion

Introduction—*Environmental exposure and breast cancer*

Air pollution and occupational exposure studies have reported positive associations with the risk of developing breast cancer (Amadou et al., 2021). Air pollution and ambient particulate matter (PM) contain a complex mixture of compounds, including polycyclic aromatic hydrocarbons (PAHs) and various metals (e.g. iron, nickel, copper), which may induce reactive oxygen species (ROS) and inflammation (Rückerl et al., 2007; Grunig et al., 2014) and stimulate the progression of breast cancer (Romaniuk et al., 2017). PAHs are generated during combustion processes and derive from various sources such as indoor fireplaces, wildfires, industrial activities, and vehicular traffic and the exposure to PAHs has been identified as a risk factor for breast cancer (Lichtiger et al., 2021; Gamboa-

Loira et al., 2022). Importantly, a stronger association of breast cancer risk was found with traffic related air pollution (TRAP) and higher PAH exposure intensity and duration of exposure (Brody et al., 2007; Nie et al., 2007; Mordukhovich et al., 2016; Large and Wei 2017; Shen et al., 2017; Lee et al., 2019). Vehicular traffic is a major ambient source of PAH exposure and the PAH benzo[a]pyrene (BaP) is classified as a human carcinogen by the International Agency for Research on Cancer (IARC, 2010). Furthermore, BaP and other PAHs have been identified as ligands of the aryl hydrocarbon receptor (AhR), a ligand-activated transcription factor, belonging to the bHLH-PAS family, which regulates multiple target genes and is best known for its role as a xenobiotic receptor (Boonen et al., 2020; Vogel et al., 2020). The activation of the AhR signaling pathway *via* environmental pollutants including dioxins and PAHs has been associated with the development of breast cancer (Birnbaum and Fenton 2003; La Merrill et al., 2010; Murray et al., 2014; Warner et al., 2011; Kolluri et al., 2017; Donovan et al., 2018; Narasimhan et al., 2018; Gearhart-Serna et al., 2020). Reports from our team and other groups suggest an important role of AhR as an immune-modulator and mediator of toxic responses triggered by particulate matter (PM) derived from TRAP (O'Driscoll et al., 2019; O'Driscoll and Mezrich, 2018; Castaneda et al., 2018; Yuan et al., 2020).

Recent studies confirmed an increased risk of breast cancer with vehicular-specific PM exposure among African American and Japanese American women living near major roads, highlighting the link between environmental injustice and health disparities (Cheng et al., 2020; Niehoof et al., 2020). Indeed, residential proximity to major roadways is a recognized risk factor beyond breast cancer, in cardiovascular disease (Hart et al., 2014; Kirwa et al., 2014; Kingsley et al., 2015; Kubil et al., 2018) and renal disease (Lue et al., 2013). Further, it disproportionately impacts racial and ethnic minoritized groups and those of lower socioeconomic status, the legacy of the widespread practice of redlining in the United States (Hwa Jung et al., 2022; Swope et al., 2022). While the Fair Housing Act of 1968 prohibited racial discrimination in housing and lending, exclusionary zoning and other practices such as gentrification has perpetuated residential segregation (https://www.brookings.edu/research/neighborhood-segregation-persists-for-black-latino-or-hispanic-and-asian-americans/). In a study of Hillsborough County in Florida, Stuart et al. (2009) found that blacks, Hispanics, and people living below the poverty line are much more likely to reside close to sources of air pollution but further from air quality monitoring sites while whites were found to live closer to monitoring sites but significantly further from pollution sources. Wu et al. (2014) found that particulate matter (PM) collected near a major Los Angeles freeway (compared to an urban background location) induced significantly higher production of the cytokines IL-6, IL-8, and TNF-α, suggesting a link between AhR activation, AhR-driven inflammation (Vogel et al., 2011; Vacher et al., 2018; Wu et al., 2021) and proximity to pollution. The interaction between environmental exposure, socio-economic related stress and psychosocial stress in under-resourced neighborhoods has been termed the environmental "riskscape" by Morello-Frosch & Shenassa, 2006 (Morello-Frosch & Lopez, 2006). As noted by Morello-Frosch, the Institute of Medicine recognizes this as a type of "double jeopardy" in which elevated stress impairs the ability of individuals living in under-resourced neighborhoods to endure the myriad health consequences of chronic environmental exposures (https://www.scientificamerican.com/article/end-double-jeopardy/#).

Role of AhR in breast cancer

Approximately 2 decades ago, AhR was found to be overexpressed in mammary cancer in rats (Trombino et al., 2000) sparking curiosity as to its role in breast cancer progression. Several studies have since shown that chemical exposure and AhR activation affect processes of mammary gland differentiation, disrupting pregnancy-related differentiation and milk production, and increasing the risk of breast cancer (Warner et al., 2002; Vorderstrasse et al., 2004; Lew et al., 2011; Belton et al., 2018; Kay et al., 2022). Further studies have elucidated AhR's molecular contribution to carcinogenic progression and ratified the oncogenic role of AhR in breast cancer cells (Wang et al., 2017; Wang et al., 2020). In support of its role as a breast cancer oncogene, AhR activation is sufficient to transform human mammary epithelial cells and promote their migration, invasion and epithelial-to-mesenchymal transition (EMT) (Brooks and Eltom 2011). Work from our group showed that chronic exposure of MCF10AT1 and MCF-7 cells to estradiol (E2) resulted in AhR overexpression and downregulation of estrogen receptor alpha (ERα) and progesterone receptor (Zou and Matsumura 2003; Wong et al., 2009) accompanied by increased proliferation, invasion, and apoptosis resistance. The resistance to apoptosis was also demonstrated in human breast cancer cell lines treated with the prototypical AhR ligand TCDD when apoptosis was induced by chemotherapeutics (doxorubicin, lapatinib and paclitaxel) (Bekki et al., 2015). Treatment with PAH mixtures which bind to and activate AhR also increased cell proliferation and expression of antiapoptotic proteins in MCF-7 cells *via* AhR signaling (Gearhart-Serna et al., 2020).

Several studies have reported AhR overexpression in human breast cancer (Li et al., 2014; D'Amato et al., 2015; Vacher et al., 2018). Using samples from breast cancer patients, we found that AhR is frequently over-expressed in ER-negative human breast tumors, and this is closely correlated with elevated expression of the NF-κB subunit RelB and inflammatory markers such as IL-8 (CXCL1 in mouse) and COX-2 (Vogel et al., 2011). This was also observed by Vacher et al. with significant overexpression of cytokines, including IL-8, in AhR high expressing tumors (Vacher et al., 2018). We demonstrated that C/EBPβ serves as a key transactivator for AhR-mediated COX-2 gene induction (Vogel et al., 2000; Vogel et al., 2004). Interestingly, COX-2, CXCL1, and IL-

8 have been identified as critical genes that mediate breast cancer invasion and metastasis to lung and lymph nodes (Freund et al., 2003; Minn et al., 2005; Ahmed et al., 2021). A recent report suggests that inhibition of COX-2 expression reduces mammary tumor multiplicity and size in the polyoma middle T antigen (PyMT) mouse model (Esbona et al., 2016). In our recent study we demonstrated that overexpression of AhRR (Aryl Hydrocarbon Receptor Repressor) suppresses AhR-driven (TCDD-stimulated) growth of syngeneic mammary tumors as well the onset, growth and metastasis of spontaneous mammary tumors in PyMT mice (Vogel et al., 2021). In human breast cancer, high expression of AhRR, the dedicated AhR repressor, independently predicts prolonged metastasis-free survival (Vacher et al., 2018), in agreement with our findings in PyMT mice (Vogel et al., 2021). Interestingly, knockdown of AhRR in normal human mammary epithelial cells resulted in anchorage-independent cell growth suggesting that the AhRR may function as a tumor suppressor gene (Zudaire et al., 2008).

In a mouse model of BRCA1-associated breast cancer, AhR was found to transcriptionally induce the EGF receptor ligand, Amphiregulin, driving tumor growth and macrophage infiltration. Of note, this was inhibited by the combination of an AhR inhibitor and an EGF receptor inhibitor, suggesting new therapeutic possibilities for this type of breast cancer (Kubli et al., 2019). The relationship between AhR activation and breast cancer-related death was recently assessed using an artificial intelligence tool to analyze the scientific literature, with strong evidence that AhR activation is an adverse outcome pathway in breast cancer (Benoit et al., 2022).

Interestingly, many studies have also provided evidence for a tumor suppressor role for AhR, with evidence that AhR can inhibit tumor growth (Fritz et al., 2007; Jin et al., 2014; Feng et al., 2020) while inhibition of AhR or AhR deficiency promotes tumor development (Abdelrahim et al., 2003; Safe et al., 2017). For example, in the ApcS580/+; KrasG12D/+ mouse model of colon tumorigenesis, intestinal epithelial specific AhR knockout promoted tumorigenesis through enhanced Wnt signaling (Han et al., 2021). In p53 deficient mice, AhR knockout significantly increased incidence of thymic lymphomas and sarcomas and decreased survival (Phillips et al., 2022). In a mouse model of sonic hedgehog type-medulloblastoma, AhR deletion in cerebellar granule cell progenitors accelerated tumorigenesis through increased TGFβ-SMAD3 signaling (Sarić et al., 2020) with high AhRR expression linked to decreased patient survival. Further, in an unbiased functional genomics screen, AhR was identified as metastasis suppressor in a lung cancer model (Nothdurft et al., 2020). In in vitro studies, AhR was demonstrated to cooperate with the Rb tumor suppressor to prevent S-phase cell cycle entry (Puga et al., 2000) while activation of AhR by the prototypical ligand TCDD inhibited the growth of MCF7 breast cancer cells (Vogel and Abel 1995). David Sherr's team investigated AhR agonists and antagonists in a direct comparison and concluded that the sustained activation of AhR drives the later, more lethal stages of some cancers, but that AhR agonists under some circumstances can counteract tumor development and may also serve as cancer therapeutics (Narasimhan et al., 2018). In this vein, O'Donnell (O'Donnell et al., 2021) and others (Rowland et al., 2019) have pursued SMAhRTs, Select Modulators of AhR-regulated Transcription, to specifically exploit the anti-cancer functions of AhR. Notably, they identified a modulator which induced AhR-dependent Fas ligand expression and breast and liver tumor cell apoptosis without increasing expression of the prototypical AhR target gene, CYP1A1, suggesting that AhR transcriptional activity can be fine-tuned, to specifically unlock its function as a tumor suppressor.

Cytokines and chemokines in breast cancer and the tumor microenvironment

The tumor microenvironment (TME) corresponds to the fact that tumor cells are surrounded in close proximity by a number of non - cancerous cells including cancer associated fibroblasts (CAFs), mesenchymal stem cells (MSCs), adipocytes, myeloid-derived suppressor cells (MDSCs), tumor associated macrophages (TAMs), tumor associated neutrophils (TANs), tumor infiltrating lymphocytes (TILs), and endothelial cells (Joyce and Pollard 2009; Lazennec and Lam 2016; Binnewies et al., 2018). In addition to direct contact with tumor cells, TME cells will interact with tumor cells though a number of different soluble factors including cytokines and chemokines, which will reshape TME to support cancer initiation, progression, and metastasis (Ali and Lazennec 2007; Lazennec and Richmond 2010; Mancini et al., 2021) (Figure 1).

In breast cancer, many chemokines and cytokines have been analyzed and identified as important factors contributing to the development of breast tumors (Narita et al., 2016; Masih et al., 2022). In particular the CXCR4/CXCL12 axes has been reported to control breast cancer metastasis and the involvement of CAFs (Muller et al., 2001; Orimo et al., 2005). The CAF-driven CXCR4/CXCL12 axis may also stimulate the accumulation of protumorigenic lipid associated macrophages which supports an immunosuppressive microenvironment in breast cancer (Timperi et al., 2022).

CCL2 and CCL5 have also retained attention in breast cancer, as they are expressed by cancer cells and promote the recruitment of TAMs and metastasis by inducing Th2 polarization of $CD4^{+}$ T cells (Chavey et al., 2007; Soria and Ben-Baruch 2008; Zhang et al., 2015; Brummer et al., 2018). In addition, the ligands of CXCR2 (CXCL1, 2, 3, 5, 6, 7, 8) have been shown in a number of studies to be involved in the aggressiveness of triple negative breast cancers (TNBC) (Bieche et al., 2007; Chavey et al., 2007; Acharyya et al., 2012). The genes of these chemokines are encoded by a small region of chromosome 4q21 and have been found to be coregulated in TNBC (Bieche et al., 2007). Moreover, cancer cells expressing high levels of CXCL1 and CXCL2 acquire an advantage in terms of survival in metastatic sites and favor the recruitment of TANs (Acharyya et al., 2012).

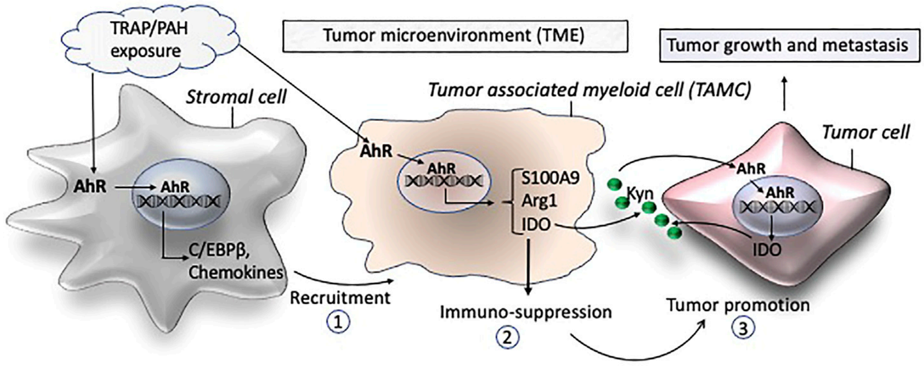

FIGURE 1
Schematic of proposed mechanisms by which traffic-associated air pollution (TRAP) activates AhR to induce the accumulation of TAMCs (1) and expression of immune suppressive factors (2) leading to a tumor promoting microenvironment (3) and growth and metastasis of breast cancer.

Interestingly, CXCR2 itself is also playing a major role in the aggressiveness of TNBC, in particular through its expression on TANs (Boissiere-Michot et al., 2020; Boissiere-Michot et al., 2021). Although the levels of CXCR2-expressing neutrophils is correlated to high grade breast cancers, its role is rather to counteract tumor progression (Boissiere-Michot et al., 2021), as it is correlated with a better survival of the patients and its deletion favors tumor growth and metastasis (Timaxian et al., 2021). There are many links between AhR and CXCR ligands in particular. For instance, we have shown that the complex of AhR and NFkB RelB was able to bind to a specific binding elements of chemokines including the CXCL8 promoter and to promote its activation though protein kinase A (Vogel et al., 2007). RelB/AhR complex is also involved in the overexpression of CXCL8 in breast cancer (Vogel et al., 2011; Bekki et al., 2015). A significant elevated level of CXCL8 mRNAs expression (56-fold) has also been found in tissue samples of high stage compared to low stage patients and adipose-derived stem cells (Razmkhah et al., 2010). AhR may also interact with NFkB RelA causing the upregulation of c-myc and stimulation of tumorigenesis in MCF-7 cells (Kim et al., 2000). Further HER2 overexpression in MCF-7 cells resulted in pro-inflammatory signaling and induction of IL-6 enhancing mammosphere formation in an AhR-dependent manner (Zhao et al., 2013). The role of AhR as a mediator of chronic inflammation in breast cancer has been recently reviewed elsewhere (Guarnieri 2020). Moreover, a recent study by Kubli et al. has shown that AhR was induced by reactive oxygen species (ROS) in mammary epithelial cells, which in turn enhance AREG (amphiregulin) production (Kubli et al., 2019). In basal-like and BRCA1-related breast cancers, ROS expression was correlated with AhR levels and the expression of the chemokines CXCL1, CXCL2, and CCL5. Targeting AhR or AREG reduced the recruitment of macrophages in tumors in mouse models and AREG expression was associated with the density of macrophages in human tumors. Another cytokine upregulated by AhR activation is IL-22 which is an important factor controlling host defense and gut immunity. However, dysregulation of IL-22 may contribute to the development of TNBC and the pathology in breast cancer (Kim et al., 2014; Voigt et al., 2017; Wang et al., 2018; Katara et al., 2020). IL-22 has also been described to mediate macrophage infiltration in the TME and the migration of breast cancer cells (Kim et al., 2020). Results from MCF-7 cells co-cultured with preadipocytes and an *in vivo* zebrafish model showed that prototypical AhR ligand TCDD enhanced the invasive and metastatic potential of MCF-7 cells implicating the importance of AhR in the TME (Koual et al., 2021).

AhR as a critical player in the tumor microenvironment of breast cancer

The development of metastatic disease, which accounts for greater than 90% of cancer mortality, requires collaboration between tumor cells and their environment. Recent studies reveal that the TME possesses remarkable cellular heterogeneity with an important role of immune cells in the development and progression of breast cancer (Ben-Baruch 2003; Place et al., 2011). The TME also consists of an acellular component (e.g., soluble cytokines, chemokines, and growth factors), that forms part of the stromal structure as described above. TAMs and MDSCs are tumor-associated myeloid cells (TAMCs) and have been identified as key players in breast cancer progression and metastasis (Cha and Koo 2020). MDSCs are myeloid cells at earlier stages of differentiation and serve as precursor of TAMs (Coffelt et al., 2009). Their presence and frequency have been directly correlated with tumor aggressiveness and is associated with poor survival rates in breast cancer (Leek et al., 1996; Mukhtar et al., 2011a; Mahmoud et al., 2012; Zhang et al., 2012; Zhao et al., 2017; Qiu et al., 2018). They have been found to drive cancer progression *via* immune regulatory functions creating a tolerogenic environment allowing the tumor to progress (Figure 1). TAMCs inhibit tumor immune responses by blocking T cell functions and proliferation, but they also directly trigger tumor growth by promoting cancer stemness, angiogenesis, EMT and metastasis formation. In breast cancer patients, levels of MDSCs in peripheral blood were found to be about 10-fold higher compared to healthy control individuals (Safarzadeh et al., 2019). Moreover, they found a direct relationship between MDSC levels and tumor stage of breast cancer patients. The study underlines the importance of MDSCs in tumor progression and invasion which was supported by Diaz-Montero et al. (Diaz-Montero et al., 2009) showing that MDSC levels are associated with the clinical stage and metastatic disease burden in patients with breast cancer. MDSCs possess strong immunosuppressive activities and interact with other immune cells to regulate their functions. The number and abundance of TAMs and MDSCs is considered to be an important factor in the clinical success of cancer immunotherapy, underlining their critical role in suppression of immunity in breast cancer patients (Gnant et al., 2011; Gomez-Roca et al., 2015).

AhR plays a critical role in carcinogenesis and tumor immunity (Murray et al., 2014; Xue et al., 2018). Activation of AhR *via* Kynurenine (Kyn) produced by the immunosuppressive enzyme indoleamine 2, 3-dioxygenase (IDO) in glioblastoma cells has been found to induce the accumulation of TAMs (Takenaka et al., 2019; McKay et al., 2021). They reported that the AhR ligand Kyn is able to activate AhR in TAMs, leading to an increased expression of the chemokine receptor CCR2 by TAMs, which enhances the recruitment of TAMs in response to CCL2. Moreover, AhR stimulates the production of the exonucleotidase CD39 by TAMs, interfering with the function of cytotoxic $CD8^+$ T cells (Takenaka et al., 2019). In melanoma patients, high levels of IDO1 are associated with high levels of Kyn and immunosuppression (Campesato et al., 2020). Using a melanoma model, it was shown that tumors expressing high levels of IDO1 present an enrichment of TAMs and selective inhibition of AhR decreases tumor progression, by inhibiting the immunosuppression mediated by IDO1. Another link of AhR with immune response in cancer is highlighted by the fact that AhR mediates the induction of the poliovirus receptor CD155 by IL-4 and LPS in macrophages, as CD155 is suppressing T cell function (McKay et al., 2021). In the same line, the inhibition of AhR activity in a model of pancreatic cancer promotes the infiltration of $CD8^+$ T cells and improves the response to immune therapy (Hezaveh et al., 2022). This study also showed that AhR is highly expressed in TAMs, involved in their polarization, and associated with a reduction of iNOS, CCL4, and TNFα levels. Further, Neamah et al. (2019) found that treatment with the AhR ligand TCDD induces the accumulation of MDSCs in the peritoneal cavity. Interestingly, we found an accumulation of CD11b+ F4/80+ and CD11b+ F4/80- Ly6G + cell subsets in adipose tissue associated with a significant increase of the chemokine CXCL5 in TCDD-treated mice (Vogel et al., 2016) which indicates accumulation of TAMs and MDSCs (Ugel et al., 2015). Although TAMs and MDSCs are regarded as separate populations, some markers including CD11b are shared among TAMs and MDSCs (Ugel et al., 2015). There are specific markers (e.g., Ly6G and Ly6C) that can be used to distinguish them. Further, MDSCs and TANs express high levels of S100A9 and the immunosuppressive enzymes IDO and arginase 1 (Arg1) which are specific for their immune-suppressive activity in TME of breast cancer (Fridlender et al., 2009; Ostrand-Rosenberg 2016).

The polarization of TAMs and MDSCs within the TME is highly dependent on the local milieu of immune regulatory factors (e.g., C/EBPβ and S100A9) and cytokines and chemokines which can originate from stromal cells (Figure 1). Recently, we identified C/EBPβ as a critical transcription factor in AhR-dependent induction of S100A9 after treatment with PM rich in PAHs (Dahlem et al., 2020). The S100 calcium binding protein S100A9 has been shown to play a critical role in mediating the expansion of MDSCs in breast cancer models (Zhao F et al., 2012). Moreover, S100A9 can act as a transcriptional coactivator during breast cancer development (Song and Struhl 2021) and promotes the immune-suppressive activity of MDSCs (Ostrand-Rosenberg 2016). Regardless of any direct lineage link and distinction between MDSCs, TANs and TAMs, the most important criteria for their role in carcinogenesis are their immune-suppressive and pro-tumoral activities. Importantly, the AhR has been demonstrated to regulate the expression of immune-regulatory markers including Arg1, IDO, IL-10, COX-2, C/EBPβ, and S100A9 (Vogel et al., 2008; Bankoti et al., 2010; Benson and Shepherd 2011; Simones and Shepherd 2011; Vogel et al., 2013; Neamah et al., 2019; Dahlem et al., 2020), which are critical factors in the pathogenesis of breast cancer (Yu et al., 2013; Yu et al., 2014; Dey et al., 2021). Moreover, TCDD increased the activity of the immunosuppressive enzyme IDO which mediates tumor immunity in breast cancer cells (Bekki et al., 2015). Interestingly, AhR as well as NFkB RelB have been shown to induce IDO expression (Vogel et al., 2008; Yu et al., 2014), which is also critically involved in the immunosuppressive mechanisms of myeloid-derived suppressor cells (MDSCs) in breast cancer (Yu et al., 2013). The number and frequency of TAMs and MDSCs have been directly correlated with tumor aggressiveness, and indirectly correlated with clinical outcome in breast cancer (Mukhtar et al., 2011b). The literature also shows that accumulation of TAMCs is a significant prognostic factor in breast cancer (Zhao et al., 2017). A significant heterogeneity of TAMCs in mammary tumors has been described (Movahedi et al., 2010) and the activation of AhR has been shown to activate TAMs (Takenaka et al., 2019) and induce the accumulation of MDSCs (Neamah et al., 2019). The mechanisms that are driving the polarization of immune-suppressive TAMCs in the TME by AhR signaling activated through the exposure to PM, PAHs, and dioxin like chemicals are not clear yet. In summary, data from the literature strongly suggest AhR's

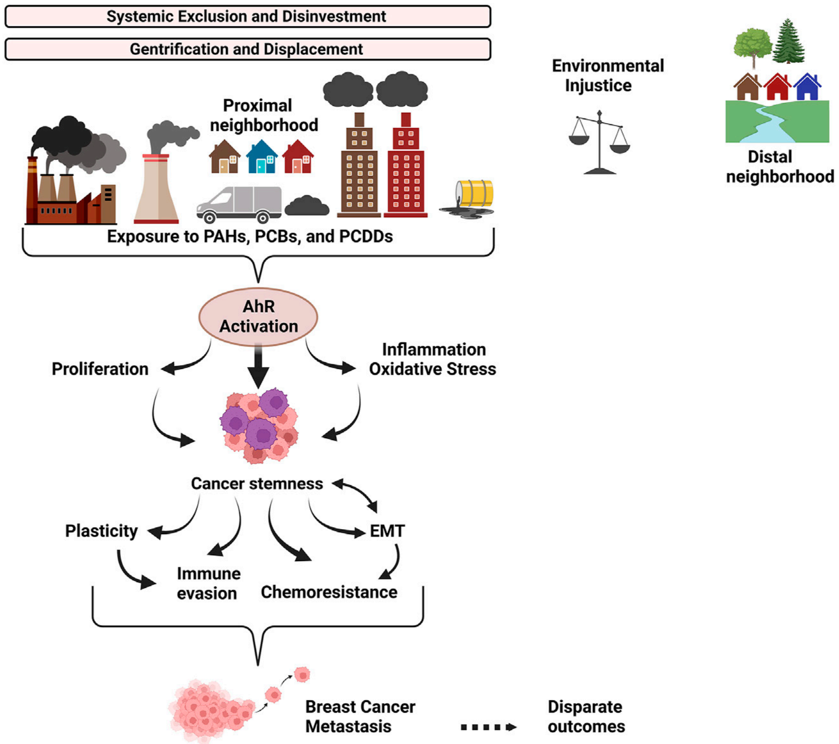

FIGURE 2
Overview of the link between systemic exclusion, environmental injustice, and AhR-driven tumor biology. Discriminatory housing and lending policies (ex: redlining) drove neighborhood racial/ethnic and socioeconomic segregation which persists today due to ongoing systemic discrimination and gentrification. Resources were and are disproportionately allocated to wealthier neighborhoods, contributing to neighborhood disinvestment. The proximal neighborhood has more traffic, pollution-generating factories and dump sites. It has less green space for stress relief and exercise, worsening the riskscape that individuals in the proximal neighborhood must navigate. Individuals living in the proximal neighborhood are chronically exposed to environmental toxins, tipping the scales of environmental justice against them. Polycyclic aromatic hydrocarbons (PAHs), Polychlorinated dibenzo-p-dioxins (PCDDs), and Polychlorinated biphenyls (PCBs) are generated by combustion processes as components of ambient particulate matter (PM) derived from urban areas and industrial activities. PAHs, PCDDs and PCBs robustly activate the AhR signaling pathway, promoting cancer stemness and interrelated functional outcomes, including plasticity, chemoresistance, EMT and immune evasion, which synergize to drive breast cancer metastasis and disparate outcomes for individuals in proximal neighborhoods.

critical role in the microenvironment of mammary tumorigenesis promoting tumor progression and metastasis.

The intersection between environmental exposure and cancer stemness

Breast cancer stem cells (BCSCs), a small but highly plastic subpopulation of tumor cells, have taken center stage in the interplay between chemoresistance, recurrence, and metastasis (Shan et al., 2021). BCSCs, capable of both self-renewal and recapitulation of tumor heterogeneity, are multidrug-resistant (MDR) and highly immune-evasive. MDR is due in part to robust expression of the ABCG2 efflux protein, also known as Breast Cancer Resistance Protein (BCRP) (Zhou et al., 2001; Zattoni et al., 2022), a direct transcriptional target of AhR (Tan et al., 2010). Substantial efforts have focused on strategies which will lead to the effective elimination of BCSCs, however it is recognized that standard endocrine and chemotherapy regimens paradoxically enrich for BCSCs with mesenchymal features, driving tumor recurrence (Li et al., 2008; Creighton et al., 2009; Famta et al., 2022).

AhR has been implicated in cancer stemness and immune evasion in various tumor types serving as a “molecular bridge” between environmental exposure and poor patient prognosis. In lung and nasopharyngeal carcinoma cells, AhR was shown to drive the expression of a panel of stemness genes, including ABCG2 (Yan et al., 2018). Interestingly, ABCG2 has been directly implicated in expanding the stem population in osteosarcoma cells (Zhou et al., 2001). In non-small cell lung carcinoma, the deubiquitinase UCHL3 promoted cancer stemness through stabilization of AhR (Ouyang et al., 2020). Recently, activation of AhR by the endogenous ligand kynurenine was linked to colon cancer stemness, immune evasion through PD-L1 induction and metastasis (Miyazaki et al., 2022). In an oral squamous cell carcinoma model, tumor cell- and immune cell-expressed AhR collaborated to promote tumor immune evasion with AhR knockout in tumor cells restoring anti-tumor immunity (Kenison et al., 2021).

In breast cancer, tranilast, a tryptophan metabolite and AhR agonist, was shown to inhibit the BCSC population in MDA-MB-231 (triple negative) breast cancer cells and abrogate metastasis in a tail vein injection model (Prud'homme et al., 2010), in an AhR dependent manner. In agreement with these findings, several studies reported that AhR activation inhibits the BCSC population (Saito et al., 2021; Yamashita et al., 2021). In MCF7 (ER+) cells expressing a constitutively active AhR or treated with the AhR agonists 3-Methylcholanthrene (3 MC) or β-naphthoflavone (β-NF), the BCSC population was decreased (Zhao S et al., 2012). Most recently, camalexin, an indole phytoalexin and AhR agonist was shown to decrease the BCSC population of MCF7 and T47D (ER+) breast cancer cells (Yamashita et al., 2022). Conversely, AhR activation by the potent agonists TCDD and DMBA was found to increase the breast cancer stem cell population and was implicated in doxorubicin resistance of MCF-7 breast cancer cells (Al-Dhfyan et al., 2017). In Tamoxifen-resistant MCF7 cells, AhR antagonism inhibited the BCSC population and also inhibited tumor growth (Dubrovska et al., 2012). In Hs578T (triple negative) and SUM149 (inflammatory) breast cancer cells, AhR was shown to augment the BCSC population, and its inhibition decreased tumor growth and sensitized cells to both adriamycin and paclitaxel (Stanford et al., 2016). This study also found a significant correlation between AhR activity and "cancer stem cell- and migration/invasion-associated gene sets" in an analysis of 79 human breast cancer cells lines and more than 1,850 human breast cancers. In inflammatory breast cancer, AhR was linked to BCSC maintenance through the Wnt5a/β-catenin signaling pathway (Mohamed et al., 2018). AhR crosstalk with Wnt/β-catenin signaling in the regulation of CSCs has been reported in several studies (Al-Dhfyan et al., 2017; Akhtar et al., 2022).

The role of AhR in cancer stemness and breast cancer stemness more specifically is complex, influenced by mode of AhR activation, engagement with various signaling pathways and cell context. Nevertheless, the collective evidence strongly suggests that AhR activation by environmental toxins and endogenous ligands (Ala 2021) aligns with chemoresistance, recurrence and metastasis, the hallmarks of cancer stemness. This places AhR at the intersection between racial/ethnic and socioeconomic disparities in toxin exposure in under-resourced neighborhoods, as discussed previously, and cancer stemness, undermining response to cancer therapy, worsening the riskscape that an individual must navigate. In a recent review by Lagunas-Rangel, the authors pose the question "Can Exposure to Environmental Pollutants Be Associated with Less Effective Chemotherapy in Cancer Patients?" The authors summarize evidence which strongly supports this hypothesis, which includes toxins which activate AhR (Lagunas-Rangel et al., 2022). Therachiyil examines this from the perspective of gynecological cancers. (Therachiyil et al., 2022).

Conclusion

Collectively, the body of literature indicates that the role of AhR in cancer is complex, with ample evidence for both an oncogenic and tumor suppressor function, depending on cell and tissue context and mode of AhR activation. However, exposure studies indicate that environmental pollutant-mediated activation of AhR is consistently oncogenic, highlighting the potential for cautious therapeutic intervention. The data from human and *in vivo* studies, as well as *in vitro* experiments suggest that exposure to environmental pollutants especially PAHs and dioxin-like chemicals, potent ligands for AhR, increases breast cancer risk and worsens outcome through chemoresistance, immune evasion, EMT, tumor cell proliferation, and metastasis, linked functional outcomes of cancer stemness (Figure 2). Some critical questions remain, including how AhR activation modulates the tumor microenvironment. This review also highlights the role of AhR at the interface between historical and existing systemic practices - which reinforce residential segregation and environmental injustice - and the molecular drivers of aggressive tumor biology. While policies and molecules are not frequently in the same conversation, greater dialogue is needed and opportunities for "upstream" disease prevention through systemic change should be prioritized.

Author contributions

Review concept: CS, GL, and CV. Review design: CS and CV. Manuscript preparation: CS, GL, and CV. Manuscript editing: CS and CV. Manuscript review: CS, GL, and CV.

Funding

This work was supported by pilot funding from the Molecular Oncology Program at the UC Davis Comprehensive Cancer Center and R21ES030419, R01ES032827 (CV).

Acknowledgments

CS gratefully acknowledges the dedicated mentorship of Dr. Jann Murray-Garcia.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Materials

TYPE Review
PUBLISHED 23 March 2023
DOI 10.3389/fmats.2023.1143411

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Polymeric and Composite Materials, a section of the journal Frontiers in Materials

RECEIVED 13 January 2023
ACCEPTED 13 March 2023
PUBLISHED 23 March 2023

CITATION
Mazumder N-U-S, Hossain MT, Jahura FT, Girase A, Hall AS, Lu J and Ormond RB (2023), Firefighters' exposure to per-and polyfluoroalkyl substances (PFAS) as an occupational hazard: A review.
Front. Mater. 10:1143411.
doi: 10.3389/fmats.2023.1143411

Firefighters' exposure to per-and polyfluoroalkyl substances (PFAS) as an occupational hazard: A review

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The term "firefighter" and "cancer" have become so intertwined in the past decade that they are now nearly inseparable. Occupational exposure of firefighters to carcinogenic chemicals may increase their risk of developing different types of cancer. PFAS are one of the major classes of carcinogenic chemicals that firefighters are exposed to as occupational hazard. Elevated levels of PFAS have been observed in firefighters' blood serum in recent studies. Possible sources of occupational exposure to PFAS include turnout gear, aqueous film-forming foam, and air and dust at both the fire scene and fire station. Preliminary discussion on PFAS includes definition, classification, and chemical structure. The review is then followed by identifying the sources of PFAS that firefighters may encounter as an occupational hazard. The structural properties of the PFAS used in identified sources, their degradation, and exposure pathways are reviewed. The elevated level of PFAS in the blood serum and how this might associate with an increased risk of cancer is discussed. Our review shows a significant amount of PFAS on turnout gear and their migration to untreated layers, and how turnout gear itself might be a potential source of PFAS exposure. PFAS from aqueous film-forming foams (AFFF), air, and dust of fire stations have been already established as potential exposure sources. Studies on firefighters' cancer suggest that firefighters have a higher cancer risk compared to the general population. This review suggests that increased exposure to PFAS as an occupational hazard could be a potential cancer risk for firefighters.

KEYWORDS

PFAS, firefighters, cancer, turnout gear, AFFF, DWR, repellent finish, occupational hazard

1 Introduction

"Firefighter" and "cancer" are two words that have become unfortunately linked over the past decade. In 2022, the International Agency for Research on Cancer (IARC) re-classified the firefighting occupation as a "Group 1" carcinogen (carcinogenic to human) (Demers et al., 2022). This occupation was first classified in 2010 as "Group 2B" meaning possibly carcinogenic (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2010). Several studies examined the cancer risk and mortality rate among firefighters. Though studies have found inconsistent results, general indication of elevated risk of several cancers in firefighters have been reported, such as studies reported elevated summary risk estimates (SRE) for multiple cancers including non-Hodgkin lymphoma (NHL), myeloma, testicular and prostate cancers (LeMasters et al., 2006; Soteriades et al., 2019; Laroche and L'Espérance, 2021). Another study reported the cancer risk among firefighters with standardized incidence ratios (mSIR); this study found an increase in mSIR for skin melanoma and prostate cancer among firefighters (Casjens et al., 2020). Studies funded by the National Institute of Occupational Safety and Health (NIOSH) also reported elevated cancer mortality and incidence rates (Daniels et al., 2014; Daniels et al., 2015). Similarly, a study in Indiana found higher malignant cancer mortality for firefighters compared to non-firefighters (Muegge et al., 2018). Significantly elevated risk of skin, thyroid, testicular, and prostate cancer was also reported for male firefighters in Florida (Lee et al., 2020). Likewise, studies in many other countries and the United States also have found elevated rates of several types of cancer such as kidney, bladder, testicular, prostate, multiple myeloma, and non-Hodgkin's lymphoma (Delahunt et al., 1995; Bates, 2007; Kang et al., 2008; Ahn et al., 2012). It has been documented that firefighting involves exposure to both known and potentially carcinogenic chemicals (Soteriades et al., 2019; Laroche and L'Espérance, 2021). Even though the exposure time could be shorter, levels of exposure could still be high (Jalilian et al., 2019).

Injuries caused due to the thermal and thermo-physiological comfort hazards during the firefighting are common among the firefighters (Mandal et al., 2021; Mazumder, 2021; Mazumder et al., 2022). In addition to thermal and thermo-physiological comfort hazards, exposure to harmful chemicals that may contribute to the increased cancer risk has become an increasing concern in the firefighting community (Trowbridge et al., 2020; Muensterman et al., 2021). Studies have shown that firefighters are exposed to hazardous substances during structural fires (Fent et al., 2014), overhaul phases (Jones et al., 2016; Oliveira et al., 2017) and vehicle fires (Fent and Evans, 2011; Jalilian et al., 2019). The compounds found in fire smoke and their toxicities vary considerably depending on the burning conditions and materials since every burn has its unique pattern (Golka and Weistenhöfer, 2008; Casjens et al., 2020). However, studies reported polycyclic aromatic hydrocarbons (PAHs) (Keir et al., 2020), 1,3- butadiene (Laitinen et al., 2012), metal (Keir et al., 2020), formaldehyde (Driscoll et al., 2016) and per- and polyfluoroalkyl substances (PFAS) (Jin et al., 2011; McGuire et al., 2014) are the most concerning chemicals (Muensterman et al., 2021). In addition, besides the fire scene, hazardous chemicals have also been found in fire station dust, aqueous film-forming foams (AFFF), contaminated fire equipment, and in turnout gear (Brown et al., 2014; Fent et al., 2015; Shen et al., 2015; Alexander and Baxter, 2016; Barzen-Hanson et al., 2017).

PFAS are a large class of fluorinated aliphatic chemicals, which have diversified use (Young et al., 2021). Due to their extreme toxicity, persistency, and bioaccumulation, these chemicals are a significant concern for the environment and human health (Blum et al., 2015; Cousins et al., 2016; Wang et al., 2017; Goldenman et al., 2019). PFAS are detected in the blood serum of over 98% of Americans (Calafat Antonia et al., 2007). The general population gets exposed to PFAS through drinking water, contaminated food, food packaging, cookware, indoor dust, and ambient air (Nadal and Domingo, 2014; Sjogren et al., 2016; Mastrantonio et al., 2018; Domingo and Nadal, 2019). Among many other PFAS, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) were most extensively used and studied. However, their use has been banned or heavily regulated in many countries for several years. Studies show that elevated levels of PFAS exposure is associated with adverse health effects such as testicular and kidney cancers (Vaughn et al., 2013; Vieira Verónica et al., 2013). Similarly, studies have also reported links between PFOA and cancers such as mesothelioma, prostate, testicular, and non-Hodgkin's lymphoma (Vaughn et al., 2013; Chang et al., 2014). These four cancers are among the top eight that firefighters have increased risks of compared to the public (LeMasters et al., 2006; Daniels et al., 2014). Therefore, concern of PFAS exposure in the fire service and health risk of the firefighters are reasonable.

Increased risk of cancer in firefighters may be contributed from the occupational exposures to PFAS (Trowbridge et al., 2020). PFAS are particularly relevant to firefighting since these chemicals are used in firefighter protective clothing and equipment to impart water and oil repellency (Peaslee et al., 2020; Muensterman et al., 2021; van der Veen et al., 2022), as polymeric membranes in moisture barriers, in AFFF which are used in extinguishing fuel and oil fires (Kissa, 1994; Kissa, 2001; Barzen-Hanson et al., 2017), and recent studies have also found elevated PFAS levels in dust and air of fire stations (Henry et al., 2018; Young et al., 2021). Turnout gear worn by firefighters is extensively treated with fluoropolymers (one form of PFAS) or side-chain fluoropolymers to obtain the highest levels of water and oil repellency (Henry et al., 2018; Young et al., 2021). PFAS also includes polytetrafluoroethylene (PTFE), a highly repellent material used in the moisture barrier to limit the migration of water and bodily fluids through the turnout gear (Islam et al., 2020; Muensterman et al., 2021). Firefighters may also be exposed to PFAS chemicals during training and firefighting from fluorinated firefighting foams, which mainly contain PFAS from the sulfonated acids category (Dauchy et al., 2017). In addition, one recent study has found elevated levels of PFOS in the dust collected from the living area of fire stations: fifteen times higher than the median level (Young et al., 2021).

A few systemic review studies on human cancers and PFAS have been done (Sunderland et al., 2019; Imir et al., 2021; Steenland and Winquist, 2021; Boyd et al., 2022). Firefighters' cancers (LeMasters et al., 2006; Ahn et al., 2012; Jalilian et al., 2019; Soteriades et al., 2019; Casjens et al., 2020; Lee et al., 2020; Laroche and L'Espérance, 2021) and PFAS in blood serum levels (Dobraca et al., 2015; Gribble et al., 2015; Rotander et al., 2015; Olsen et al., 2017; Graber et al., 2019; Kotlarz et al., 2020; Trowbridge et al., 2020) also have been studied extensively. The presence of PFAS in AFFF and hence contamination of groundwater has also thoroughly been studied (Rotander et al., 2015; Barzen-Hanson et al., 2017; Høisæter et al., 2019; Gonzalez et al., 2021). During the last decade, the presence of hazardous chemicals in fire station dust has also been reported by a few studies (Brown et al., 2014; Banks et al., 2020; Hall et al., 2020; Young et al., 2021). However, only a few recently published research studies mentioned the presence of PFAS in the turnout gear itself (Peaslee et al., 2020; Muensterman et al., 2021; van der Veen et al., 2022). Additionally, a recent study reviewed the PFAS exposure in firefighters from aqueous film forming foam (Rosenfeld et al., 2023). However, to the authors' best knowledge, no comprehensive review on all the sources of PFAS that firefighters may be exposed to as an occupational hazard and their exposure pathways has been conducted. Therefore, this review covers explicitly the sources of PFAS as occupational exposure, their pathways, and how they might cause increased cancer risk in firefighters.

2 Methods

This review was performed in three steps. Firstly, introductory discussion was done on PFAS, which includes definition, classification, and chemical structures of most common PFAS. In the second step, the sources of PFAS exposure as firefighting occupational hazards were identified. The sources of PFAS including their chemistries and degradation pathways were discussed as identified in the literature. In the third step, elevated levels of PFAS in blood serum and associated increased rate of firefighters' cancer were identified.

Step 1: Classification of PFAS

The definition and classification of PFAS were discussed as mentioned in different literature. A universally accepted definition for PFAS is still missing. Commonly found PFAS were identified from the literature. In addition, PFAS that are mostly associated with fire service were also identified considering firefighters' occupational hazard as reported in the literature.

Step 2: Identification of sources of PFAS as firefighting occupational exposure

As reported in many peer-reviewed journals, one of the most common sources of firefighters' exposure to PFAS is from AFFF, which is used to extinguish Class B fires. AFFF have been extensively used in firefighting and are one of the major causes of the ground water contamination with PFAS (Houtz et al., 2013; Cousins et al., 2016; Barzen-Hanson et al., 2017; Peaslee et al., 2020). Therefore, an occupational health concern of PFAS from AFFF has become more pervasive for firefighters (Laitinen et al., 2014; Gao et al., 2015; Grandjean and Clapp, 2015; Rotander et al., 2015; Mastrantonio et al., 2018). PFAS that could come out from the durable water- and oil-repellent (DWR) finish of the turnout gear have become an emerging topic very recently (Peaslee et al., 2020; Muensterman et al., 2021). PFAS have been detected in new and used turnout gear (Rewerts et al., 2018; Peaslee et al., 2020; Muensterman et al., 2021; Shinde and Ormond, 2021). The outer shell of the turnout gear is typically treated with side-chain fluorinated polymers, followed by a polytetrafluoroethylene-based (PTFE) moisture barrier (Holmquist et al., 2016; Henry et al., 2018). In addition, firefighters also could be exposed to PFAS while extinguishing structural or car fires, which may off-gas PFAS in the smoke due to the burning of different materials containing PFAS. Moreover, high concentrations of PFAS have been detected in the dust and air inside the fire stations (Hall et al., 2020; Young et al., 2021). Therefore, the surrounding environment of the fire scene and fire station is also a potential source of PFAS exposure (Hall et al., 2020; Muensterman et al., 2021; Young et al., 2021). Leaching of both volatile and non-volatile PFAS substances from the turnout gear and AFFF could be associated with the higher amount of PFAS in fire stations.

Step 3: PFAS in blood serum and firefighters' cancer

As discussed above, the firefighting occupation has been classified as a known carcinogen by IARC (Demers et al., 2022). Multiple pathways of PFAS exposure for firefighters are explored. Ingestion, inhalation, and dermal absorption are the most common exposure pathways as reported by literature. Elevated PFAS levels in blood serum and their association with certain types of cancer risk is discussed. Several studies on PFAS in blood serum (Gribble et al., 2015; Olsen et al., 2017; Graber et al., 2019; Kotlarz et al., 2020) and firefighters' cancers have been reported (LeMasters et al., 2006; Soteriades et al., 2019; Casjens et al., 2020; Laroche and L'Espérance, 2021).

3 Definition and classification of PFAS

In 2011, PFAS was defined by Buck et al. (2011) as "aliphatic highly fluorinated substances that contain one or more C atoms on which fluorine atoms have substituted all the hydrogen atoms, so that the substance contains the perfluoroalkyl moiety C_nF_{2n+1}." However, the Organization for Economic Co-operation and Development (OECD) reported in 2018 that molecules having fully fluorinated carbon atoms but lacking the -CF_3 group, thus did not meet the requirements of the previous definition by Buck et al., 2011 (OECD, 2018). Therefore, to resolve this disagreement, OECD has proposed to define PFAS as: "fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), e.g., with a few noted exceptions (represented by a carbon atom instead having H/Cl/Br/I atoms attached), any chemical with at least a perfluorinated methyl group (−CF_3) or a perfluorinated methylene group (−CF_2−) is a PFAS" (OECD, 2021). Therefore, it might be quite surprising but a universally accepted definition of PFAS is still wanted (Panieri et al., 2022).

Grouping the PFAS into two broad categories, polymeric and non-polymeric (Figure 1) molecules is the most adopted PFAS classification system, was proposed by Buck et al. (2011). The non-polymeric PFAS can be further divided into perfluoroalkyl and polyfluoroalkyl substances. The length of the fluorinated carbon chain is mostly used while classifying non-polymeric PFAS. The bioaccumulation, physico-chemical, and protein binding properties in addition to environmental fate distribution could be predicted by the length of the fluorinated carbon chain (Dai et al., 2013; Zhao et al., 2016; Johnson et al., 2021; Lu et al., 2021). If all the hydrogen atoms in each carbon atom have been replaced by fluorine except the terminal end the compound is known as a perfluoroalkyl substance (Figure 1) (Bank et al., 1994). The first available PFAS substances were perfluoroalkyl sulfonates (e.g., perfluorooctane sulfonate, $C_8F_{15}SO_3$-, PFOS) and perfluoroalkyl carboxylic acids (e.g., perfluorooctanoic acid, $C_7F_{15}COOH$, PFOA), which were manufactured using an electrochemical fluorinated (ECF) process (Simons, 1949). High thermal and chemical stability and lowering surface tension in aqueous systems even at low concentration are unique properties for the widespread use of PFAS substances (Grajeck and Peterson, 1959; Holzapfel, 1966; Buck et al., 2011). Perfluoroalkyl acids (PFAAs) are the most commercially produced perfluorinated surfactants, which include perfluoroalkyl sulfonic acid ($F(CF_2)_nSO_3H$, PFSA), perfluoroalkyl carboxylic acid ($F(CF_2)_nCO_2H$, PFCA), perfluoroalkyl phosphonic acid ($F(CF_2)_nP$ $(=O)(OH)_2$, PFPA),

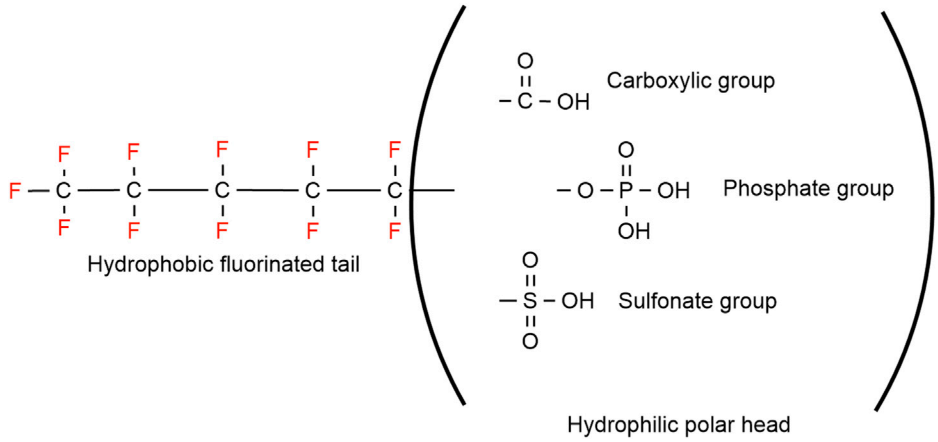


FIGURE 1
General structure of non-polymeric, perfluorinated PFAS substances.

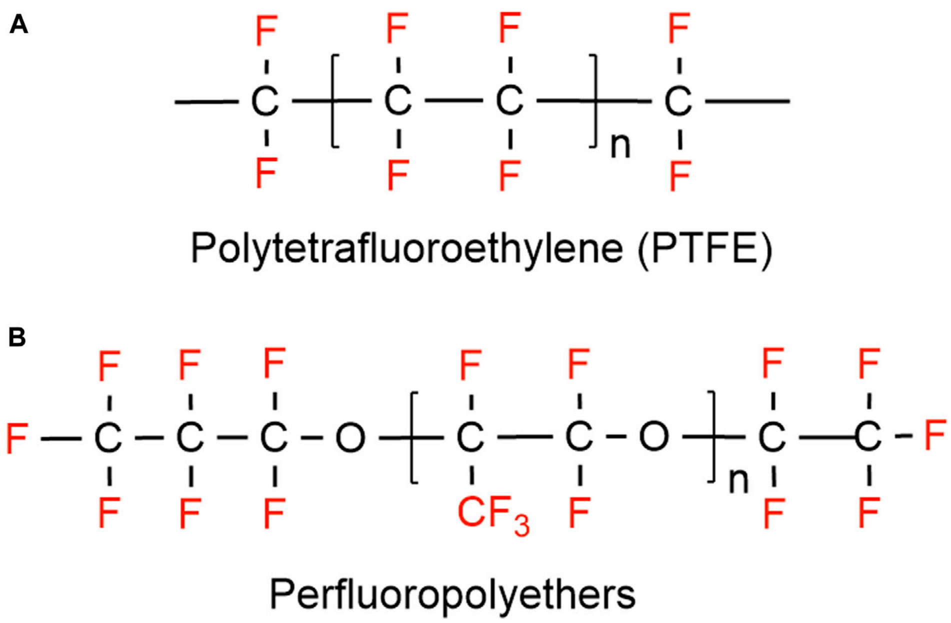


FIGURE 2
Polymeric PFAS substances, **(A)** PTFE, **(B)** perfluoropolyethers.

and perfluoroalkyl phosphinic acid ($F(CF_2)_nP$ (=O)(OH), PFPIA) (Buck et al., 2011).

On the other hand, substances where not all the hydrogen atoms (but more than one) have been substituted with fluorine, are classified as polyfluoroalkyl substances (e.g., 6:2 fluorotelomer alcohol (FTOH)) (Smart, 1994). Different types of polyfluoroalkyl substances are: 1) fluoropolymers, substances where if not all, most of the hydrogen atoms of the carbon chain are replaced by fluoride atoms (e.g., PVDF, PTFE), 2) side-chain fluorinated polymers, where a poly/perfluorinated carbon chains are attached to non-fluorinated carbon chains (e.g., fluorinated acrylate polymers), 3) perfluoropolyethers where the backbone chain contains oxygens and fluoride atoms directly bound to the carbon chain, are classified as polymeric PFAS (Figure 2) (Panieri et al., 2022).

The classification of PFAS has been summarized in Table 1.

4 Sources of PFAS exposure

Firefighters could be exposed to several types of PFAS in the course of their daily duties. The common potential sources of firefighter occupational exposure to PFAS are discussed below.

TABLE 1 List of the PFAS according to their categories and subgroups [adapted from (Panieri et al., 2022)].

	Perfluorinated		Polyfluorinated	
	Subgroup	Example	Subgroup	Example
Non-polymeric PFAS	Perfluoroalkyl acids (PFAAs) Perfluoroalkane sulfonic acids & sulfonates (PFSAs) Perfluoroalkane sulfinic acids (PFSIAs) Perfluorocarboxylic acids & carboxylates (PFCAs) Perfluoroalkyl phosphonic acids (PFPAs) Perfluoroalkyl phosphinic acids (PFPIAs)	PFBS, PFHxS, PFOS PFOSI PFBA, PFHXa, PFOA C8-PFPA C8/C8-PFPiA	Fluorotelomer compounds (FT)	6:2 FTO, 8:2 FTI
			Perfluoroalkane sulfonamido compounds (Me/Et/Bu-FASAs Miscellaneous)	MeFOSA, FOSE 4,8-Dioxa-3H-perfluorononanoate
	Perfluoroalkyl ether acids (PFEAs)	GenX, Adona, F-53B		
	Perfluoroalkane sulfonamides (FASA)	FOSA		
	Perfluoroalkane sulfonyl fluorides (PASFs)	PBSF, POSF		
	Perfluoroalkyl iodides (PFAIs)	PFHxI		
	Perfluoroalkanonyl fluorides (PAFs)	POF		
	Perfluoroalkyl aldehydes (PFALs)	PENAL		
Polymeric PFAS	**Subgroup**		**Example**	
	Fluoropolymers		PVDF, FEP, PFA, ETFE, PTFE	
	Side-chain Fluorinated Polymers		Fluorinated urethane/acrylate/methacrylate/oxetane polymers	
	Perfluoropolyethers (PFPEs)		PEPE-BP, Fluorolink-PFPE	

4.1 Firefighter turnout ensemble

4.1.1 Outer shell

Water and oil repellent finishes provide the fabric with the ability to resist wetting when contacted by water and oily substances. With a high level of repellency, both water and oil drops should stay on the fabric surface and easily roll off (Sayed and Dabhi, 2014). A simple coating of paraffin or wax is the oldest form of water repellent finish, which would eventually wash out (Sayed and Dabhi, 2014). The fabric surface can be made hydrophobic by simply treating them with a hydrocarbon wax or silicone oil, that will repel water. However, finishing a fabric surface that will repel both water and oil is rather difficult (Mahltig, 2015). All oil repellents are also water repellents, but not all water repellents are oil repellents. The surface tension of most oils is below 15 dyn/cm, therefore, oil repellency required a surface tension below 15 dyn/cm, which is only achievable using fluorocarbon treatments. The repellency of water (surface tension 72 dyn/cm) is easily achievable with silicones, hydrocarbon waxes, and other technologies. The contact angle of water on the surface can be used to simply determine and classify the wetting behavior (Figure 3) (Marmur, 2006; Posner, 2012). Surfaces with 90° or higher contact angle against water are usually considered hydrophobic (Mahltig, 2015). Rough surfaces like textiles were reported to have even higher than 150° contact angle against water (Shibuichi et al., 1998). The term "surface tension" is used instead of contact angle to get an estimate of wetting. The surface tension is usually dependent on the chemical composition of that particular material (e.g., solid material or liquid). The surface tension of the textile surface needs to be lower than that of desired liquid (e.g., water, oil) to repel the liquid (Mahltig, 2015). Fluorinated compounds are a class of material that are repellent to both water and oil (Mahltig, 2015).

Fluorinated compounds exhibit excellent thermal and chemical properties, particularly important for durability against cleaning and care of the product such as laundering, drying, etc. In addition, the fluorinated compounds' considerable reduction in surface tension property is essential to be classified as water- or oil-repellents (Sayed and Dabhi, 2014). The critical surface tension of textiles treated with acrylic polymers decreases rapidly with increasing chain length, which reaches to a minimum surface tension value at a nine-carbon chain (-$(CH_2)_8$-CF_3) (Audenaert et al., 1999). As the surface tension significantly decreases the water and oil repellency increases considerably (Guo et al., 2008; Sayed and Dabhi, 2014; Gargoubi et al., 2020). Thus, a gradual increase in the fluorinated chain length from 1 to 9 enhances the water and oil repellency of the material (Sayed and Dabhi, 2014).

Most durable water repellents (DWR) typically have hydrophobic or oleophobic side-chains which are linked to a backbone polymer (Holmquist et al., 2016). These side-chains are based on silicones, hydrocarbons, or per- and polyfluoroalkyl moieties (Figure 4) (Dechant, 1985; Kissa, 2001; Holmquist et al., 2016). These repellent groups need to be closely packed and oriented to achieve the repellent property. The best water and oil repellency properties result from the fluorinated side-chain polymers since they have the lowest critical surface energy (Fox and Zisman, 1950). The silicone- and hydrocarbon-based side-chains provide excellent water repellency but lack in their ability to effectively repel most oils. Since all the DWR finishes function according to these principles, the more densely these groups are packed, the more hydrophobicity will result (Wang et al., 1997). Any conformation

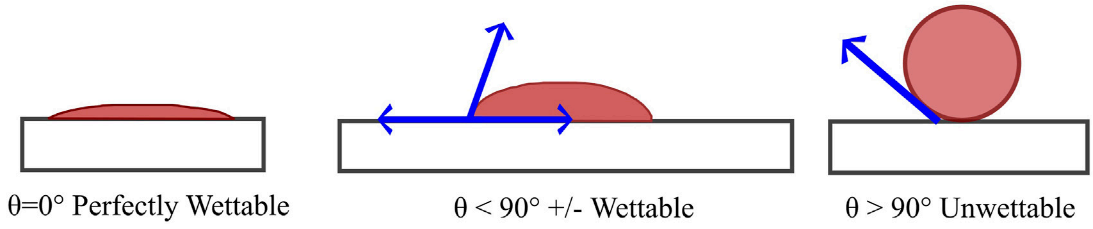


FIGURE 3
Wettability and contact angle of a substrate.

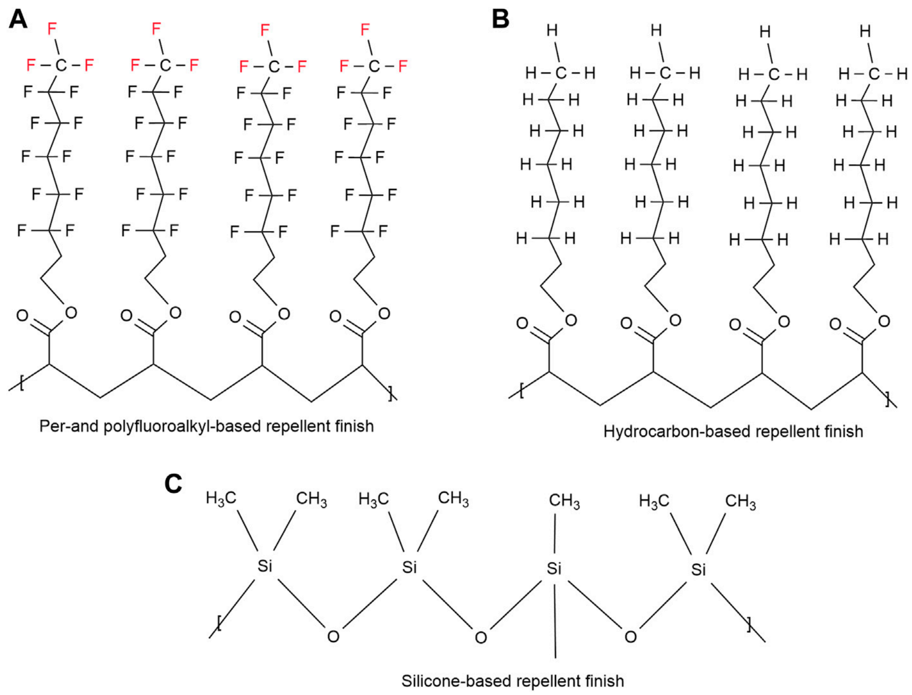


FIGURE 4
Structural examples of **(A)** side-chain fluorinated polymer, **(B)** hydrocarbon based repellent finish **(C)** silicone.

changes would cause fewer hydrophobic groups on the textile surface and hence less water repellency (Holmquist et al., 2016). In addition, a certain length of hydrophobic chain is required to protect the fabric from polar water droplets (Honda et al., 2005; Water, 2012).

Side-chain fluoropolymers are a form of PFAS used on the outer shell of firefighters' turnout gear primarily to impart the durable water and oil repellency (Holmquist et al., 2016; Henry et al., 2018; Peaslee et al., 2020). Therefore, the outer shell material of turnout jackets and pants along with any other fabric surfaces in hoods, gloves, or boots that exhibit water and oil repellency have traditionally contained some form of fluorinated acrylate side-chain polymers, which may be built into the fabric or applied after the fabric is woven (Holmquist et al., 2016; Peaslee et al., 2020). Although the turnout gear has typically been treated with the side-chain fluoropolymer chemistries, many studies have reported the presence of non-polymeric PFAS on the textile materials (Gremmel et al., 2016; Schellenberger et al., 2018; Peaslee et al., 2020; Liagkouridis et al., 2021; Muensterman et al., 2021; van der Veen et al., 2022). A previous study reported that decomposing of side-chain polymeric PFAS could release non-polymeric PFAS (Washington et al., 2015). Fluorinated side-chain polymer treated durable water- and oil-repellents may release perfluoroalkyl carboxylic acids (PFCAs) and fluorotelomer alcohols (FTOHs) (Posner, 2012; Gremmel et al., 2016). Additionally, a study found two acylates; fluorotelomer acrylates (FTAC) in 28% and fluorotelomer methacrylate (FTMAC) in 58% of their air samples (n = 57) (Winkens et al., 2017). These volatile PFAS could potentially be the unreacted residual monomers from various side-chain fluorinated polymers (Russell et al., 2008). Therefore, degradation of the PFAS finish and textile surface due to ultra-violet light, washing, and high temperature exposures could release small volatile PFAS molecules as well as fabric dust/lint and subsequently serve as a source of PFAS exposure through inhalation, ingestion

TABLE 2 Estimated elimination Half-lives.

Perfluoroalkyls	Estimated elimination half-lives
PFOA	2.-10.1 years
PFOS	3.3–27 years
PFHxS	4.7–35 years
PFNA	2.5–4.3 years
PFBS	665 h
PFBA	72–81 h

and dermal contact (Peaslee et al., 2020). For example, PFOA is a product of terminal degradation of C8-based side chain fluorinated polymer, which is a known persistent, bio-accumulative, and toxic substance. Similarly, alternative side-chains fluorinated polymers DWRs such as PFHxA (C6-based fluorotelomer) and PFBS (C4-based fluorotelomer) are equally persistent in the environment. The estimated elimination half-lives for selected perfluoroalkyl substances are provided in Table 2 (Substances and Registry, 2021).

Studies have reported significant quantities of PFAS in every layer of turnout gear including the thermal liner (Rewerts et al., 2018; Peaslee et al., 2020; Shinde and Ormond, 2021). Though most thermal liners are not intentionally treated with PFAS-based chemicals, studies found significant amounts of fluorine in all thermal liners tested (Peaslee et al., 2020; Muensterman et al., 2021). Some researchers have proposed that this finding suggests the migration of PFAS from the treated fabric layer to the untreated layer of clothing that may contact directly with the skin (Peaslee et al., 2020). Peaslee et al. (2020) found that most of the identified PFAS are short- and long-chain fluoroalkyl acids including PFOA. While that may be a possible route, another potential explanation is that PFAS in the smoke environment at a fire scene can easily infiltrate the turnout gear at the collar or waist interfaces as these ensembles are not vapor protective. A third possible route for the inner thermal liner to be contaminated with PFAS could be during the process of washing the gear. In this case the PFAS could be coming from the water source, a contaminated washer extractor, or from the contamination on the moisture barrier fabrics from the fire scene. In the washing process, the outer shell of the gear is separated from the moisture barrier and thermal liner and washed separately, so it is not as likely that any free PFAS from the outer shell would be able to transfer during laundering.

Muensterman et al. (2021) evaluated both the volatile and non-volatile PFAS in new turnout gear. The study found higher amounts of volatile PFAS than non-volatile PFAS in all layers of the turnout gear. The highest amount of both volatile and non-volatile PFAS was found in the moisture barrier, followed by the outer shell and thermal liner for volatile PFAS and thermal liner and outer shell for non-volatile PFAS (Muensterman et al., 2021). Longer chains fluorotelomer alcohols (FTOH) including 6:2, 8:2, 10:2, and 12:2 were measured in gear manufactured in 2003, suggesting that use of C8 chemistry at that time. However, shorter 6:2 FTOH were detected in the new turnout gear, which may reflect the switch from C8 to C6 chemistry in the early 2000s (2005–2015) (Muensterman et al., 2021). Studies suggest that significant amounts of PFAS may be released from the fluorinated textiles used in PPE for firefighters during the service of the garment (Peaslee et al., 2020; Muensterman et al., 2021). PFOA precursor material may leach from the side-chain fluorinated polymer, which could provide a route of exposure to the users of turnout gear (Peaslee et al., 2020).

Due to the undesirable toxicological and environmental behavior of long-chain side-chain fluorinated polymers, the industry is trying to move to alternative chemicals such as shorted chain fluorinated polymers and non-fluorinated durable water repellent finishes (Hill et al., 2017; Schellenberger et al., 2018; van der Veen et al., 2022). As a part of an alternative chemical analysis, Schellenberger et al. (2018) and Hill et al. (2017) evaluated the performance and durability of available fluorinated and non-fluorinated durable water repellent finishes on polyester and polyamide fabrics, which are usually used for outdoor performance clothing. van der Veen et al. (2022) evaluated the release of PFAS chemicals from C8 and C6-based fluorinated DWR on polyester and polyamide fabrics. As predicted, C8-based durable water repellent finishes showed the highest resistance to water and the highest contact angle, followed by C6 and C4-based DWR (Hill et al., 2017; Schellenberger et al., 2018). Hydrocarbon and silicone-based non-fluorinated DWR showed satisfying water repellency, but their repellency and durability performance were not consistent to make them alternative to fluorinated DWR (Hill et al., 2017; Schellenberger et al., 2018). Only the fluorine-based DWR showed resistance to oils, which was highest for C8-based DWR and reduced with the shorter chain length (Hill et al., 2017; Schellenberger et al., 2018). Similar patterns were observed in terms of durability and chain length of fluorinated DWR, decreasing water repellency was observed with decreasing chain length from 8 to 6 carbons. In addition, formation of longer chain perfluoroalkyl acids increased with ageing from C6 and C8-based DWR (van der Veen et al., 2022). However, non-fluorinated DWR showed good durability and was comparable in terms of durability and water repellency to the best fluorinated DWR (Schellenberger et al., 2018). C4-based DWR lost the oil repellency almost entirely whereas C8-based showed a strong drop after 10 cycles of washing (Schellenberger et al., 2018).

4.1.2 Moisture barrier

In protective textiles, the moisture barrier is used to provide a breathable barrier that is resistant to water and many other liquids, however, it allows moisture vapor to pass through. In this way, the wearer gets protection from hot water and other toxic liquids while maintaining a heat balance by evaporating sweat vapors in high temperatures (Song and Lu, 2013; Shaid et al., 2018). The moisture barriers are either a hydrophobic membrane, coating, or microporous membrane (Holmes, 2000). Typically, a moisture barrier is composed of a two-layered membrane; a flame-resistant woven or non-woven fabric is bonded to a porous polymer film. The polymer film is typically composed of polyester, polyurethane, or expanded polytetrafluoroethylene (ePTFE). While all three polymers may perform similarly in moisture management, ePTFE exceeds the other two in terms of thermal protective performance and breathability. Polyester and polyurethane coatings start to degrade at around 150°C, and melt at 170°C–180°C. In contrast, the ePTFE membrane shows the high level of performance as the outer shell fabrics, which can withstand up to 350°C temperature. Therefore, most commercially available moisture barriers are ePTFE coated. In addition, moisture vapor transfer property of ePTFE membrane is the reason that these membranes are widely used compared to the polyester and polyurethane membranes. In the high heat environment, that added breathability is critical to limit the heat stress and reduce thermal burden.

As previously stated, PTFE is a form of PFAS that could be a potential source of PFAS exposure (Peaslee et al., 2020). The exposure could occur from the degradation of PFAS and be either inhaled or dermally penetrate (Peaslee et al., 2020). Studies have found that applied PFAS on textile materials degrade over time from heat, sunlight, and water exposure (van der Veen et al., 2020). A recent study found moisture barriers contain higher amounts of volatile and non-volatile PFAS compared to outer layers and thermal liners (Muensterman et al., 2021). The same study also reported total fluorine in all layers, which was measured by Particle-induced gamma ray emission (PIGE) and Instrumental neutron activation analysis (INAA) techniques. Both techniques gave the highest total fluorine value in moisture barrier compared to the outer layer and thermal layer (Muensterman et al., 2021). Though Peaslee et al. (2020) found PFAS in each layer of the turnout gear, they could not quantify the amount of fluorine on the moisture barrier since it was above the limit of detection in the (PIGE). Studies have reported off very high amount of fluorine concentration in the moisture barrier and were attributed to the PTFE fluoropolymer (Peaslee et al., 2020; Muensterman et al., 2021). Presence of PFOA in the newest moisture barrier (manufactured after 2012) had lowered PFOA than the minimum detection, which might be due to the shifting from long-chain PFAS solvent aids during the manufacturing of PTFE (Peaslee et al., 2020).

PTFE falls under the subgroup of fluoropolymer PFAS. Henry et al. (2018) suggested that fluoropolymers should be considered as low concern polymers, defined by OECD as polymers which have an insignificant effect on human health and the environment (OECD, 2009). However, the US Environmental Protection Agency (EPA) has now accepted side-chain fluorinated polymers as polymers of low concern considering the risk posed by polymeric PFAS but has not acted on fluoropolymers intrinsically (EPA, 2010). Lohmann et al. (2020) classified PFAS products as fluoropolymer substances, products, and finished articles. PTFE is an example of a substance where the chemical structure is known, whereas the commercial product is the actual product available in the market sold by different manufacturers, which may contain impurities from the production. The ePTFE moisture barrier used in firefighters' turnout gear is an example of a finished article, which is manufactured from products (Lohmann et al., 2020). Though there is not enough evidence to justify keeping the fluoropolymers in the same toxicity group of non-polymeric PFAS, the emission of low molecular weight PFAS which are used as polymer processing aids during the manufacturing process of some type of fluoropolymers still can pose significant health and environmental effects (Henry et al., 2018; Hopkins et al., 2018; Brandsma et al., 2019; Lohmann et al., 2020). Therefore, Lohmann et al. (2020) suggested that fluoropolymer should not be considered as a polymer of low concern.

4.2 Aqueous film-forming foams

Fires involving hydrocarbon and other flammable liquids are Class B fires (Laitinen et al., 2014). Since water is more dense than liquid hydrocarbon fuels, it ends up at the bottom layer of a burning hydrocarbon surface and becomes ineffective at extinguishing the fire (Korzeniowski et al., 2018). In addition, the burning temperature of most fire scenes (≥175°C) is significantly higher than the boiling temperature of water (100°C), which causes vaporization of water to form steam. This could cause burn injuries and spread the fire rapidly (Korzeniowski et al., 2018). Therefore, aqueous film-forming foams (AFFF) which have excellent thermal stability and are capable of forming a film that sits on top of the fuel are used to extinguish this class of fires. Typical ingredients of aqueous film-forming foam are water, organic solvents, hydrocarbon surfactants, fluorosurfactants, polymers, and other additives (Peshoria et al., 2020). AFFF was developed in the 1960s and has been utilized to extinguish Class B fires ever since (Darwin et al., 1995). A considerable improvement in AFFF was achieved in 1970s through the manufacturing of fluorosurfactants-based foam. Per-fluorinated acids and salts of eight carbon atoms and other fluorinated compounds have been used mostly in film-forming foams (Kissa, 1994; Kissa, 2001). Naval Research Laboratory and 3M started working on AFFF containing fluorosurfactants-based on electrochemical fluorination (ECF) chemistry in the early 1960s, which led to the development of 3M's "Lightwater" AFFF (Gipe and Peterson, 1972). ECF and the fluorotelomer are two chemistries used to synthesize fluorosurfactants. Perfluoroalkyl sulfonates (PFSAs) (e.g., perfluorooctane sulphonate [PFOS], $C_8F_{17}SO_3$-) and perfluoroalkyl carboxylic acids (PFCAs) (e.g., perfluorooctanoic acid [PFOA], $C_7F_{15}COOH$) were the first commercially available fluorosurfactants, which were manufactured by the ECF process (Taylor, 1999; Kissa, 2001; Pabon and Corpart, 2002; Buck et al., 2012; Kempisty et al., 2016; Korzeniowski et al., 2018).

The strong carbon-fluorine bonds of the surfactants contribute to the high performance of AFFF (e.g., resistance to acid, alkali, oxidation, and reduction) even at high temperature. These surfactants play a unique role in reducing the surface tension of AFFF (Kissa, 1994; Kissa, 2001; Porter, 2013). "Surface active" properties of these fluorosurfactants come from the polar hydrophilic head and long non-polar fluorocarbon tail (Moody and Field, 2000; Buck et al., 2012; Baduel et al., 2017). The unique property of fluorosurfactants has made them almost irreplaceable in many unique industrial applications including extinguishing Class B fires (Jochyms et al., 2015). Firefighting foams are one of the reasons for the widespread presence of PFOS and PFOA, also known as long-chain fluorosurfactants, in the environment. Significant increase in using fluorosurfactants has caused an increased awareness concerning the adverse effect of AFFF on human health and the environment (Bursian et al., 2020). These chemicals are bio-accumulative in humans and wildlife, and persistent in the environment due to their strong carbon-fluorine bond. Discharges of these long-chain fluorosurfactants have been a concern by researchers globally (Lau et al., 2007; Post et al., 2012).

Non-biodegradable fluorosurfactants used in AFFF have a long life in the environment. There is a desire to find alternatives to fluorosurfactants due to their persistent nature (Wang et al., 2018). Usually, substances degrade or become immobilized when released into the environment but perfluorinated substances experience neither. Hence, these substances are highly soluble, transferable, and bioaccumulative (Peshoria et al., 2020). Bioaccumulation occurs when substances have affinity towards the biological component such as fat and protein and are stored in the fatty regions (Liu et al., 2011). Long-chain fluorosurfactants, which were used in traditional firefighting foam, have been recognized for their affinity toward liver, kidney, and blood protein (Pizzurro et al., 2019). Fluorosurfactants have been identified as the principal component of AFFF that causes their negative environmental impacts (Høisæter et al., 2019).

Different PFAS such as perfluorooctanoic acid or its salt, perfluorooctanesulfonic acid or its salt, and perfluorohexanesulfonic acid have been detected in blood, human serum, and milk (Calafat Antonia et al., 2007; von Ehrenstein et al., 2009; Gützkow et al., 2012). Studies on perfluoroalkyl acids (PFAAs), including PFOS and PFOA, have shown that these compounds may affect total and LDL cholesterol and are associate with breast cancer (Steenland et al., 2009; Nelson et al., 2010; Bonefeld-Jorgensen et al., 2011). A study conducted by Shaw et al. (2013) found that firefighter exposure to fire retardant chemicals, such as polychlorinated and polybrominated dibenzo-p-dioxins and dibenzofurans have similar effects.

Elimination of long-chain fluorosurfactants, while continuing to deliver the unique and valuable properties of fluorosurfactants, led manufacturers to develop short-chain alternatives (Peshoria et al., 2020). Studies have shown that short-chain alternatives have a less impact on environment and human health compared to long-chain chemistry (EI Corporation, 2014; Buck, 2015). However, there is still controversy about whether short-chain PFAS have less impact on environment and human health compared to long-chain PFAS. Some sources say that short chain PFAS are better while some do not. Carbon chain lengths greater than or equal to six within the perfluoroalkane sulfonate ($C_nF_{2n+1}SO_3(H)$) (PFSA) family are considered as long-chains. However, in the perfluorocarboxylic acid ($C_{x-1}F_{2x-1}COOH$) (PFCA) family carbon chain lengths greater than or equal to eight are considered as long-chains (Kempisty et al., 2016; Korzeniowski et al., 2018). This is due to the significant differences in toxicity and bio-accumulation properties between the two families (Gannon et al., 2011).

A study found increased levels of perfluorohexanoic acid (PFHxA) and perfluorooctanoic acid (PFNA) in the firefighters' blood serum after the training session, where the firefighters were exposed to AFFF (Laitinen et al., 2014). However, these elevated PFAS were not the main components of the AFFF. It was hypothesized that long-chain fluorotelomers decomposed during the jet fuel fire (Laitinen et al., 2014). Firefighters' exposure to PFAS from AFFF could be through inhalation and dermal routes. Ingestion is possible from hand-to-mouth transfer from contaminated turnout gear after a suppression or training (Laitinen et al., 2014).

4.3 Fire scene

Research found that the risk of PFAS exposure is higher for firefighters compared to the general public (Laitinen et al., 2014; Grandjean and Clapp, 2015; Rotander et al., 2015; Mastrantonio et al., 2018; Peaslee et al., 2020). Although the use of PFOA and PFOS has been stopped mostly over the last 15 years, these compounds were commonly used in furniture, carpet, paper, or industrial products (Beecher and Brown, 2018; Mazumder and Islam, 2021). Many of the products containing these compounds are still available in our daily life. PFAS are also currently used in several applications including apparel, semiconductors, and pharmaceuticals (Figure 5) (Rizzuto, 2020). The highest quantity of PFAS in the USA is used in electronics. PFAS are used in electronic products such as wire, cables, liquid crystal or flat panel displays. Electronic devices used as testing equipment like sensors and fluids used for heat transfer are also required to use PFAS as fluorinated compounds significantly improve the applications of these devices (Glüge et al., 2020; Tansel, 2022).

PFOA and PFOS can be produced from these PFAS containing products once these precursor compounds break down. During a fire, PFAS compounds (both polymeric and non-polymeric) may break down into precursor compounds like fluorotelomers alcohols that can further degrade into the terminal PFOA, PFOS, or other fluorinated compounds and be released into the environment. Firefighters or first responders on the fire scene would be exposed to these compounds during firefighting activities in emergency response and during training scenarios.

Tao et al. (2008) investigated perfluorochemicals from blood plasma samples of first responders due to the exposure to dust and smoke generated from the collapse of the World Trade Center (WTC). Plasma levels of PFOA and perfluorohexane sulfonate (PFHxS) were found more than twofold in the body of first responders compared to the general public (Tao et al., 2008). Firefighting foam, furniture, or other materials used inside the buildings might be the possible source of perfluorochemicals like PFOS and PFOA which were released in and around the site followed by the collapse. The findings of this research suggested that greater exposure to smoke and dust might cause the high concentrations of fluorochemicals in the body of first responders. They also found that smoke exposure contributed more compared to dust exposure to elevate the concentration of PFOA and PFHxS. Like the WTC incident, firefighters perform their duties in numerous structural burns and expose themselves to a high concentration of toxic chemicals including fluorochemicals present in smoke and dust generated from the burn of pulverized building materials and contents.

Previous studies showed that various volatile and semi-volatile compounds can off-gas from the surface of turnout gear for a certain period which raises concern regarding PFAS as firefighters get exposed to AFFF on a fire scene or smoke generated from PFAS-containing consumer products (Fent et al., 2015; Fent et al., 2017; Mayer et al., 2019). If generated PFAS from the fire scene can adsorb to the surface of ensembles, the exposure will be transferred to where the gear is stored in the fire station. Therefore, further research is required to investigate whether PFAS-contaminated gear works as an additional source of PFAS presence inside the fire station.

4.4 Dust and indoor air

According to the US EPA, adults and children ingest almost 30 mg and 60–100 mg of indoor dust per day respectively (Moya et al., 2011). For the general public, indoor environments, including dust and air, are considered as a source of PFAS or organic fluorine exposure (De Silva et al., 2012). PFAS concentrations for

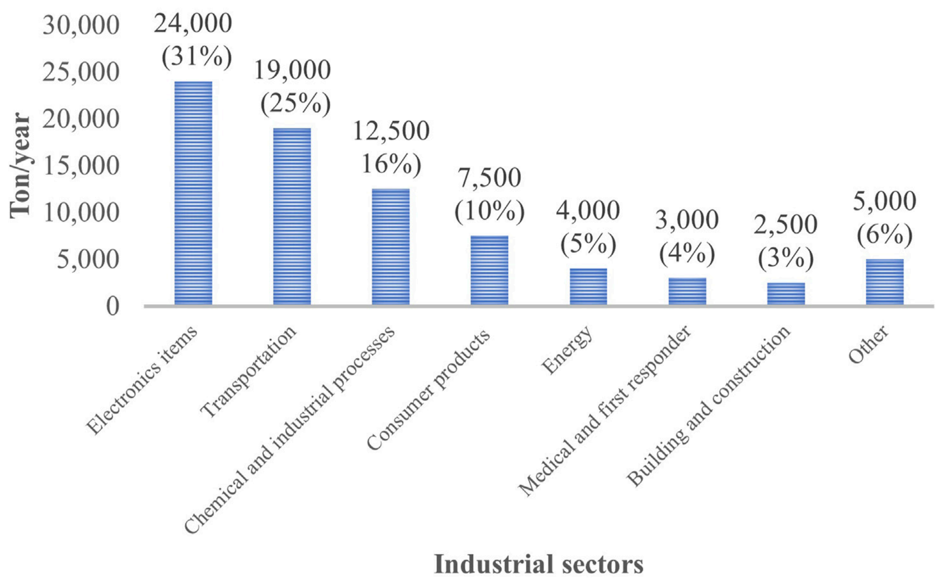


FIGURE 5
Use of fluoropolymers (in tons) by United States industrial sectors in 2018 (Kempisty and Racz, 2021).

compounds such as PFCAs, PFSAs, FTOHs, and perfluorooctylsulfonamides (PFSAm) have been reported to be higher in indoor air compared to outdoor air (Shoeib et al., 2005; Harrad et al., 2010). Shoeib et al. (2005) found that a semi-volatile neutral precursor, PFSAm, was 10–20 times higher in indoor air compared to outdoor air. A similar trend was observed for some natural volatile precursors such as PFSAs and PFCAs when indoor and outdoor air were compared (Shoeib et al., 2011). Fraser et al. (2012) investigated indoor air from 30 offices and found significantly high concentrations of polyfluorinated compounds (PFC) inside these offices. They also observed the highest FTOH in the most recently constructed building among other offices and concluded that off-gassing of FTOHs from the new carpets or furniture from the new buildings is mostly responsible for this elevated concentration (Fraser et al., 2012).

In addition to turnout gear, firefighters also store other sources of PFAS, such as AFFF and upholstered furniture, in fire stations. With these items, firefighters may bring residual PFAS contamination into the fire station which can act as a source of PFAS by contaminating indoor air or releasing air-prone dust. Previously, dust has been found to be an important exposure pathway of flame-retardant chemicals for firefighters (Jones-Otazo et al., 2005; D'Hollander et al., 2010; Stapleton et al., 2012; Mazumder and Islam, 2021). Therefore, it was required to investigate the role of indoor air and dust as the potential source of PFAS exposure for firefighters. Recent research found significantly high concentrations of PFAS in fire station dust which is alarming for firefighters as they spend most of their shift inside fire stations (Hall et al., 2020; Young et al., 2021). Young et al. (2021) analyzed dust samples from 15 fire stations in Massachusetts targeting 24 PFAS. The median dust concentration of these 24 PFAS in fire stations was 98.7 ng/g with N-EtFOSAA, 6:2 FtS, PFDS, 8:2 FtS, and PFOS being the prominent components. The targeted 24 PFAS account for only 1.2% of the total detected fluorine mass which indicates the presence of unidentified non-polymeric and polymeric PFAS in the dust (Robel et al., 2017; Schultes et al., 2019). They also found a higher concentration of fluorine from the dust of turnout gear locker rooms compared to the dust collected from living rooms in fire stations. Since turnout gear is kept in locker rooms in some stations (in others it is kept in the engine bay), this demonstrated that turnout gear could be a major source of PFAS exposure to firefighters.

PFAS contaminated dust could be originated from external contamination during firefighting activities or the PFAS intentionally added to gear. Laundering also may release some of the PFAS used in turnout gear because it has been found that side-chain fluoropolymers from the individual fiber can be released during washing of outdoor jackets (Schellenberger et al., 2019). When the fluorine-containing fibers release in the environment, the backbone of the fluorinated polymer may be cleaved over time and form short-chain perfluoroalkyl acids. Little information has been obtained yet regarding the release of PFAS compounds used in firefighting ensembles due to laundering. Therefore, the contribution of laundering to the release of PFAS compounds should be explored further. Hall et al. (2020) investigated indoor dust samples collected from 49 fire stations located both in United States and Canada and found 6:2 FTOH to be the most prominent PFAS detected (760 ng/g dust). They also collected dust from North Carolina homes and found significantly higher PFOS, PFOA, PFHxS, PFNA, and 6:2 diPAP in fire station dust compared to residential dust. Median dust levels of PFOS, PFHxS, and 6:2 diPAP were 15 times, 3 times, and 2.5 times higher, respectively, in fire station dust compared to home dust (Hall et al., 2020). Although this finding does not guarantee similar trends all over the country, this indicates higher exposure to PFAS inside fire stations compared to residential areas. Authors found that PFAS concentration in the dust of United States fire stations is significantly higher compared to the dust collected from Canadian fire stations although they hypothesized that differences in data collection period could be responsible for this difference (Hall et al., 2020). PFOS was predominantly present in the dust collected from United States fire stations.

PFAS have been detected on almost every layer of turnout gear since PFAS are used in the turnout gear to impart heat stable and oil resistance properties (Peaslee et al., 2020). Young et al. (2021) found PFAS on the surface of turnout gear collected by gear wipes. The highest detected amount of PFAS was 84,500 ng/wipe whereas over 50% of the total PFAS mass on gear wipes consisted of perfluoroalkyl carboxylic acids (PFCAs). PFOA, PFHxA, PFDA, PFNA, PFHpA, and 8:2 FtS were the most frequently detected PFCAs. The concentration of volatile PFAS is found higher in turnout gear compared to non-volatile PFAS (Muensterman et al., 2021). PFAS used in gear can degrade over time from exposures to heat, water, and sunlight, which indicates used PFAS in firefighters' ensembles also can be shed into the environment and act as a source of exposure for firefighters (Rankin et al., 2014; Rankin, 2015; van der Veen et al., 2020). Peaslee et al. (2020) compared between 10-year-old unused ensembles and ensembles used for 10 years of service. They found that used samples lost 80% of total fluorine from the outer shell surface within 10 years of service. The loss of fluorine indicates that PFAS likely shed off into the external environment. They also ran methanolic extraction of the dust samples collected from the workstation floor of a PPE processing facility and observed n-Et-FOSAA. Dust sample analysis indicates that it likely originated from PPE ensembles rather than AFFF since short and long fluorotelomer sulfonate and fluoroalkyl sulfonates were not detected in the samples (Place and Field, 2012; Barzen-Hanson et al., 2017; Peaslee et al., 2020). Methacrylate esters are generated from Et-FOSE which acts as the backbone polymer of fabric finishes and Et-FOSE is eventually turned into Et-FOSAA when it is decomposed and hydrolyzed (Plumlee et al., 2009; Benskin et al., 2013; Liu and Avendaño, 2013; Wang et al., 2014; Washington and Jenkins, 2015). Therefore, detection of Et-FOSAA in dust samples indicates side-chains of fluoropolymers are already degraded. Since Et-FOSE was presumably oxidized into PFOA, decay products from Et-FOSAA may eventually expose firefighters to PFOA precursor materials and enter into the firefighters' body (Plumlee et al., 2009).

5 Uptake pathways

The three primary routes of exposure are ingestion, inhalation, and dermal absorption. PFAS is known to be distributed throughout the environment, so all three routes are worth considering (Fraser et al., 2012; Peaslee et al., 2020). Ingestion of food and drink has been identified as the prominent uptake pathway of PFAS to the general public (Poothong et al., 2020). For instance, AFFFs and other environmental contaminants disperse through groundwater and soil from nearby sites (Backe et al., 2013; Houtz et al., 2013; Dauchy et al., 2019). PFAS can then accumulate in the human body directly from contaminated water or through foods including red meats, eggs, vegetables, snacks, seafood, animal fat, etc. (Huang et al., 2020).

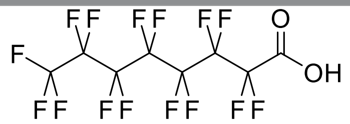
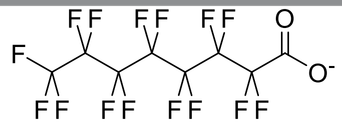
Since dietary consumption is a concern for the general public, firefighters should also be concerned (Trudel et al., 2008; Fromme et al., 2009; Haug et al., 2011a; Egeghy and Lorber, 2011). One study identified produce grown at a fire station as a major source of PFAS exposure (Tefera et al., 2022). This study showed that the consumption of eggs produced at firehouses appeared to be the leading route of PFAS exposure, followed by the consumption of fruits and vegetables and skin contact with dust-contaminated surfaces. Based on median and typical exposures, food consumption accounted for 82% of the total PFAS intake of firefighters, followed by incidental ingestion and dermal exposure to PFAS in dust (15%). Accidental ingestion and skin absorbed PFAS from soil and utensil cleaning resulted in <1% (Tefera et al., 2022). These findings broadly support the work of many other studies in which food consumption was identified as the most important route of PFAS exposure (Haug et al., 2011a; Haug et al., 2011b). Estimated dietary intake of PFAS in this study was much higher than previous estimates of dietary intake for the general population (Chain et al., 2018). Although this study focused on occupational firefighters, the dietary exposure routes identified here have wider relevance to the general public, especially those who consume food grown in or near PFAS-contaminated areas. This study is the first to describe a unique dietary PFAS exposure pathway in the context of professional firefighters.

In addition, due to occupational activities, the risk of dermal and respiratory absorption of PFAS is significantly higher for firefighters. For instance, PFAS used in turnout gear may transfer from the gear to the firefighter's skin. Another firefighting specific source is contact with AFFFs. Besides that, smoke generated from consumer products containing PFAS can contaminate turnout gear and skin as well as being an inhalation hazard. While no studies confirm the sources of PFAS on the fire scene, PFAS is still commercially used, so it should be present in soot or smoke. There is a need to determine the disposition and amounts of PFAS generated and released during fire suppression activities.

From these sources, the inhalation pathway should be limited assuming the proper and consistent use of self-contained breathing apparatuses (SCBA). Any volatilization of contaminants from smoke, AFFF, or the gear itself should not be inhaled during use of SCBAs during active fire supression. However, the use of SCBAs for each firefighter on a fire scene throughout the entire duration of the incident is not consistent across or within departments. Incident commanders and pump operators rarely use SCBAs on scene, and firefighters on interior or exterior attack may remove their facepieces during or after on-scene decontamination when they are still within reach of the smoke. This common misconception has resulted in few studies investigating the contribution to PFAS exposure of inhalation at a fire scene. Aside from the inhalation route, dermal absorption is most likely the next primary uptake pathway. Previous research has reported that chemical contaminants can transfer from fabrics to skin (Blum et al., 1978; Appel et al., 2008; Rossbach et al., 2014). Research needs to be done to determine the extent that PFAS can off-gas or leach from fabrics and then transfer and absorb into skin.

PFOA is a fluorochemical that has been detected in the blood of most Americans during the last decade, though the concentration is starting to decrease. Franko et al. (2012) investigated the possibility of dermal penetration of PFOA into human skin. They found that PFOA can penetrate human skin and dermal absorption of fluorochemicals could be a major route of PFAS exposure (Franko et al., 2012). The study showed that PFOA at

TABLE 3 Ionization states of perfluorooctanoic acid.

Un-ionized PFOA	Ionized PFOA
	

pH 2.25 has a 3-order of magnitude increase in the skin permeability coefficient compared to a pH of 5. This difference in pH affects the ionization state of PFOA, which has a pKa of 3.8 (Franko et al., 2012). Below the pKa value, PFOA is mostly un-ionized. Un-ionized compounds have better lipid solubility than their ionized counterparts and can more readily penetrate the lipid matrix of skin. The pH of skin is approximately 5.5 so PFOA is expected to be mostly ionized in skin. Although in general, PFOA penetration should be low for human skin as most of the exposures occur in the ionized state (Table 3), it is still a concern in the case of a higher level of exposure.

In vivo methods have been used to analyze the dermal absorption and effect of PFAS. Abraham and Monien (2022), was concerned about the absorption of PFAS through cosmetics so they measured the amount of dermally absorbed PFOA from a prepared sunscreen solution. The sunscreen solution (^{13}C4-PFOA concentration of 3.7 μg/g) was directly applied to the individual's whole body surface and allowed to maintain on the skin for 48 h before the individual took a shower. Blood samples were taken, and plasma analyzed with UHPLC-MS/MS. Starting at the initial application of sunscreen, PFOA was detected to be increasing for the first 10 days then stayed at a level rate for the next 110 days of sampling. Researchers estimated that 1.6% of the applied dose of the PFOA was absorbed over the exposure. This study helps illustrate that in this cosmetic dosing vehicle, PFOA can be absorbed dermally and is not quickly metabolized or excreted. A study showed that brominated and chlorinated chemicals, which are structurally related to PFAS, are dermally bioavailable and can result in significant body burdens. This suggests that dermal exposure could be an important exposure pathway to PFAS, especially with the consumer products that are relevant to dermal contact (i.e., water-proof fabrics, cosmetics) (Ragnarsdóttir et al., 2022).

Other *in vivo* studies have focused more on the toxicological impacts of PFAS. Franko et al. (2012) looked at cytokine expression on mouse skin and found no significant expression compared to the control. Dermal exposures of PFBA and PFOA have been found to increase liver weight and alter the PPAR pathway in mice (Shane et al., 2020; Weatherly et al., 2021). Han et al. (2020) also investigated the effect of dermal exposure to several PFAS (PFOA, PFHpA, PFHxA and PFPeA) on human skin and found no significant toxicological effects. The *in vivo* study of PFHpA found tubular and hepatocellular necrosis and germ cell degradation. While knowing the potential impacts is important, a large dose was used for the *in vivo* study and seems unreasonable for human exposure. Fasano et al. (2005) used rat and human skin to investigate PFOA penetration if dermal contact occurs. They found that PFOA can penetrate through both human and rat skin although the penetration rate is 34 times slower in human skin compared to rat skin. There is a need for more data on the dermal toxicological effects of PFAS, the mechanisms of action, and how it relates to humans. Moreover, no research has been conducted particularly addressing the dermal absorption of PFAS from new or contaminated turnout gear to firefighters.

One study conducted on children found that dust ingestion may have similar impacts to dietary ingestion of PFCs (Egeghy and Lorber, 2011). PFAS has already been demonstrated to be found in large concentrations inside fire stations (Hall et al., 2020; Young et al., 2021). Therefore, ingestion of dust and indoor air inside fire stations are major sources of PFAS for firefighters through the respiratory track besides most commonly recognized dietary sources like food and water (Sunderland et al., 2019; Chain et al., 2020). PFAS exposure to firefighters may also impact their children. In addition to potentially carrying PFAS into their homes, it can be transferred through breastmilk. One researcher found a strong correlation between higher PFAS concentration in maternal serum and breast milk (Inoue et al., 2004). Women make up approximately 5.1% of the firefighting population, their exposures need to be considered (Hulett et al., 2007; Trowbridge et al., 2020). This indicates children of female firefighters may get exposed to PFAS for a long-term at an early age through placenta or lactation (Inoue et al., 2004; Gützkow et al., 2012; Cariou et al., 2015; Chen et al., 2017). This could make children more vulnerable to adverse health effects (Inoue et al., 2004).

Young et al. (2021) recommended that as firefighters spend almost 72% of their time on a 24-hour shift inside the fire station, there needs to be minimal PFAS in the station. Indoor air samples need to be monitored regularly to determine the PFAS exposure level. To minimize both dermal and respiratory exposure to PFAS particles, firefighters should use protective ensembles including SCBA and turnout gear consistently at the fire scene. Wearing PFAS free clothing under protective ensembles, storing PFAS containing ensembles from other clothes, and washing hands after touching ensembles are also necessary to reduce the risk of dermal or respiratory exposure to PFAS (Young et al., 2021).

6 PFAS in blood serum

Historically, firefighters have been exposed to harmful chemicals from fire smoke and firefighting foams containing high levels of various PAHs and PFAS (Jalilian et al., 2019; Gasiorowski et al., 2022). Additionally, a new concern has been raised regarding firefighters' exposure to PFAS through turnout gear. Several studies have observed the association between PFAS exposure and a range of adverse health outcomes (Graber et al., 2021). Although PFAS are potentially harmful to human health, the exact threshold at which these risks may increase has remained unknown (Gasiorowski et al., 2022). Like other chemical substances, their ability to produce adverse health effects depends on exposure circumstances, such as magnitude, duration, and route of exposure (Fenton et al., 2021). In addition, individuals' age, sex, ethnicity, health status, and genetic predisposition may also influence adverse health outcomes (Fenton et al., 2021). Nonetheless, several long-chain PFAS have been associated with cancer risks (Temkin et al., 2020). Among them, PFOA has been classified as a possible human carcinogen for kidney and testicular cancers by the International Agency for Research on Cancer (Rotander et al., 2015; IW Group, 2016).

Per- and polyfluoroalkyl substances are particularly concerning because of their persistent, bioaccumulative properties (Li et al., 2018; Graber et al., 2021). They can stay in the human body for long periods of time without being changed and can interfere with the bodily functions (Li et al., 2018). They accumulate in organisms by binding to plasma protein and sequestration into the liver, kidney, and lungs (Meegoda et al., 2020). The ability to bind to blood proteins, slow urinary excretion, and low clearance are predictors of a bioaccumulative chemical with a long half-life (Tonnelier et al., 2012). Long-chain PFAS such as PFOS and PFOA have a half-life of 5.4, and 3.8 years, respectively (Li et al., 2018). PFOS alternatives, such as perfluorohexanesulfonic acid (PFHxS) has a much longer half-life of 8.5 years (Li et al., 2018). Other short chain alternatives, such as perfluoropentanoic acid (PFPeA) and perfluorobutane sulfonate (PFBS), have a shorter half-life of a couple of weeks (Li et al., 2018). Although PFOA and PFOS have been extensively studied, the health outcomes of their alternatives have not been studied as thoroughly. The presence of these PFAS alternatives in the human body is still a matter of concern despite having a shorter half-life and being at a low level.

Due to their widespread use and ubiquitous presence in the environment, most Americans have background exposure to some PFAS (Graber et al., 2021). However, firefighters' exposures can be occupationally related as they are exposed to PFAS through multiple pathways, making them more vulnerable to exposure. The commonly detected PFAS among firefighters are PFOA (ranging from 1.15 to 2.15 ng/mL), PFOS (ranging from 4.11 to 8.63 ng/mL), PFHxS (ranging from 1.83 to 6.15 ng/mL), PFNA (ranging from 0.46 to 0.97 ng/mL), PFDA (ranging from 0.25 to 0.31 ng/mL), and PFUnDA (ranging from 0.11 to 0.18 ng/mL) (Trowbridge et al., 2020; Graber et al., 2021). Firefighters with a history of using AFFF have elevated serum levels of PFOS and PFHxS (Rotander et al., 2015). In this regard, several studies reported higher serum levels of some long-chain PFAS among firefighters compared to the general population of similar demographic subsets (Dobraca et al., 2015; Rotander et al., 2015; Leary et al., 2020; Trowbridge et al., 2020; Graber et al., 2021) (Table 4). These studies used participants from the National Health and Nutrition Examination Survey (NHANES) as the representative of the US general population. The survey is administered by the Centers for Disease Control and Prevention (CDC) and published on a 2-year cycle.

One recent study conducted among male New Jersey volunteer firefighters observed that average serum concentrations of PFNA (+53%), PFDA (+39%), and PFDoA (+50%) were significantly higher than the NHANES population (Graber et al., 2021). Another study in the Southwest Ohio region found higher serum PFOS (+29%) and PFHxS (+74%) concentrations among suburban firefighters than the US adult male (NHANES 2015 to 2016 data) (Leary et al., 2020). In contrast, the serum levels of PFOS (−43%) and MeFOSAA (−88%) were significantly lower than the general population (Graber et al., 2021). The lower serum level coincides with the phase-out of some long-chain PFAS, including PFOA and PFOS, from consumer products and firefighting equipment (Rotander et al., 2015). However, these compounds are anticipated to persist for many years because of their long half-lives. The study also observed a positive association between serum levels of PFDA and PFDoA with years of firefighting (Graber et al., 2021). The findings were consistent with a 2015 biomonitoring study of Southern California firefighters (Dobraca et al., 2015). Both studies reported that the average serum concentrations of perfluorodecanoic acid (PFDA) were three times higher than those in NHANES participants. An all-female cohort study conducted in San Francisco found similar results, where women firefighters had higher geometric mean concentrations of PFNA, PFHxS, and PFUnDA than the office workers (Trowbridge et al., 2020). This study was unique in the sense that it compared firefighters to other non-firefighters in the same geographic area. One thing to be noted is that comparing with NHANES samples does not necessarily reflect what is the overall PFAS exposure scenario in a particular area.

Though these study findings were consistent across different US geographic locations regarding higher serum levels in firefighters' blood, serum profile and levels of PFAS varied across different areas. One study in Southern California did not find any detectable serum levels of PFDoA (Dobraca et al., 2015), while another study in New Jersey detected significantly elevated serum levels of PFDoA (Graber et al., 2021). The PFDoA serum level was twice as high as in the NHANES participants (Graber et al., 2021). Similarly, the mean serum levels of PFHxS and PFOS varied across location. Background exposure stemming from consumer product use (Lindstrom et al., 2011), food and drinking water contamination (Xu et al., 2021), proximity to industrial sites (Steenland et al., 2009; Schroeder et al., 2021), and military airbases (Xu et al., 2021) may also contribute to the high levels of some PFAS in different geographical areas. In a study, female firefighters assigned to the airport fire station reported having two times higher PFNA levels than firefighters assigned to other stations in San Francisco (Trowbridge et al., 2020). Airport firefighters in the Southwest Ohio region had 21%–62% higher PFAS serum concentrations than suburban firefighters (Leary et al., 2020). Likewise, a study in Finland observed that training activities involving AFFF to extinguish jet fuel fires increased firefighters' serum PFNA concentrations (Laitinen et al., 2014). Although PFNA is not considered a main ingredient in AFFF, these observations indicate other possible PFAS sources in fire scenes than firefighting foam. Observational studies have found female firefighters had lower levels of most PFAS compared to male firefighters (Wong et al., 2014; Trowbridge et al., 2020). Perfluorinated compounds have a higher affinity toward fatty acid-binding proteins in the blood, and therefore some PFAS might be eliminated from the body during blood donation or menstruation cycles (Jones et al., 2003; Rickard et al., 2022). Blood donor firefighters were found to have lower PFAS levels than non-donor firefighters with equivalent exposure (Rotander et al., 2015),

TABLE 4 Study PFAS Concentration in Firefighter Blood Serum (geometric mean ng/mL ±95% CI).

	Rotander et al. (2015)	Dobraca et al. (2015)	Trowbridge et al. (2020)	Leary et al. (2020)	Graber et al. (2021)
Sample Year	2013	2010–2011	2014–2015	2018–2019	2019
Cohort Size	149	101	86	36	135
Region	Queensland, Australia	Southern California	San Francisco	Southwest Ohio	New Jersey
Compound					
Perfluoroheptanoic acid (PFHpA)	0.1	0.13 (±0.02)			
Perfluorooctanoic acid (PFOA)	4.6	3.75 (±0.38)	1.15 (±0.10)	2.15	2.07 (±0.18)
Perfluorononanoic acid (PFNA)	0.76	1.15 (±0.10)	0.67 (±0.06)	0.46	0.97 (±0.08)
Perfluorodecanoic acid (PFDA)	0.29	0.90 (±0.12)	0.25 (±0.02)		0.31 (±0.02)
Perfluoroundecanoic acid (PFUnDA)	0.16	0.24 (±0.03)	0.18 (±0.04)		0.11 (±0.01)
Perfluorododecanoic acid (PFDoA)	NC		NC		0.14 (±0.01)
Perfluorobutane sulfonic acid (PFBS)	NC	NC	0.13 (±0.03)		
Perfluorohexane sulfonic acid (PFHxS)	33	2.26 (±0.26)	3.79 (±0.55)	6.15	1.83 (±0.22)
Perfluorooctane sulfonic (PFOS)	74	12.5 (±1.16)	4.11 (±0.43)	8.63	4.25 (±0.55)
Perfluoroactane sulfonamide (PFOSA)		0.032 (±0.005)			
2-(*N*-methyl-PFOSA) acetic acid (MeFOSAA)		0.16 (±0.03)			0.08 (±0.01)
2-(*N*-ethyl-PFOSA) acetic acid (EtFOSAA)		0.016 (±0.002)			

NC—Not calculated due to low detections.

suggesting plasma donation could be a possible elimination pathway (Wong et al., 2014; Silver et al., 2021).

7 PFAS exposure and cancer

There has been extensive research examining possible relationships between PFAS levels in blood and harmful health effects in people (Fletcher et al., 2013; Wielsøe et al., 2015; Croce et al., 2019; Jain and Ducatman, 2019; Wang et al., 2019; Li et al., 2021). PFOA and PFOS are two of the most widely studied PFAS compounds, followed by PFHxS and PFNA (Kim et al., 2021). These studies suggest that high levels of some PFAS exposure may lead to a variety of adverse health outcomes. These health effects include carcinogenicity (Jalilian et al., 2019), hormonal disruption (Chain et al., 2018), immunotoxicity (Chain et al., 2018), liver function alterations (Gleason et al., 2015), low fetal weight (Wikström et al., 2020), increased lipid level (Steenland et al., 2009), tumor induction (Chain et al., 2018), and obesity (Graber et al., 2021). Exposure level of PFAS can be different depending on where people live or what occupations they are involved in. Also, low levels of exposure over long periods of time may pose different types of health risks. Research on long-term effects of low-level exposure to certain PFAS is still in progress.

Adverse health effects reported in firefighters are like those of other occupational groups and the general population exposed to PFAS, including risks for certain cancers (Goodrich et al., 2021). Given the higher rates of certain types of cancer and cancer-related deaths among firefighters, several studies have examined the associations between firefighters' occupational exposures and cancer incidence (Jalilian et al., 2019; Soteriades et al., 2019). Results have been inconsistent but generally suggest an increased risk of some cancer types such as colon, prostate, and testicular cancers (Soteriades et al., 2019). Besides PFAS, firefighters are exposed to a number of chemical agents, some of which are known carcinogens such as benzene and benzo [a]pyrene (Guerreiro et al., 2016). Little is known about the potential adverse effects of chronic exposure to such complex mixtures. Most of the existing studies so far have focused on health outcomes of individual perfluorinated compounds, with a few exploring their combined effects (Ojo et al., 2020; Ojo et al., 2021). To mimic real-life exposure and for accurate risk assessment, future research focus needs to move to the investigation of such complex mixtures of chemicals instead of single chemicals. However, one of the challenges of mixture risk assessment is the possible interaction between chemicals (i.e., synergistic or antagonistic effects) that may influence the combined activity.

Although a growing body of literature suggests a link between increased serum PFAS levels and cancer incidences, the carcinogenic mechanisms of PFAS are yet to be fully understood. A possible epigenetic mechanism is that occupational exposures in firefighters changes DNA methylation, a process that plays an important role in the healthy regulation of gene expression (Zhou et al., 2019; Goodrich et al., 2021). Changes in DNA methylation pattern can cause inactivation of certain tumor-suppressor genes and thus increase cancer risk (Zhou et al., 2019). In recent years, an increasing number of studies have examined epigenetic changes associated with PFAS exposure. Epigenetics studies focus on alterations in gene expression with no changes in DNA sequence resulting from environmental factors such as chemical exposure (Kim et al., 2021). DNA methylation, histone modification, and microRNA (miRNA) expression are three categories of epigenetic mechanism (Kim et al., 2021). PFAS-induced metabolic alteration is another proposed mechanism for the pro-carcinogenic actions of PFAS. Metabolic reprogramming is an important cancer hallmark (Phan et al., 2014). PFAS can interfere with the body's metabolic processes and induce biochemical and physiological changes (Jiang et al., 2015; Imir et al., 2021). Due to having structural similarity with fatty acids, PFAS can alter systemic metabolisms by binding to fatty acid transporters and metabolic enzymes (Jiang et al., 2015; Roth et al., 2020; Imir et al., 2021). Both animal and human studies have found evidence of PFAS-induced adverse metabolic effects (Knox et al., 2011; Geiger et al., 2014; Yu et al., 2016; Alderete et al., 2019).

Considering the liver is a primary target organ for long-chain PFAS storage, some researchers have studied the influence of PFAS in human liver cells (Ojo et al., 2020; Ojo et al., 2021). *In vitro* study results have shown dose-dependent association between PFOA exposure and altered DNA methylation (Tian et al., 2012). Other studies highlighted oxidative stress as the possible cause for epigenetic modification. PFOS exposure to hepatic (liver) cells reduced cellular activity and increased reactive oxygen species (ROS) levels in a concentration-dependent manner (Ojo et al., 2020). However, tested doses of PFAS were higher than levels found in the environment indicating these studies may be poor predictors of human reactions to PFAS exposure. Different animal models have also studied the carcinogenic activity of some PFAS. Exposure to PFOA in rodent models was found to be associated with the development of tumor cells in liver, pancreas, and testicles (Steenland and Winquist, 2021). Likewise, studies in rainbow trout observed PFOA exposure promoted the development of liver tumors (Steenland and Winquist, 2021). A recent study by the National Toxicology Program (NTP) found evidence of malignant liver tumor formation in male rats (Sprague-Dawley) induced by PFOA exposure (Program, 2020). The observed association between plasma concentrations of PFOA and tumor incidence suggested the potential link between high PFAS level in blood serum and increased cancer risks (Program, 2020). Similarly, exposure to PFOS in Albino Wistar rat liver showed PFOS-induced changes in miRNA expression and association with liver carcinogenesis (Wang et al., 2012). Although these animal studies provide support for the potential cancer development process, these mechanisms may not appear as relevant in humans.

In addition, PFOA and PFOS-focused work may not give a comprehensive understanding of the relationships between PFAS exposure and firefighter cancers. In this regard, human epidemiological studies can avoid such uncertainties associated with interspecies extrapolation. Several epidemiological studies suggested an association between high-level PFAS in blood serum and increased risk of cancers (Steenland et al., 2020; Bartell and Vieira, 2021). A recent meta-analysis reported that per 10 ng/mL increase in serum PFOA increases the average risk for kidney and testicular cancers, 16% and 3%, respectively (Bartell and Vieira, 2021). Another study concluded that the epidemiologic evidence remains supportive but not definitive for PFOA exposure and kidney and testicular cancer incidences (Steenland et al., 2020). Other epidemiologic studies have shown evidence of PFAS-induced epigenetic changes in both adult populations and birth cohorts (Kim et al., 2021). However, the number of studies is limited when it comes to the context of firefighters' exposure. One epigenetic study reported an association between years of firefighting and altered DNA methylation (Zhou et al., 2019). The study also observed DNA methylation varied among non-smoker male incumbent firefighters and new recruits (Zhou et al., 2019). Altered miRNA expression has also been linked to PFAS exposure associated with years of firefighting (Jeong et al., 2018). Epigenetic changes are part of the process that leads to cancer (Lu et al., 2020). PFAS-induced epigenetic changes could thus serve as a biomarker to predict the potential health effects in the exposed firefighter community. Given the unpredictability and challenges of fire scenes, monitoring firefighters' exposure is very complicated. Recent focus has shifted to biomonitoring which may overcome some of the challenges and could serve as a valuable tool for health effects assessment. In this case, the level of biomarkers may vary depending on factors such as pre-existing health conditions (Jabeen et al., 2020), smoking habits (Soteriades et al., 2019), and second job exposure (Soteriades et al., 2019). Future studies should consider these factors while examining the association between firefighters' PFAS exposure and cancer incidence.

8 Challenges of PFAS in hazard assessment

Determining the health risk assessment of PFAS and their precursors is difficult. This is because 1) PFAS are a large, diverse group of substances which inhibits the easy distinction for assessment and management. This makes understanding which PFAS may be relevant for potential human health risk assessment difficult. 2) Very limited information is available on PFAS toxicity and its effects on public health, which makes the chemical-specific evaluation of the diverse PFAS nearly impossible. 3) Humans are frequently exposed to unknown mixtures of PFAS which may cause synergistic effects. 4) Toxicity studies often lack similarities between assays in animals and observation in humans, which makes the relevance of these studies on toxicity uncertain (Anderson et al., 2022).

Grouping of PFAS for mixture assessment is a challenge due to the complexities in the database and differences in regulatory guidance between countries. Hazard assessments for PFAS are usually based on research studies that include representative lead compounds, such as PFOA, PFOS, PFHxS, for which chemical, toxicity, and occurrence information is available (Colnot and Dekant, 2021). There are critical gaps in the understanding of PFAS chemistries and toxicities that inhibit the approach of standard mixtures risk assessment. There is a substantial variation within a PFAS class in their physico-chemical properties. The diversity in their chemical structures, applications, and subsequently their release in the environment and exposure together make the exposure-hazard assessment model very complex. Kwiatkowski et al. (2020) suggested that PFAS should be considered as a single class, and the risk assessment should be performed accordingly (Kwiatkowski et al., 2020).

9 Conclusion

PFAS are extensively used in firefighters' turnout gear, AFFF, and are also present in air and dust of the fire scene and fire station. Therefore, the risk of PFAS exposure is higher for firefighters compared to general population due to the occupational activities during firefighting. Increased cancer rate among the firefighters compared to the general population, and links between PFAS and cancer has raised the concern of PFAS exposure in the fire service. Turnout gear could be a potential source of PFAS exposure as PFCAs and FTOHs may be released from the turnout gear *via* degradation of water and oil repellent finishes or from release of PFAS contamination for the fire scene. These non-polymeric PFAS could then be potentially absorbed through inhalation, ingestion, and dermal absorption into the firefighter's body. The ePTFE used in the moisture barrier of the turnout gear is usually considered as a low concern polymer. However, the manufacturing process of ePTFE uses low molecular weight PFAS as polymer processing aids. Therefore, depending on the adulteration, PTFE polymer still could pose adverse health effects by releasing non-polymeric PFAS. Although turnout gear has been identified as a source of PFAS, more research is required to evaluate the PFAS exposure level from turnout gear to firefighters. Besides that, turnout gear may get contaminated by PFAS from the smoke of a structural fire or PFAS-containing AFFF which subsequently act as a source of exposure. Using AFFF during fire extinguishment has been a major source of PFAS exposure for firefighters and the public due to groundwater contamination. The adverse effects of using PFOA and PFOS in AFFF has already forced manufacturers to move to shorter-chain alternative PFAS and more recently fluorine-free alternatives. However, short-chain alternatives may still have adverse health effects and ecotoxicity that cannot be overlooked. Unknown fluorinated components of AFFF and their degradation products still need to be identified. Dust inside fire stations may act as a chemical reservoir of PFAS once compounds leach out from contaminated products. Therefore, indoor air and dust inside fire stations contain high concentrations of PFAS originating from contaminated gear, AFFF usage, or other PFAS-containing products that are present inside the fire station. Other sources of PFAS inside fire stations need to be further explored to achieve a PFAS-free environment in fire stations. Ingestion and inhalation of indoor dust and air are common PFAS exposure pathways. Dermal absorption may also be a dominant exposure pathway for firefighters which takes place due to skin exposure to PFAS contaminated sources. To date, only a few targeted PFAS have been analyzed to determine the risk of dermal absorption. Extensive research is required to better understand dermal absorption of other PFAS compounds. The high level of PFAS exposure at the workplace over a long period of time may increase the risk of firefighters developing health-related issues, including cancer. However, the complex exposure patterns of PFAS coming from multiple sources make it challenging to predict associated risks. Future studies need to address the interactions of PFAS mixtures while evaluating their potential toxicity and health outcomes. Additionally, researchers could leverage epigenetic studies to characterize firefighters' occupational exposure and their association with the development of work-related diseases. Firefighters are suggested to limit the exposures to PFAS as much as possible. The firefighting community has already started using PFAS-free outer shell materials for their turnout gear and have started transitioning to fluorine-free foams. However, intentionally added PFAS in turnout gear and foams may not be the only sources of occupational PFAS exposure that firefighters experience. Given the volume of PFAS used in consumer products, electronics, building materials, structures, and vehicles it is feasible that these chemicals can be released during combustion and lead to additional exposures to firefighters responding to the incident. These exposures may include respiratory hazards, direct dermal contact, or though settling on and contaminating the turnout gear, as has been shown with multiple other fireground contaminants and carcinogens such as polycyclic aromatic hydrocarbons. Therefore, a general recommendation is not to wear turnout gear where it is not needed (i.e., medical call, personal use, certain types of training, etc.). Also, decontamination should be the done carefully after every fire call to ensure fire stations are not contaminated by the fire scene carcinogens.

Author contributions

N-U-SM, AH, and RO contributed to the conception and design of the manuscript. N-U-SM, MH, and FJ wrote the first draft of the manuscript. AG, AH, and JL wrote sections of the manuscript. AH and RO reviewed it critically for important intellectual content. RO supervised the writing of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Funding

The funding of the project has provided by the Fire Prevention and Safety Grants (EMW-2020-FP-01120), part of the Federal Emergency Management Agency's Assistance to Firefighters Grant Program.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Materials

TYPE Original Research
PUBLISHED 24 April 2023
DOI 10.3389/fmats.2023.1175559

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RECEIVED 27 February 2023
ACCEPTED 12 April 2023
PUBLISHED 24 April 2023

CITATION
McQuerry M, Kwon C and Poley-Bogan M (2023), Female firefighters' increased risk of occupational exposure due to ill-fitting personal protective clothing.
Front. Mater. 10:1175559.
doi: 10.3389/fmats.2023.1175559

Female firefighters' increased risk of occupational exposure due to ill-fitting personal protective clothing

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Despite the growing female firefighter population, firefighting gear was originally designed with only the male human form in mind. As a result, women in the fire service experience issues of improper fit and injuries at rates exponentially higher than their male counterparts. Areas of ill-fit, specifically in interfaces, can increase the risk of occupational exposure for women in the fire service. The purpose of this research was to determine fit and sizing issues of personal protective clothing (PPC) to improve female firefighters' comfort, mobility, and safety. A mixed methods approach was adopted including a nationwide questionnaire, end-user focus groups, and remote three-dimensional body scanning of 189 female structural and wildland firefighters. Between 15%–21% of female firefighters were found to intentionally leave off a part of their PPC at least "sometimes," if not "nearly always," with the coat and pants being the primary items not donned. 100% of participants had wrist and ankle circumferences smaller than the smallest size garment's wrist and pant leg openings per the wildland sizing system, indicating interface areas and wildland PPC have the greatest opportunities for design and fit improvement. This study gathered and created the first and largest U.S. female firefighter anthropometric database. Overall results indicate female firefighters are wearing PPC with significant fit issues that not only reduce their comfort and restrict their mobility but pose increased safety risks related to occupational exposure.

KEYWORDS

female firefighter, personal protective clothing, turnout gear, wildland, protection, fit, sizing

1 Introduction

As of 2020, there were over 89,000 female firefighters in the United States making up 9% of the fire service (Fahy et al., 2022), a statistic that has continued to increase over the past several years. With more and more females entering the fire service, they must be properly outfitted with appropriate personal protective equipment (PPE) to ensure they are as protected as their male counterparts. Despite the growing female firefighter population, structural firefighting turnout gear was originally designed with only the male human form in mind (Boorady, Barker, Lin, et al., 2013). Previous research has shown 80% of female firefighters experience issues with ill-fitting PPE, a rate four times greater than their male counterparts' self-reported fit issues (Hulett et al., 2008). In turn, female firefighters experience a 33% greater risk of injury due to ill-fitting PPE (Liao et al., 2001; Boorady, Barker, Lin, et al., 2013; Andersen et al., 2016; Hollerbach et al., 2017; 2020). A lack of available and properly designed PPE for women in the fire service leads to a lack of protection, an increased risk of onsite injury, a reduction in mobility, and poor wear comfort due to areas of improper fit (McQuerry et al., 2019).

Improper fit can have severe consequences, especially in interface areas (e.g., sleeve/glove, neck/hood, coat/pant, and boot/pant) that allow for greater opportunity for liquid, chemical, and heat exposure. Firefighters' risk of hazardous exposure is evident in the recent uptick in awareness of firefighter cancer (Daniels et al., 2014; Lee et al., 2020; Ma et al., 2005; 2006; U.S. Fire Administration (USFA, 2019). As the International Association of Fire Fighters (IAFF) reports, occupational cancer is the leading cause of line-of-duty deaths in the fire service, especially when tracked longitudinally across their long service careers (International Association of Fire Fighters, 2023). Recent research into interface testing of PPE has exposed these vulnerable areas, as seen by the visual assessments from the Fluorescent Aerosol Screening Test (FAST) (Ormond et al., 2019). Based on the conditions of the emergency scene, smoke and particulates can seep through gaps and spaces at the neck, waist, wrists, and ankles. This is of particular concern for female firefighters as female turnout coats are often smaller, shortened versions of jackets made from patterns designed for men. Women in the fire service have reported lower satisfaction with the fit and functionality of their turnout ensemble in multiple areas as compared to their male counterparts (Park & Hahn, 2014). Specifically, female firefighters have reported oversized necklines and sleeve cuffs with too wide of openings (Jahnke et al., 2012; Park and Hahn, 2014).

A study by McQuerry (2020) demonstrated differences in male *versus* female firefighter turnout suit fit and the consequential impact on ergonomic range of motion (McQuerry, 2020). This study body scanned female (n = 6) and male (n = 10) firefighters in a stationary three-dimensional body scanner while wearing loose-fitting base layers and department-issued turnout suits. Differences in circumferential measurements between clothing configurations and sex were analyzed. Indeed, female firefighters experienced issues of improper fit and limited mobility in areas different from male firefighter participants (McQuerry, 2020). This study was limited, however, by the small sample size of female firefighter participants and the lack of tight-fitting base layers which prohibited the gathering of true body anthropometric measurements.

Few studies have collected the body measurements of United States (U.S.) female firefighters. Up until recently, PPE manufacturers have been forced to assume that female firefighters are the same anthropometrically as the general U.S. population female (Mcdowell et al., 2008; SizeUSA, 2003; Kuebler et al., 2019). The widely used SIZE United States® study was the first and only U.S. apparel-focused anthropometric database, however, it only included the general U.S. female population and is now considered by some to be outdated (SizeUSA, 2003). Recent general U.S. population databases have been published, however, none focus specifically on the female firefighter population and most lack the number and type of anthropometric measurements needed for firefighting PPE design (Center for Health Statistics, 2015; Kuebler et al., 2019). For example, the Center for Disease Control's (CDC) 2021 report on health statistics for U.S. adults collected from 2015–2018 only includes female waist circumference, mid-upper arm circumference, upper arm length, and upper leg length (Center for Health Statistics, 2015).

Hsiao, et al. (2014) published the first available U.S. national firefighter database of 71 anthropometric measurements including 88 female firefighters (Hsiao et al., 2014; NIOSH, 2015). This work was conducted in collaboration with the National Institute for Occupational Safety and Health (NIOSH) and the results demonstrated that women in the fire service were, on average, 29 mm taller than their female counterparts in the general U.S. population (Hsiao et al., 2014; NIOSH, 2015). This finding demonstrates the need for specific female firefighter anthropometric measurements. Although firefighter specific, the NIOSH database was limited by the heavy focus on male firefighters (n = 863) and the specific fire apparatus design application that impacted measurement selection.

Other occupational anthropometric surveys have been conducted previously such as the 1988 and 2012 Anthropometric Surveys of U.S. Army Personnel (Gordon et al., 1998; 2014) and the Anthropometric Source Book which is a handbook of weightless anthropometric data produced by the National Aeronautics and Space Administration (NASA) for engineers engaged in the design of equipment and clothing for the NASA Space Shuttle program (National Aeronautics and Space Administration (NASA, 1978). Most recently, a female firefighter anthropometry survey was completed and published in the United Kingdom (United Kingdom) (Stirling, 2022). Approximately half of the national United Kingdom female firefighting population was represented in the dataset and a total of 61 measures were included from body mass to handgrip strength (Stirling, 2022). Few circumferential measures, however, were taken and many more could be included.

The United Kingdom female firefighter anthropometry database rightly points out the common belief amongst many PPE designers that women are scaled-down versions of men (Stirling, 2022). Stirling also points out that while this general rule of thumb may be true for a few measurements such as height and weight, many other dimensions should not be handled in the same manner such as the head, hands, and feet. This was illustrated using the 1998 Anthropometric Survey of U.S. Army Personnel (ANSUR) (Gordon et al., 1998; Stirling, 2022). This further demonstrates the need to collect specific U.S. female firefighter anthropometry to address the high self-reported rate of improper fit and dissatisfaction with gear comfort, mobility, and performance. Therefore, the purpose of this research was to determine the root cause of female firefighter personal protective clothing (PPC) design, fit, and sizing issues to improve their comfort, mobility, and ultimately, protection.

2 Methods

A mixed methods research approach was adopted and implemented for this study. This approach allowed for the collection and analysis of both quantitative and qualitative data that offers a deeper comprehension of the research problem. This study employed a user needs questionnaire, end-user focus groups,

TABLE 1 Female firefighter user needs questions related to PPE occupational exposure.

Survey section	Question	Answer type
Selection	Is the sizing of your turnout suit/wildland PPC female specific or sized in women's sizes?	Y/N
Fit	Have you ever encountered problems with ill-fitting turnout gear/wildland PPC?	Y/N
Fit	How well does your turnout suit/wildland PPC fit?	5-pt Likert
Fit	Do you believe your turnout suit/wildland PPC fits you properly?	Y/N
Mob	Do you believe the improper fit of your PPC limits your mobility?	Y/N
Mob	Does the limited mobility of your turnout suit/wildland PPC significantly affect your: comfort, safety, thermal protection, liquid protection, chemical protection, and smoke and particulate protection?	Y/N
Mod	How often do you leave off a part of your turnout/wildland gear because it does not fit?	5-pt Likert
Mod	Do you have to modify your turnout gear (coat and pants)/wildland gear (shirt and pants) in any way?	Y/N
Mod	Have you ever modified or customized any part of your turnout/wildland gear?	Y/N

and three-dimensional body scanning to collect female firefighter body measurements.

2.1 User needs questionnaire

To meet the objectives of this research, a 77-question nationwide end-user questionnaire was disseminated electronically via Qualtrics to structural and wildland female firefighters across the United States. The questionnaire was developed in collaboration with multiple industry, research, and fire service experts through the project's technical panel and in collaboration with Women in Fire (WIF). Over 2,000 responses were received with 954 fully completed surveys included in the dataset. After gathering informed consent, per our institutions' Internal Review Board (IRB) requirements, the survey began with a 9-question demographic section that immediately eliminated any male participants. The remaining four sections were split to analyze structural and wildland firefighter groups separately. A general section on firefighting PPC selection was asked (11 questions for structural, 6 for wildland), followed by a section on fit (8 questions), mobility (9 questions), and design modifications (8 questions). Only those questions related to fit, protection, or other topics relevant to the potential increased risk of exposure for female firefighters are included in the scope of this article. These questions are detailed in Table 1.

2.2 End user focus groups

To facilitate end-user focus groups, approximately 37 female firefighters were recruited to participate in research regarding their impressions and experiences with their current personal protective clothing. Focus group participants were also attendees at the 2021 Women in Fire (WIF) national conference in Spokane, Washington.

Participants of all fire service types were invited to join; this included structural, wildland, and wildland-urban interface (WUI) firefighting. Recruited female firefighters ranged in fire service type, as well as the length of service. Additionally, there were overall more career female firefighters than volunteers based on responses regarding department resources and interactions with PPE manufacturers.

The IRB-approved end-user focus groups with 37 female firefighters were conducted to gather information regarding their current PPC. Focus groups were organized based on the availability and schedule of participants at the WIF conference–this study had a total of six focus groups with each group accommodating between two to nine female firefighters. Each of the sessions lasted approximately 90 min and firefighters were asked open-ended questions regarding fit, mobility, design, and safety concerns about their PPC. These six sessions were recorded for analysis purposes and transcribed.

2.3 Three-dimensional body scanning

A three-dimensional remote body scanning application was utilized to collect female firefighter body measurements. The MeThreeSixty (Size Stream, LLC) application, available on iOS and Google devices, provides a simple, accurate method for collecting anthropometrics (Size Stream, 2022) via remote scanning technology when a physical three-dimensional body scanner cannot be relocated. A standardized protocol for all body scans was developed to ensure consistent measurements were taken across all scanning locations. The protocol included providing participants with form-fitting clothes, if necessary, collecting height and weight measurements, and taking a pre-scan reference photo. Scans were taken using a portable tablet device placed on a stationary tripod at designated heights to ensure proper placement of the participant within the scanning application. Each scan took less than 20 s to complete and gathered more than 240 body measurements per participant. Within the scope of this paper, 14 measurements corresponding to the National Fire Protection Association (NFPA) standard sizing requirements for structural and wildland firefighting PPC were analyzed, including chest circumference, sleeve length (r), waist circumference, inseam (r), neck circumference, front jacket length, wrist circumference, hip circumference, seat circumference, thigh circumference, knee circumference, ankle circumference, front rise, and back rise.

TABLE 2 Example coding of content analysis used for synthesis.

Question 5: How satisfied are you with your current size and fit of your turnout coat, pants, and/or wildland shirt and pants?	
Coding Category	*Participant Response*
B. Dissatisfied	I do not like my gear. It just depends on which pants I'm wearing. So again, it goes back to having the same size pants but they're not the same size pants so most of problems I have are with our pants and it's the crotch issue
C.2. Problem Area regarding Crotch	

These measurements were analyzed to determine differences between female firefighter body measurements and women's PPC sizing requirements for structural and wildland firefighting.

Similar body scanning technology and equipment have been utilized in previous studies to assess the fit of firefighting PPE (McQuerry, 2020; Jo et al., 2022; Sokolowski et al., 2022). Firefighter body scanning occurred in three locations: Spokane, WA, Orlando, FL, and Raleigh, NC. All body scan data was immediately uploaded in real-time to a shared, password-protected drive that only the research team had access to, per IRB approval. In total, 189 U.S. female firefighters were scanned, creating the largest anthropometric database to date. The female firefighter anthropometric data was then compared to current NFPA standard sizing requirements for structural and wildland firefighting PPC.

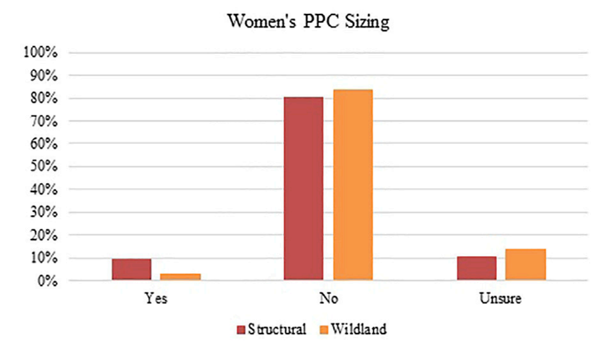

FIGURE 1
Percentage of female structural and wildland firefighters with women's sized gear.

2.4 Data analysis

Descriptive statistics of questionnaire participants' selection, fit, mobility, and modifications to their PPC were used to determine the prevalence of women's sized gear, the prevalence and type of fit and mobility issues for women in the fire service, and the occurrence of gear modification. This analysis is similar to previous questionnaire-based studies (Huang et al., 2012; Park et al., 2014; McQuerry et al., 2018).

The interpretative thematic analysis method was used for the synthesis of the focus group data. All focus group sessions were recorded, transcribed, and coded by three independent researchers for content analysis (Spiggle, 1994). Coding categories were determined by the frequency and prevalence of keywords or phrases that appeared amongst participants in each focus group–these were also developed based on questions asked by the research moderators. Once a category was established within the context of the question and conversation theme, alpha and/or an alphanumeric code was assigned. This method was adopted given its common use in previous firefighter user needs studies (Boorady, Barker, Lee, et al., 2013; Boorady, Barker, Lin, et al., 2013; Park and Hahn, 2014). An example of a question from a single focus group session, a participant's response, and its corresponding code can be seen in Table 2. Once each focus group session was coded individually, a full synthesis of all focus group sessions occurred, identifying holistic themes and categories from the qualitative data.

Descriptive statistics were also utilized to provide the average, median, mode, minimum, and maximum body measurements of the 187 female firefighters that were body scanned in this study in 14 specific locations. These locations were selected based on their correlation with women's sizing requirements included in the NFPA 1971 *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* and NFPA 1977 *Standard on Protective Clothing and Equipment for Wildland Fire Fighting and Urban Interface Fire Fighting*. The number and resulting percentage of participants whose body measurements fell outside of the women's size range for each specific sizing requirement in the NFPA standard was calculated.

3 Results

3.1 User needs questionnaire

All questionnaire participants were female with 62.9% between 20 and 39 years of age. The majority of participants (86%) identified as white/Caucasian and worked in the southeastern region of the United States. 70.5% were career firefighters with the most common rank being a firefighter (59%). Most (61%) identified as structural firefighters while the rest (39%) indicated they perform both structural and wildland firefighting. A broad range of experience was represented with 30.7% having less than 5 years of experience followed by another almost 30% with 11–20 years of experience.

In the section of the questionnaire related to PPC selection, participants were asked if the sizing of their turnout or wildland gear was female-specific or sized in women's sizes. Figure 1 illustrates these results. For structural firefighters, just under 10% indicated their gear was specifically sized for women. For wildland female firefighters, this percentage was drastically lower at just 2.8%.

In the second section on PPC fit, participants were asked if they had ever encountered problems with ill-fitting structural turnout suits or wildland shirts and pants. Results of how well structural and wildland female firefighters' PPC fits are shown in Figure 2. Similar

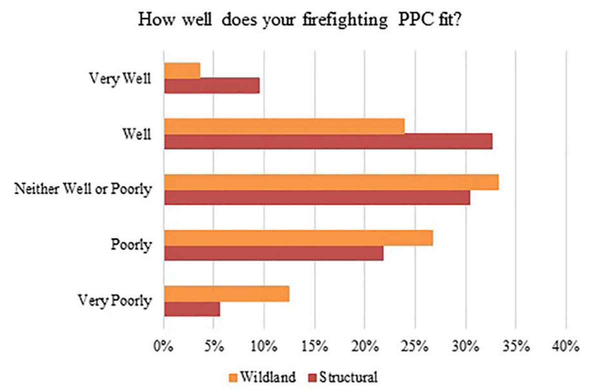

FIGURE 2
Overall fit ratings of wildland and structural turnout PPC for female firefighters.

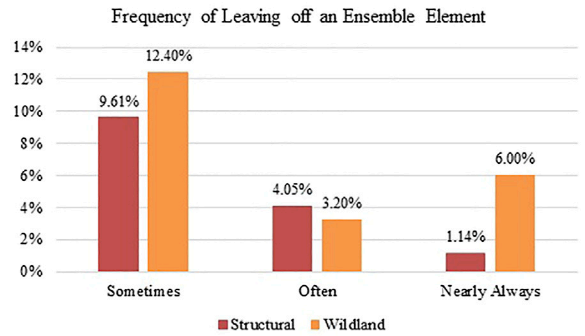

FIGURE 4
Percentage of structural and wildland female firefighters who "sometimes", "often", or "nearly always" leave off a part of their turnout or wildland gear due to improper fit.

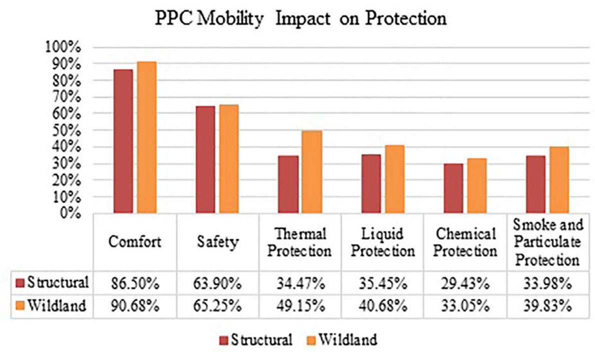

FIGURE 3
Percentage of female firefighters perceiving an impact on their protection from improperly fitted PPC.

to Hulett, et al.'s findings, 82.9% of structural and 52.1% of wildland female firefighters indicated they have encountered problems with ill-fitting PPC. When asked how well their PPC fits, less than 10% of structural female firefighters and less than 4% of wildland female firefighters reported their PPC fits them "very well". Overall, more than half of female firefighters (54.88%, structural; 59.29%, wildland) reported they do not believe their PPC fits them properly.

Close to 80% of participants reported the improper fit of their clothing limits their mobility, further reducing their ability to perform their job safely. Figure 3 illustrates how female firefighters felt this limited mobility impacted their comfort and safety, specifically their thermal, liquid, chemical, and smoke/particulate protection. Between 86%–90% indicated the improper fit of their PPC leads to reduced mobility that negatively impacts their comfort. On average, 64.5% of female firefighters feel this reduced mobility impacts their safety. For structural female firefighters, the biggest protection concern was liquid, followed closely by thermal and smoke/particulate protection (34%–35.4%). For wildland firefighters, concerns were even higher between 40%–49% regarding thermal, liquid, and smoke/particulate protection.

When asked how often a part of their firefighting ensemble is not donned because of ill-fit, 15% of structural and 21% of wildland female firefighters reported they "sometimes", "often", or "nearly always" leave off a part of their gear because it does not fit properly, as illustrated in Figure 4. Shockingly, the number one PPE item that was intentionally not worn was the turnout coat or wildland jacket (58/140; 41.4%) due to improper fit in the bust, arms, sleeves, hips, and/or neck. This was closely followed by the turnout or wildland pants (28/140; 20%). 19% of female structural firefighters and 20% of female wildland firefighters reported they have to modify their coat/shirt or pants in some way to simply wear them on their body. Almost a quarter (23.6%) of female structural firefighters in this study indicated they have modified or customized a part of their turnout gear. For wildland PPC, 12% of female firefighters in this study indicated they have also modified or customized their gear in some way.

3.2 End user focus groups

Through the six focus group sessions, themes of improper fit, lack of mobility, discomfort, and PPC design issues were most prevalent. Most coding categories were based on the dissatisfaction with the female firefighter's current PPC as well as desired areas for improvement. These included but were not restricted to, bulkiness and excess material in structural turnout coats and pants, and oversized and long wildland shirts and pants. Specific issues cited also included oversized collars and restrictions in mobility due to tightness in areas such as the hips and across the chest. Many participants emphasized that the pant crotch length was very prohibitive when performing many on-job duties such as climbing on and off the fire truck or up a ladder. Due to the excess length and drop of the pant crotch, female firefighters are having to adjust their approach before executing movements such as crawling or entering smaller spaces; this includes "hiking up" the waist of their pants or else "the pants get stuck so it is hard for me to be able to move my knee up".

While a small handful of female firefighters had no issues with their current PPC, most participants agreed that design

TABLE 3 Descriptive statistical analysis compared to NFPA standards/.

Body measurement (cm)	Average	Median	Mode	Min	Max	NFPA 1971 range	NFPA 1977 range
Chest Circumference	106.1	104.1	110.5	85.3+	141.5[a]	71–127	99–150
Sleeve Length	77.7	77.8	78.6	70‡	92.3‡	71–86	77.5–90
Waist Circumference	89.3	87.9	88.9	71	123.5+	71–127	58–94
Inseam	77.3	77.5	78	67.6+	91[a]	61–86	71–91.5
Collar Circumference	36.7+	36.3+	37.2+	31.8+	43	n/a	37.5–50
Front Length	74	74	74.2	65.8	82.8+	n/a	63–75.5
Wrist Circumference	16.8+	16.7+	17.1+	15+	19.5+	n/a	30.5–37
Hip Circumference	114	112	114.5	97	114.6	n/a	96.5–147
Seat Circumference	112	109.8	112.7	94.6	145+	n/a	94–130
Thigh Circumference	64.6	63.4+	63.4+	53.4+	83+	n/a	63.5–81
Knee Circumference	40+	39.5+	38.9+	34.6+	48.9	n/a	45–58
Ankle Circumference	25.5+	25.5+	25.5+	22.5+	29+	n/a	38–47
Front Rise	25	25.2	25.2	15.4+	33.4+	n/a	22.5–28
Back Rise	26.2+	26.6+	28.4+	18.4+	33.7+	n/a	37.8–43.3

[a]Outside NFPA 1971 size range; + outside NFPA 1977 size range; ‡ outside both NFPA size ranges.

improvements are needed to address issues with mobility, comfort, and safety. Those few participants that were satisfied with their gear mentioned that it was comfortable due to the specific "female fit" and noted that they were able to don their suit for "a few hours doing training. without feeling like I need to take it off."

Most female firefighters noted that their PPC has a direct impact on their on-duty performance and that along with their improperly fitting PPC, they felt their auxiliary PPE did not perform as intended due to ill-fitting interfaces between the helmet and collar, sleeve and gloves, and self-contained breathing apparatus (SCBA) and jacket. In one case, a participant stated that their PPC was causing hindrance to their vision due to their coat collar covering "my whole face since I have a smaller head. you just can't fold it down because it is so stiff and it is about 5 inches." Several others pointed to sleeve lengths on shirts and jackets as being "too long" and having to modify the sleeves to get their gloves on which in turn "limits the mobility of arm movement".

In addition to fit, comfort, and mobility issues of their PPC, user wear confidence was also a predominant theme in the focus group sessions. This relates to concerns about injuries that could be sustained while wearing their PPC and the aesthetics and perception of others on how a female firefighter looks in what they perceive as ill-fitting gear. Notably, one female firefighter mentioned that her self-confidence is impacted as she sees her male counterparts "doing the skills and being efficient" while she "can't move in the same way they can because of my gear".

Lastly, focus group participants highlighted the need for appropriate female sizing and design for future turnout suits for structural and wildland firefighting. This included thoughtful placement of pockets for accessories such as radios and small hand tools as well as flared shaping for coats, so they zip over the hips easier. As one participant commented "There is actually a female fire gear that could actually fit our bodies better, so that would just be nice to have that option."

3.3 Female firefighter anthropometrics

Of the 189 body scans collected, 187 met the criteria for inclusion in the U.S. female firefighter anthropometric database. Descriptive statistics (Table 3) were calculated for 14 identified measurements related to the sizing requirements in the NFPA 1971 and NFPA 1977 standards for structural and wildland firefighting PPC, respectively.

4 Discussion

4.1 Availability and suitability of Women's firefighting PPC

Questionnaire findings indicate less than 10% of structural female firefighters in the U.S. are wearing PPC designed specifically for the female human form. These results were much lower than Jahnke's findings which reported 20% of female firefighters have access to and wear women's gear. Jahnke's study, however, surveyed female firefighters throughout North America, including Canada. End-user focus group data also uncovered that a small portion of female firefighters are unaware that firefighting gear made specifically for the female body exists on the market. A handful of participants noted during discussions regarding their current PPC that they did not know that "female-sized gear" was even an option for them.

Regarding fit satisfaction, results from this study are similar to findings by Jahnke, et al. in that the majority of participants in both studies also indicated their turnout gear fit them well (32.2% *versus* 40.8%, respectively). The second largest and most frequent response in Jahnke's study, however, was that their gear fit them "very well" whereas, in this study, which was specific only to U.S. female firefighters, the second most frequent response was that women's turnout suits fit "neither well or poorly" at 30.6%. For wildland female firefighters, the majority of responses (33.5%) reported neutral satisfaction followed by 26% who felt their shirt and pants fit "poorly". These results indicate wildland female firefighters are even more dissatisfied with the fit of their gear than structural female firefighters at over 36% compared to 27% of structural firefighters.

Possibly the most concerning finding from the end user questionnaire was that 15% of structural and 21% of wildland female firefighters reported they "sometimes", "often", or "nearly always" leave off a part of their gear because it does not fit properly. These results indicate women in the fire service feel their protective clothing is unsuitable and so ill-fitting that it hinders their performance to the point they choose not to wear their two primary PPE elements for personal protection, which covers the largest portions of their bodies. This finding most certainly indicates that female firefighters are at greater risk for occupational exposure due to improper fitting PPC.

Participants who stated they had a female-sized suit, mainly structural and wildland-urban interface firefighters, usually commented that they had a preference for their "female set" compared to their "male set". This preference was because female firefighters were more comfortable and had increased mobility in gear that was patterned and tailored to the female form. This finding also highlights the fact that most female firefighters are still forced to wear a turnout suit designed for males, as only one provided set is often female-specific.

While many participants who had access to female-sized gear preferred it to male-centered designs, findings indicate there is still much room for improvement. Complaints related to female-sized gear were often due to having the incorrect or "wrong" size because of inconsistencies in PPE manufacturers' sizing systems and measuring protocols. This points to the need to streamline manufacturer and departmental sizing practices and fit-function assessments. Female firefighters who had been sized for female gear reported they often had the opportunity to have ill-fitting gear amended or fixed, however, some mentioned that regardless of the amendments made, their PPC ended up "being awful" and one participant reported ultimately going back to men's gear.

4.2 Anthropometric comparison to NFPA sizing standards

For structural turnout gear, there are only four sizing requirements included in NFPA 1971; two for the coat and two for the pants. These include chest circumference, sleeve length, waist circumference, and inseam. All four measurements have specific sizing requirements for female *versus* male firefighters. Sizing requirements in NFPA 1977 for wildland firefighting PPC include nine upper-body and eight lower-body measurements. However, female sizing is only required for the eight lower body measurements.

In general, it was found that minimum size range measurements for wildland PPC are much larger overall than for structural turnouts, by as much as 28 cm in the chest. In addition, the largest size required for the wildland pant waist circumference was 33 cm greater than the largest waist circumference required for turnout pants. These discrepancies are important as a large portion (39%) of female respondents to the end user questionnaire indicated they perform both types of firefighting. The comparison of the two PPC sizing systems alone illustrates the need for more consistent sizing in the fire service industry as required by the NFPA standards.

Descriptive statistics of the participant average, median, mode, minimum, and maximum measurements were compared to the size ranges for each measurement as required by each NFPA standard (Table 3). The chest circumference, sleeve length, waist circumference (pants), and inseam measurements are required by both NFPA standards. For wildland PPC, however, female sizing is only provided for the waist circumference and inseam, therefore the chest circumference and sleeve length size ranges apply to both male and female wildland firefighters.

Large percentages of female firefighter anthropometrics were found to lie outside of the required size ranges for both structural and wildland PPC. For chest circumference, 31% of female firefighters in this study were found to be smaller than the minimum NFPA 1977 sizing requirement of an XS wildland jacket and 5.8% had a chest circumference larger than the biggest turnout suit size required by NFPA 1971.

The greatest area for fit improvement was found to be in the sleeve with 47% of female participants having sleeve length measurements less than the smallest size of the wildland shirt. In the waist, almost a quarter (23.5%) of female firefighters measured in this study were larger than the largest NFPA 1977 sizing requirement in the pants, which is sized specifically for women. In fact, the smallest waist circumference measured in our study was 71 cm indicating the required size range from 58 to 70 cm is irrelevant. These large discrepancies between the required size range and the actual anthropometry of women in the fire service point to a major issue with the body proportions and overall design of the wildland PPC in relation to the female human form.

The current standard inseam lengths most closely fit the anthropometric measurements of the female firefighters in this study. Less than 5% of participants had inseams smaller than the NFPA 1977 requirements and less than 2% had inseams longer than NFPA 1971s maximum size requirement.

4.3 Wildland PPC interface exposure

Additional measurements were analyzed for wildland PPC according to NFPA 1977 including collar, wrist, hip, seat, thigh, knee, and ankle circumferences, as well as, front jacket length, front pant rise, and back pant rise. Of these areas, the most critical for ensuring firefighter protection from outside exposure is the interface areas: collar/hood, wrist/glove, ankle/boot, and coat hem/pant waist. At the neck, 68% of female firefighters in this study had a collar circumference up to 5.7 cm smaller than the minimum collar circumference requirement for wildland shirts. Even when factoring in the 2.5 cm ease requirement, 30% of female firefighters would still have excess ease in the collar when wearing the smallest, size extra small (XS) shirt, which is not applicable for most female firefighters. This statistic alone indicates female firefighters are at a greater risk of exposure due to oversized interface openings in the neck/collar area.

Similar findings of improper PPC fit were found in the wrist/glove and ankle/boot interface areas. 100% of the 187 female firefighters scanned in this study had wrist circumferences and ankle circumferences less than the smallest size wrist and leg cuff openings required in the standard. Female firefighter wrist measurements were between 11 and 15.5 cm less than the smallest size XS sleeve cuff circumference requirement. Ankle measurements were at least 9 cm less than the smallest size leg cuff opening requirement. Factoring in ease values of 15+ cm for the wrist cuff and 28 cm for the ankle may alleviate some of these drastic fit discrepancies, however, that is assuming all participants in this study wear the smallest size shirt and pants, which they do not. This assessment also highlights confusion within the standard regarding where and how the specified sizing measurements should be taken on the body and how the ease measurements were determined and are to be appropriately used by designers and manufacturers. The current version of the NFPA 1977 standard does not include measurement drawings, diagrams, or written instructions for the specified sizing measurements. This limits garment design, patternmaking, certification, end-user satisfaction, and the ability to directly analyze anthropometric data.

In terms of the coat/pant interface, front coat length, front pant rise, and back pant rise were analyzed. 34% of participants had a front coat length larger than the maximum size requirement of 74 cm. Even with the required ease of 2.5 cm + extending below the top of the hip line, a large portion of the wildland female firefighters in this study would be wearing shirts that were not long enough for them. Couple that with ill-fitting pants that may not possess a high enough front rise and the risk for exposure, especially when arms are lifted overhead, can occur. For front pant rise, 33% of participants would not fit into a wildland pant according to the NFPA 1977 sizing requirements. For back rise, 100% of all female firefighters scanned had back rise lengths less than the minimum sizing requirement for the smallest size pants. When considering the ease measurement of 28 cm for back pant rise, even the smallest back pant rise measured (18.4 cm) would far exceed the maximum pant size of 43.3cm, indicating ease measurements need to be further considered for their inclusion in the standard. These data points are in line with a majority of qualitative feedback received during the focus groups that the crotch area is the most ill-fitting area due to excess length which prohibits their mobility.

4.4 PPC ill-fit and increased risk of exposure

Ultimately, findings from the questionnaire, focus groups, and anthropometric sizing system comparisons highlight the great need and opportunity for female firefighter wildland PPC development and improvement. It is evident by the results of the questionnaire, with only 10% of female firefighter respondents wearing women's cut PPC, that few offerings are available. In the structural space, "women's gear" has been manufactured for over 2 decades, albeit with many issues that remain to this day, however, even fewer options are offered in the wildland firefighting space for women. With almost half of the questionnaire participants indicated they perform both types of firefighting activities, and therefore must wear both types of PPC, it is imperative that the fit and sizing of structural and wildland clothing be designed in such a way that the same female firefighter can fit into both. From our anthropometric comparison analysis, however, that is not the case.

Far more participants fell within the structural firefighting sizing requirements in NFPA 1971 than those for wildland PPC in NFPA 1977. It should be considered that wildland PPC must meet almost four times as many sizing requirements as structural PPC, however, much larger discrepancies were found in the wildland sizing system than the structural sizing system when assessing the same four measurements. Further, a significant portion of female firefighters in this study fell outside all wildland sizing requirements except for hip circumference. In general, results demonstrate that the wildland sizing system is too narrow and/or too oversized in most all measurements, with exceptions. For example, in the waist measurement where the smallest waist measured in this study was 71cm, the NFPA size range begins at 58 cm and only goes to 94cm, with the maximum waist measurement in this study being 124 cm. A third of the wildland waist circumference size range was irrelevant on the lower end and it was far too narrow to capture larger waist measurements for the sample collected in this study.

These anthropometric results are supported by female firefighters' fit perceptions as evidenced by the outcomes of the questionnaire with more female firefighters being dissatisfied with their wildland PPC at 36% than their structural PPC at 27%. Further, respondents indicated they leave off their wildland PPC (21%) at a greater rate than their structural PPC (15%). This could, in part, be due to the inherent differences in the two types of firefighting with wildland posing less of a direct thermal exposure threat, in some cases. But in terms of smoke and carcinogenic exposure, when considering short term *versus* long term duration, the risk and concerns remain the same. Therefore, it is imperative that the issues highlighted in the results and discussion sections above pertaining to wildland PPC fit, especially in the interface areas, be addressed by the NFPA technical committees and end users.

5 Conclusion

This study includes the largest U.S. female firefighter anthropometric database for women's PPC. The results from this study indicate female firefighters are wearing PPC with significant fit issues that not only reduce their comfort and restrict their mobility but pose increased safety risks related to occupational exposure. Interface areas and wildland PPC have been identified as the areas of female firefighter protective clothing with the greatest opportunities for design and fit improvement according to the end user feedback and anthropometric data. With 40% of questionnaire participants indicating they wear both structural and wildland firefighting PPC, there is a large need to close the gap between how these two types of protective clothing are sized for women in the fire service. This study identified large discrepancies between minimum and maximum sizing requirements for female firefighters in the chest, sleeve length, and waist areas. This identifies an opportunity to collaborate with the NFPA standard technical committees to close the gap between these two types of PPC in terms of sizing and their consequential fit for both women and men in the fire service.

The majority of questionnaire data highlighted the greatest need for fit and performance improvement lies within PPC for women in the wildland fire service. These findings were further supported by the anthropometric measurements when compared to the NFPA 1977 sizing standard. By far, there appears to be larger dissatisfaction with the fit and performance of wildland gear for women and greater discrepancies between female firefighter anthropometrics and the current sizing system for wildland PPC. This underlines a large opportunity to close the gap between sizing, fit, performance, and safety for women in the wildland fire service.

Additional research is needed on the fit and function of specific ensemble elements connected to the interface areas to ensure occupational exposure is reduced for women in the fire service. This study was the first to assess U.S. female firefighter anthropometrics and the user needs of both structural and wildland female firefighter PPC. Limitations of this research include the exclusion of all other PPE elements outside of the specific shirt, coat, jacket, and pants worn for structural and wildland firefighting operations. From end-user feedback in this study and previous research (Boorady, Barker, Lin, et al., 2013; Park et al., 2014), there is a great need to address improper fitting boots, gloves, helmets, hoods, self-contained breathing apparatus (SCBA), and face masks for women in the fire service.

This research was possible because of the recent development of remote body scanning technology, however, the lack of historical use of this type of technology presents a limitation. Additional work is needed to validate remote body scanning technologies in their correlation to pattern development, sizing development, and the ultimate resulting fit on the wearer. Future research should assess PPC sizing systems and prototypes created with the female firefighter anthropometrics gathered in this study to determine improvements in the fit and function of PPE for women in fire services.

Data availability statement

Data are not publicly available due to the privacy of the human participants involved.

Ethics statement

The studies involving human participants were reviewed and approved by Florida State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MM (PI) and CK (Co-PI) led this research and the bulk of data collection. MP-B assisted with collecting 90% of the data and 100% of the anthropometric data. In terms of writing the paper, MM led the creation of the document and the writing of the introduction, methods, results, and discussion for the questionnaire and anthropometrics. CK wrote all material related to the focus groups and heavily edited the entire manuscript. MP-B pulled reports, assisted with writing the methodology and producing figures for the results. MP-B contributed to overall writing and editing of the entire manuscript.

Funding

This research was supported by the Federal Emergency Management Agency (FEMA) Assistance to Firefighters Grant (AFG) program (EMW-2018-FP-00202).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 04 May 2023
DOI 10.3389/fpubh.2023.1096771

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OPEN ACCESS

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RECEIVED 12 November 2022
ACCEPTED 04 April 2023
PUBLISHED 04 May 2023

CITATION
Cheng P, Wang L, Zhou Y, Ma W, Zhao G, Zhang L and Li W (2023) Post-traumatic stress disorder and depressive symptoms among firefighters: a network analysis.
Front. Public Health 11:1096771.
doi: 10.3389/fpubh.2023.1096771

Post-traumatic stress disorder and depressive symptoms among firefighters: a network analysis

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Background: Firefighters, as first responders with a high risk of occupational exposure to traumatic events and heavy working stress, have a high prevalence of PTSD symptoms and depressive symptoms. But no previous studies analyzed the relationships and hierarchies of PTSD and depressive symptoms among firefighters. Network analysis is a novel and effective method for investigating the complex interactions of mental disorders at the symptom level and providing a new understanding of psychopathology. The current study was designed to characterize the PTSD and depressive symptoms network structure in the Chinese firefighters.

Method: The Primary Care PTSD Screen for DSM-5 (PC-PTSD-5) and the Self-Rating Depression Scale (SDS) were applied to assess PTSD and depressive symptoms, respectively. The network structure of PTSD and depressive symptoms was characterized using "expected influence (EI)" and "bridge EI" as centrality indices. The Walktrap algorithm was conducted to identify communities in the PTSD and depressive symptoms network. Finally, Network accuracy and stability were examined using the Bootstrapped test and the case-dropping procedure.

Results: A total of 1,768 firefighters were enrolled in our research. Network analysis revealed that the relationship between PTSD symptoms, "Flashback" and "Avoidance," was the strongest. "Life emptiness" was the most central symptom with the highest EI in the PTSD and depression network model. Followed by "Fatigue" and "Interest loss." Bridge symptoms connecting PTSD and depressive symptoms in our study were "Numb," "High alertness," "Sad mood," and "Compunction and blame," successively. The data-driven community detection suggested the differences in PTSD symptoms in the clustering process. The reliability of the network was approved by both stability and accuracy tests.

Conclusion: To the best of our knowledge, the current study first demonstrated the network structure of PTSD and depressive symptoms among Chinese firefighters, identifying the central and bridge symptoms. Targeting interventions to the symptoms mentioned above may effectively treat firefighters suffering from PTSD and depressive symptoms.

KEYWORDS

post-traumatic stress disorder, depression, network analysis, firefighter, mental health

1. Introduction

Post-traumatic stress disorder (PTSD) is a chronic severe mental disorder after traumatic exposure, which is composed of four core symptoms, intrusion symptoms associated with the traumatic events, avoidance of traumatic stimuli, negative alterations in cognitions and mood, and marked alterations in arousal and reactivity (1). Given that over 70% of people may experience a traumatic event in their lifetime (2), previous studies indicate that people with PTSD symptoms are more likely to have other psychiatric symptom comorbidities (3), especially depressive symptoms (4). The high rate of symptom co-occurrence of PTSD and depression is demonstrated in populations with different categories (natural disasters, combat violence, the break of an intimate relationship, etc.) of traumatic exposures (5–8). Either PTSD symptoms or depressive symptoms are associated with higher final mortality and morbidity of physical symptoms [musculoskeletal pain, cardio-respiratory (CR) symptoms, gastrointestinal (GI) symptoms, etc.] (9, 10). Moreover, emerging research suggests that the co-occurrence of PTSD and MDD possibly has more severe adverse effects on mental health and life quality than either of them alone (11).

Firefighters, first responders with a high risk of occupational exposure to traumatic events and heavy working stress (12), are the population with a high prevalence of PTSD symptoms and depressive symptoms. A systematic review suggests that the mean prevalence of PTSD among firefighters is 12.3%, and the mean prevalence of depression is 18.7%. Both of them are higher than those of the community population (13). Since stressful and frightening working situations are almost inevitable for firefighters, the potential risk of a series of negative results caused by PTSD and depression is extremely serious, including alcohol abuse, occupation burnout, and even suicidal ideation or attempt (14–16). Besides, from the clinical perspective, there is a substantial amount of symptoms overlap between PTSD and depression, like sleep disturbance, inattention, avoidance, and withdrawal, etc. Diagnostic confusion brought by the similarity of symptoms is common, especially when clinicians lack information of traumatic event history (17). The concealment of psycho-trauma related information is not unusual in the Asian population, as high levels of stigma are general in the Asian culture and mental disorders are regarded as a sign of weakness (18). Therefore, we consider that it is meaningful to figure out the potential relationships and significance hierarchy among symptoms of PTSD and depression, which can provide references for accurate psychological intervention for firefighters.

In recent years, network analysis has become a widely applied method for exploring the associations among individual psychiatric symptoms and ascertaining their relative significance in psychopathology (19). Network analysis posits that psychiatric disorders/syndromes can be modeled as phenomena arising as a complex network of interacting and mutually reinforcing symptoms (20). Thus, specific symptoms act as positive roles in activating and maintaining mental disorders instead of passive indicators of mental disorders (21). Compared with the traditional statistical analysis method mainly investigate the unidirectional association (e.g., structural equation modeling, regression analysis, etc.) (22, 23), which demands a hypothesis of the potential relationships among symptoms, network analysis can identify the dynamic and reciprocal associations between various symptoms (24, 25).

Network analysis can provide the corresponding centrality and predictability index for each symptom node to test its significance and controllability in the whole network (26, 27). The centrality index can be used to ascertain central symptoms which contribute to the majority of the network stability, for further understanding mechanisms about the onset and maintenance of a disorder or syndrome and potential targets for clinical interventions (24). Moreover, when individuals suffer from different psychiatric disorders, some specific symptoms of one disorder may increase the risk of the other disorder, which is considered as bridge symptoms in the network. The bridge symptoms of the network play essential roles in maintaining and developing comorbidities, suggesting references for clinical prevention and treatments (28).

Previous studies of the network of the comorbidity of PTSD and depression were mainly conducted in veterans (29, 30), though heterogeneity exists between different studies, indicating higher centralities of symptoms "Flashback," "Getting upset by trauma reminders," "concentration difficulties," and "anhedonia." Another network analysis enrolling male participants with domestic violence indicates that symptoms "Feelings of worthlessness" and "Avoiding internal reminders of the traumatic experiences" are the most central symptoms (31). To the best of our knowledge, similar studies involving the comorbidity of PTSD and depression are rarely conducted in firefighter samples. Concerned about the difference in exposure to traumatic events and the potential effect of stigma rooted in Asian culture on mental symptoms, we speculated that features of the network of comorbidity of PTSD and depressive symptoms in Chinese firefighters might differ from those of other kind populations in the background of western culture.

As far as we know, the current study is the first study applying the network analysis method to investigate the network structure of comorbidities of PTSD symptoms and depressive symptoms among Chinese firefighters, which inspired us to conduct this study to fill the gap. The purpose of our study was to examine the associations between PTSD and depressive symptoms among Chinese firefighters, then to figure out the center symptoms and bridge symptoms of this PTSD-depressive symptoms network. Our results can provide theoretical references for establishing precise psychological interventions and normalized mental health care for firefighters.

2. Materials and methods

2.1. Participants and study design

Our study was a cross-sectional survey conducted in March 2021 in Changsha, Hunan Province, China. The Web-based questionnaire was applied in our research for higher data collection efficiency and lower risk of transmission of COVID-19. The questionnaire was set to be qualified for uploading when all items were filled correctly and checked by software, which could improve the reliability of raw data. After being approved by the administration of Hunan Fire Brigade, electronic questionnaires set by us were distributed by the management department of Hunan Fire Brigade. Inclusion criteria were (1) age above 18 years old, (2) certificated firefighters in fire stations, and (3) understanding the purpose and content of this research. Exclusion criteria were (1) not being at work due to any reasons, (2) not able to finish the whole questionnaire due to health reasons, and (3) without any experience of formal emergency mission. This study was approved by the Ethic Committee of the Second Xiangya Hospital of Central South University. All the participants have provided electronic written informed consent.

2.2. Measures

The primary care PTSD screen for DSM-5 (PC-PTSD-5) was used for assessing PTSD symptoms. PC-PTSD-5 is a five item self-report screening scale, which is set based on the diagnostic criteria of PTSD in DSM-5 (32). Items are scored dichotomously as either zero or one (0 = No; 1 = Yes). Higher scores mean more severe PTSD symptoms. The reliability of the Chinese version of PC-PTSD-5 in Chinese was validated and the cutoff score of potential PTSD was set as two points (33).

Depressive symptoms were assessed by the Self-Rating Depression Scale (SDS), which was compiled by Zung et al. (34). SDS is a classical and widely applied four-point Likert scale for depression in China (35), scored from one (a little of the time) to four (most of the time). Higher scores mean more severe depressive symptoms. According to the SDS Chinese manual (36), individuals with a total score of 40 or more were considered to have potential depression.

2.3. Statistical analysis

All the data were analyzed by the R program (37). The process of network analysis was divided into five domains, including network estimation and visualization, Exploratory community analysis, centrality and predictability analysis, network accuracy and stability, and network comparison.

2.3.1. Network estimation and visualization

Partial correlation analysis was applied to analyze the association between each pairwise nodes for controlling the confounding effects of other nodes in the network. The least absolute shrinkage and selection operator (LASSO) algorithm was used in the regularization process to shrink all edges in the network and set small correlations to zero, which enabled as few nodes and edges as possible in the network (38). Meanwhile, the extended Bayesian Information Criteria (EBIC) were also adopted to obtain a sparse and interpretable network model (39). The turning parameter was set for 0.5, which was widely applied for controlling spurious correlations in the network estimation (40).

Fruchterman-Reingold algorithm (41) was used to visualize the network. Nodes with stronger and more frequent associations with other nodes were placed closer together and more centralized in the network.

According to the parlance of network analysis, each item represented a symptom node, and each edge from one node to another was indicated as the association between two nodes. Thicker and more saturated edges meant stronger relationships. The color of edges represented the correlation, generally green for positive and red for negative (42). Concerned that the primary purpose of the current study was to investigate the inducing relationships between PTSD and depressive symptoms, and also for the simplicity and better understanding of the network structure, only positive relationships were depicted in the visualization of network. The possible negative associations among nodes were retained in the correlation matrix for the integrity of data. The R packages *bootnet* (Version 1.5) (43) and *qgraph* (Version 1.9.2) (42) were used to estimate and visualize the network.

2.3.2. Exploratory community analysis

Concerned that actual dimensions of symptoms in the PTSD and depression network might differed from initial hypothetical dimensions, we conducted the data-driven method, community detection, to identify the final dimensions of symptoms in the network. Meanwhile, the centralities (both original and bridge) of the final community detection grouping were calculated to be compared with the centralities of the original hypothetical grouping.

The Walktrap algorithm, based on the principle that adjacent nodes tend to belong to the same community (44), was applied to identify communities in the network model (45). This algorithm has been proven that performs well on psychological networks (46, 47). The function *cluster_walktrap*, available in the R package *igraph* was used to detect communities in the current study.

2.3.3. Centrality and predictability analysis

The centrality index, expected influence (EI), was calculated by the R package *qgraph* (1.9.2) (42) to quantify the importance of each symptom node in the network model. Symptom node EI refers to the sum of the value of all edges connecting to a given node, including both positive and negative values (48). Since there were not only positive associations but also negative associations in the network of our study, EI is more appropriate than other centrality indexes. Moreover, the bridge EI was analyzed to evaluate the significance of a node in connecting external symptom dimensions, by using the function *bridge* of the R package *networktools* (version 1.4.0) (49).

Predictability, an index suggesting the extent to which a node was predicted by its neighboring nodes (39), was computed by the function *predict* of the R package *mgm* (version 1.2–12) (50). Predictability represents the controllability of a node (27). In the picture of network model, the ring area around each node illustrated the value of predictability.

2.3.4. Network accuracy and stability

A total of three steps were conducted by the R package *bootnet* (version 1.5) (43) to assess the accuracy and stability of the network model in our research. Firstly, the accuracy of edge weights was estimated by constructing a 95% confidence interval (CI) with non-parametric bootstrapping method (51), which was visualized with a line diagram. A narrower bootstrapped CI of edge weights suggested a more precise estimation of the edges (52).

Secondly, the stability of symptom node EI was tested by calculating the correlation stability coefficient (CS-C), using a case-dropping bootstrap procedure (53). In this procedure, increasing percentage of cases was dropped from the dataset, and the EI indexes were re-estimated. If the EI of symptoms nodes did not change significantly after excluding a subset of the sample, the network structure could be considered stable. CS-C means the maximum proportion of samples that could be dropped while the EI correlation between the networks of original sample and case-dropping subsets was at least 0.7 with a 95% probability (43). In general, the value of CS-C needs to be above 0.25 and is preferably above 0.5 (43).

Thirdly, the significant differences between edge weights and node EI centralities were computed using the bootstrapped difference tests based on 95% CIs, which suggested that there were statistical differences between two edges weights or two EI centralities if zero was not included in the CIs (43).

2.3.5. Network comparison

Only-child status was collected as demographic information in the current study, according to which network comparison analysis was conducted to investigate the difference in network structure between only-child firefighters and non-only-child firefighters. China is a country with a huge population, family planning policy was conducted by the government so far, to control the rapid increase of population. Concerned that previous studies proved the effect of only-child status on mental health (54–56), we speculated that only-child and non-only-child firefighters might have a different network structure from each other.

The function *network comparison test (NCT)* of the R package *NetworkComparisonTest* (57) was applied to compare the network structures. The principle of NCT was a permutation-based test, which randomly regroups participants from each sub-network repeatedly (1,000 times) and then calculates the differences between networks. A total of three invariance measures were examined of sub-networks of genders, including global strength, network structure, and edge strength (57). The global strength tested the difference in overall network connectivity between sub-networks. The network structure examined the overall difference between all the possible edges between two sub-networks. Only when a statistically significant difference was found in either global strength or network structure comparisons, edge strength was further calculated to investigate the possible difference in each edge between the two networks. Moreover, the original centralities of nodes between sub-networks were also tested for the completeness of analysis.

TABLE 1 Descriptive statistics of PTSD and depressive symptom nodes.

Abbreviation	Symptom node	Mean (SD)
PCPTSD1	Flashback	0.07 (0.26)
PCPTSD2	Avoidance	0.06 (0.24)
PCPTSD3	High alertness	0.09 (0.29)
PCPTSD4	Numb feeling	0.07 (0.26)
PCPTSD5	Compunction and blame	0.04 (0.20)
Total score of PC-PTSD-5		0.34 (0.83)
SDS1	Sad mood	1.25 (0.49)
SDS2	Mood circadian rhythm	2.74 (1.08)
SDS3	Crying	1.08 (0.28)
SDS4	Sleep	1.51 (0.69)
SDS5	Appetite	2.49 (1.17)
SDS6	Sexuality	2.54 (1.17)
SDS7	Weight loss	1.26 (0.51)
SDS8	constipation	1.16 (0.44)
SDS9	Tachycardia	1.14 (0.38)
SDS10	Fatigue	1.30 (0.55)
SDS11	Confusion	2.23 (1.23)
SDS12	Ability decline	2.53 (1.19)
SDS13	Feeling of upset	1.21 (0.47)
SDS14	Hopelessness	2.02 (1.16)
SDS15	Irritability	1.25 (0.50)
SDS16	Irresolution	2.83 (1.01)
SDS17	Unworthiness	2.25 (1.13)
SDS18	Life emptiness	2.15 (1.13)
SDS19	Guilty	1.06 (0.29)
SDS20	Interest loss	2.21 (1.17)
Total score of SDS		36.21 (9.34)

PCPTSD, the primary care PTSD screen for DSM-5; SDS: the Self-Rating Depression Scale; and SD: standard deviation.

3. Results

3.1. Descriptive statistics

A total of 1,781 firefighters were included in our study. For the demographic information, all of the participants were male, 624 (35.0%) of which were only-child and 1,157 were non-only-child. The average age of sample was 26.60 [*standard deviation* (SD) = 4.82]. The average total scores were 0.34 (*SD* = 0.83) for PC-PTSD-5 and 36.21 (*SD* = 9.34) for SDS. According to the cutoff scores applied in the current research, the proportions of firefighters with potential PTSD and potential depression were 8.7 and 36.3%, respectively. The mean score and abbreviation for each symptom node are shown in Table 1.

3.2. Network structure

The network of PTSD and depressive symptoms is depicted in Figure 1. The detailed Correlation matrix is represented in Supplementary Table 1.

A total of 300 edges [25 × (25–1)/2] were initially estimated, of which 140 edges were non-zero weights and entered further analysis. For the connection between symptoms, "Flashback" (PCPTSD1) and "Avoidance" (PCPTSD2) were the strongest edges (weight = 0.46), followed by the edges between "Hopeless" (SDS14) and "Life emptiness" (SDS18) (weight = 0.33), between "Unworthiness" (SDS17) and "Life emptiness" (SDS18) (weight = 0.30), and between "Confusion" (SDS11) and "Ability decline" (SDS12) (weight = 0.30).

In terms of the predictability, the node "Life emptiness" had the highest predictability value (71.1%), while the mean level of predictability of nodes was 38.3 ± 18.2%. These results meant this symptom node was the most central symptom in the PTSD-depression interactive network but also the node highest-predicted by surrounding nodes.

3.3. Community and centrality

The Walktrap algorithm detected three communities in the comorbidity of PTSD and depressive symptoms (Figure 2). "Flashback" (PCPTSD1) and "Avoidance" (PCPTSD2) remained in the

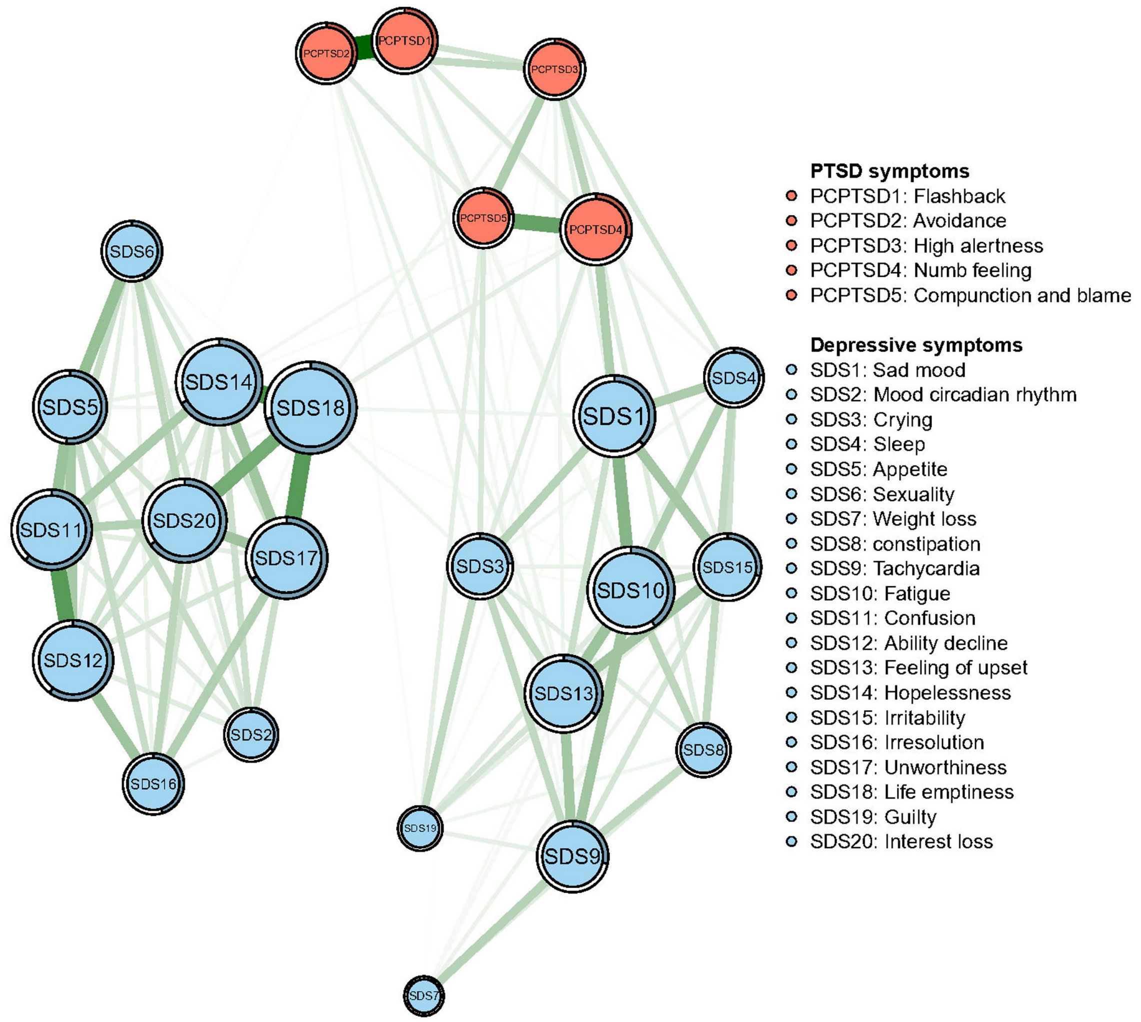

FIGURE 1
Network structure of post-traumatic stress disorder (PTSD) and depressive symptoms in Chinese firefighters. Symptom nodes with stronger associations are placed closer to each other. The dark green lines represent positive correlations. The red lines represent negative correlations. The line thickness represents the strength of the connection between symptom nodes. Ring-shaped pie charts illustrate predictability (e.g., a fully filled dark ring means that 100% of the symptom's variance can be explained by its intercorrelations with the other symptom nodes in the network).

community of PTSD (Community 2), while "High alertness" (PCPTSD3), "Numb feeling" (PCPTSD4), and "Compunction and blame" (PCPTSD5) were included in the Community 1 with depressive symptoms. The Community 3 was entirely generated by the rest depressive symptoms.

All centralities (original EIs and bridge EIs) based on the theoretical model and data-driven detected model were both calculated for comparison. Details are shown in Table 2. As the original EI, measuring the significance of a certain node in the whole network, was not affected by the dimension distribution. Thus, original EIs based on the theoretical model were as same as the data-driven detected model, which are shown in Figure 3. The depressive symptom, "Life emptiness" (SAS18), had the highest EI value, indicating that this symptom was the most central symptom in the network model, which was followed by the symptom "Fatigue" (SDS 10), "Interest loss" (SDS 20), and "Hopeless" (SDS 14).

Regarding the bridge EI, in the theoretical model, "Numb feeling" (PC-PTSD-4) had the highest bridge EI, followed by "High alertness" (PC-PTSD-3), "Sad mood" (SDS1), and "Compunction and blame" (PC-PTSD-5). Details are shown in Figure 4.

In the data-driven model (detected by the Walktrap algorithm), the bridge EIs of symptom nodes were calculated for each community (Figure 5). In community 1, "Mood circadian rhythm" (SDS2) was the node with the highest bridge EI, being significant in connecting external nodes. In community 2, "Flashback" (PCPTSD1) was the node with the highest bridge EI. In community 3, "Life emptiness" (SAS18) had the highest bridge EI.

3.4. Network accuracy and stability

For the accuracy of edge weight, as shown in Supplementary Figure 1, bootstrap 95% CIs were narrow, indicating

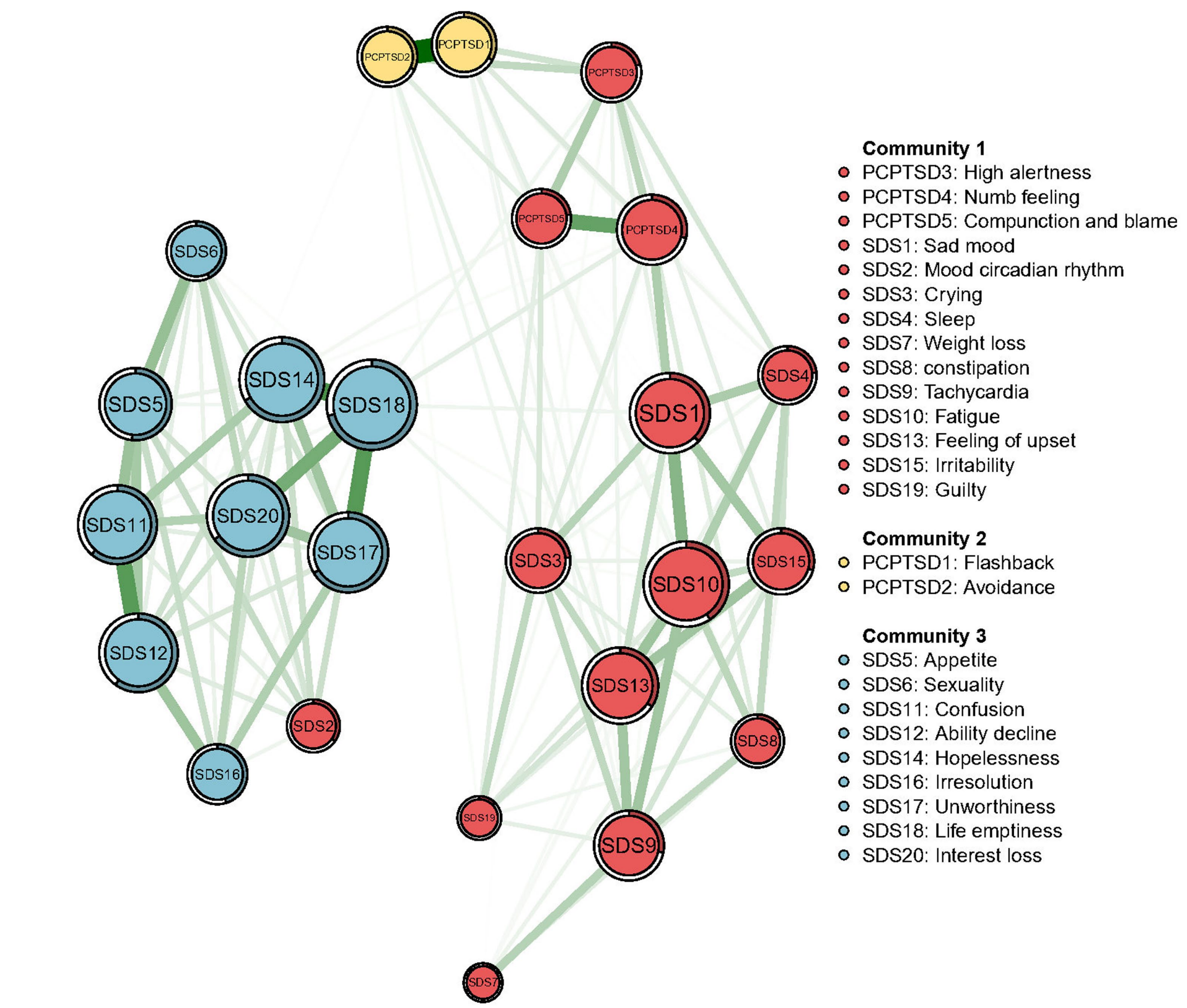

FIGURE 2
Communities detected by the Walktrap algorithm in the network of PTSD and depressive symptoms.

that the estimations of edges were reliable. As presented in Figure 6, the case-dropping bootstrap procedure indicates that the CS-C of EI was 0.75, reflecting that the network kept being stable after dropping 75% of the sample. In the Bootstrapped difference tests for the node EIs (Figure 7), central symptom nodes differed from most other nodes. And the Bootstrapped difference tests for edge weights (Supplementary Figure 2) also showed that most comparisons between edges were statistically different, especially the strongest edges.

3.5. Network comparison

The network structures for both only-child firefighter sub-network and non-only child firefighter sub-network are, respectively, shown in Supplementary Figures 3, 4. The network comparison test (NCT) did not find statistically significant difference in the global strength invariance between only-child firefighters and non-only-child firefighters (only-child: 10.497 vs. non-only-child: 9.688, Test statistic $S = 0.809$, $p = 0.125$). Meanwhile, there was no significant difference found in network structure invariance (Test statistic $M = 0.175$, $p = 0.311$). No significant difference of original centrality was detected in the comparison of only-child sub-network and non-only child sub-network (Test statistic $C = 0.133$–0.468, $p = 0.20$–0.99). Details of original centrality comparison are shown in Supplementary Table 2.

4. Discussion

To the best of our knowledge, the current study is the first study focusing on characterizing the network structure of PTSD and depressive symptoms among the firefighters in China. For the associations between symptom nodes, there were no cross-dimension edges in the strong edges. The strongest edge was the connection between "Flashback" and "Avoidance" within the PTSD sub-network.

Compared with a previous study conducted in veterans in which the edge between PTSD and depressive symptoms was the strongest in the whole network (29), our results suggested that the

TABLE 2 Original centralities and bridge centralities of PTSD and depressive nodes in the network.

Symptom node	Abbr.	Predictability	Original EI	Bridge EI of theoretical model[a]	Bridge EI of community-detected model[b]		
					Community 1 vs. others	Community 2 vs. others	Community 3 vs. others
Flashback	PCPTSD1	0.330	−0.095	0.127	0.315	0.315	0
Avoidance	PCPTSD2	0.320	−0.415	0.08	0.239	0.244	0.005
High alertness	PCPTSD3	0.207	−0.425	0.235	0.221	0.194	0.027
Numb feeling	PCPTSD4	0.288	0.216	0.384	0.108	0.06	0.048
Compunction and blame	PCPTSD5	0.228	−0.485	0.165	0.12	0.099	0.022
Sad mood	SDS1	0.373	0.792	0.191	0.007	0	0.007
Mood circadian rhythm	SDS2	0.348	−1.258	0	0.55	0	0.55
Crying	SDS3	0.234	−0.106	0.161	0.053	0.027	0.026
Sleep	SDS4	0.235	−0.525	0.11	0.025	0.025	0
Appetite	SDS5	0.516	0.239	0	0.079	0	0.079
Sexuality	SDS6	0.427	−0.531	0	0.067	0	0.067
Weight loss	SDS7	0.097	−2.789	0.003	−0.06	0	−0.06
constipation	SDS8	0.170	−0.9	0.09	0.024	0.024	0
Tachycardia	SDS9	0.282	0.281	0.039	0.022	0.022	0
Fatigue	SDS10	0.406	1.331	0.076	0.032	0.025	0.007
Confusion	SDS11	0.614	0.765	0	0.034	0	0.034
Ability decline	SDS12	0.600	0.763	0.005	0.043	0.005	0.047
Feeling of upset	SDS13	0.342	0.561	0.099	0.051	0.069	−0.018
Hopelessness	SDS14	0.668	1.019	0.031	0.09	0	0.09
Irritability	SDS15	0.293	−0.062	0.048	−0.007	0.002	−0.009
Irresolution	SDS16	0.452	−0.513	−0.009	0.018	0	0.018
Unworthiness	SDS17	0.664	0.851	0	0.002	0	0.002
Life emptiness	SDS18	0.711	1.695	0.075	0.233	0	0.233
Guilty	SDS19	0.124	−1.548	0.073	0.008	0.008	0
Interest loss	SDS20	0.652	1.139	0	0.035	0	0.035

PCPTSD, the primary care PTSD screen for DSM-5; SDS, the self-rating depression scale; Abbr., abbreviation; EI, expected influence.
[a]Symptom nodes in the network were pre-divided into two community (PTSD and depressive) based on the specific content of each item in the measurement. Details in Figure 1.
[b]Symptom nodes in the network were divided into three communities (1,2, and 3) based on the results of data-driven analysis. Bridge EIs were calculated for each community and the other nodes in the network, respectively. Details in Figure 2.

association between "Flashback" and "Avoidance" is the strongest connection, even in the symptom network simultaneously including PTSD and depressive symptoms. We speculated that our results revealed the effect of PTSD symptoms in the conjunct network was more limited in firefighters. Thus, the risk of inducing depressive symptoms caused by traumatic-related symptoms was lower.

According to the node EI and predictability results, "Life emptiness" was the most central symptom with the highest EI and the symptom node with the highest predictability. Feeling of emptiness, which could be described as a sense of deadness or absence of inner feelings, is a complexed and negative emotion, including physical component, aloneness component and component involving personal unfulfillment, and lack of purpose (58, 59). Feeling of emptiness was observed in people with depression (60) and PTSD (61), thus, it should be recognized as a transdiagnostic construct. Additionally, previous studies demonstrated that the comorbidity of PTSD and depression could be explained by similar psychopathology symptom dimensions across these two illnesses. And PTSD and depression might present a same traumatic stress construct with common related factors, especially in chronic cases (4). Based previous results, the current study further demonstrated that "feeling of emptiness" was the most significant factor in activating and stabilizing the PTSD-depression psychopathology network. Concerned the high incidence of PTSD and depression comorbidity (17, 62, 63), it is meaningful to figure out the core symptom node in the PTSD-depression network and manipulate accurate intervention aiming "feeling of emptiness" could simultaneously alleviate both PTSD and depressive symptoms.

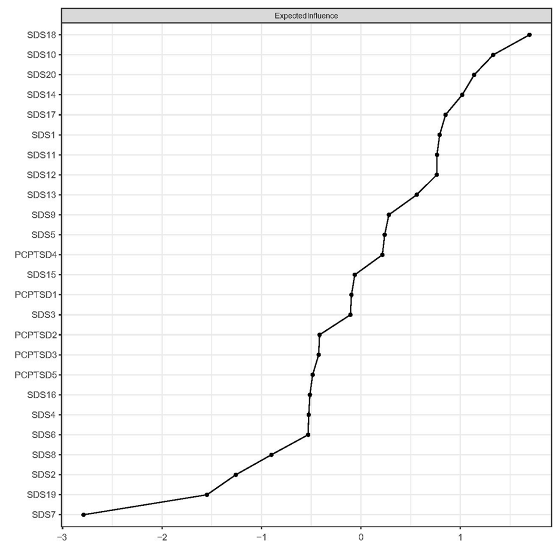

FIGURE 3
Expected influences of PTSD and depressive symptom nodes in the network (shown as standardized values *z* scores).

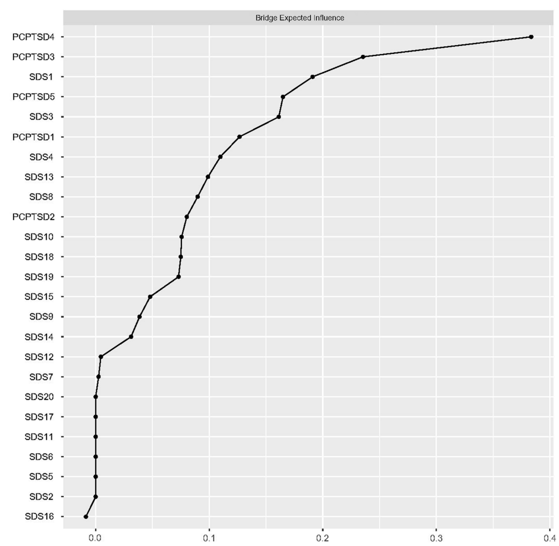

FIGURE 4
Bridge expected influences of PTSD and depressive symptom nodes in the theoretical model (shown as standardized values *z* scores).

As for the bridge symptoms, from the perspective of the association between PTSD symptoms and depressive symptoms (i.e., the theoretical model), the most influential bridge symptom node was the "Numb feeling." Numb feeling was considered as one of the hallmark symptoms of PTSD, including *markedly diminished interest in significant activities* (*Criterion C-4*), *feelings of detachment or estrangement from others* (*C-5*), *and restricted range of affect* (*C-6*), which were represented in the diagnostic criteria of PTSD of DSM-IV (64). Meanwhile, anhedonia is a symptomatic deficit in positive affect, involving the loss of enjoyment in pleasurable activities or the loss of desire to engage in them. This is similar to the Criterion C-4 criterion of numb feeling. Anhedonia was considered to be related to the core symptom of depression and was so common that approximately one-third of depressed individuals have clinically significant anhedonia symptoms (65). Based on the previous studies and the results of our study, we speculated that our results demonstrated the "Numb feeling" acted as "mediating node" between the PTSD symptom cluster and the depressive symptom cluster in the Chinese firefighters, a population with a high risk of traumatic exposure. Additionally, an emotional dysregulation model of PTSD illustrated by Litz et al. (66) held that the "emotionally numb" of individuals with PTSD was actually a result of hyperresponsivity to negative emotional stimulation, individuals with PTSD required more intense positive stimulation to access pleasure. Thus, our results verified this theoretical model among Chinese firefighters from the network analysis perspective. Concerned depressive symptoms usually followed or co-occurred with the PTSD symptoms, instead of existing alone in the context of the traumatic exposure, psychological intervention targeting at "Numb feeling" might control the comorbidity of PTSD and depression.

Notably, the bridge symptoms in the network were also supported by the results of data-driven model. "High alertness," "Numb feeling," and "Compunction and blame," three PTSD symptom nodes with relatively high bridge EI were divided into a community with some depressive symptom nodes. While "Flashback" and "Avoidance" composed a community without depressive nodes. Our results suggested that among PTSD symptom nodes, "Flashback" and "Avoidance" were the two traumatic-event related but less associated with depressive symptoms, while "High alertness," "Numb feeling," and "Compunction and blame" were highly related to the depression. The results of community detection could act as a theoretical reference for the clinical diagnosis. Concerning the similarity of clinical symptoms between PTSD and depression (1), if firefighters were only observed with PTSD symptoms mentioned above which were closely related to depressive symptoms, the possibility of single depression diagnosis, instead of PTSD, should not be overlooked.

Additionally, "Mood circadian rhythm" and "Life emptiness" were the depressive nodes with the highest bridge EI in the respective community. As "Life emptiness" was also the node with the highest original EI, the data-driven results again proved its significance in the PTSD and depressive symptom network. Whereas, "Mood circadian rhythm" had a relatively low original EI but the highest bridge EI. Combined with the location of "Mood circadian rhythm" node in the total network (mainly connecting Community 2 and Community 3), we considered that this situation reflected the circadian rhythm of a series of depressive symptoms in Community 3. Given that the node with high bridge EI play a critical role in inducing the external community symptoms, and that Chinese firefighters are a high-risk, high-stress occupation with a lack of work routines, individualized psychological interventions based on the circadian rhythms of depressive symptoms are essential. Meanwhile, ensuring their healthy life routines can promote the recovery of depressive symptoms.

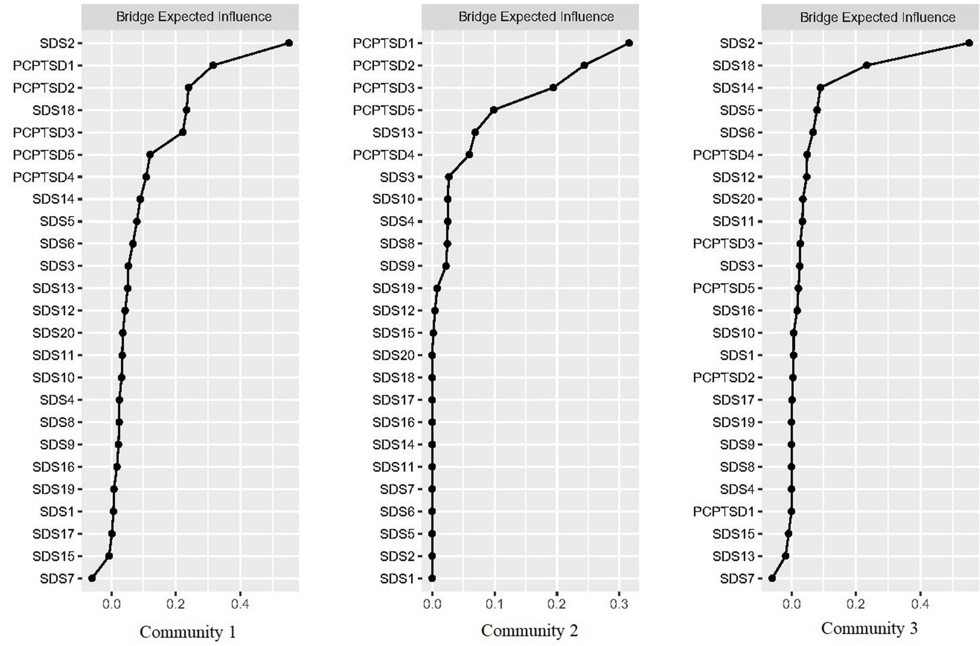

FIGURE 5
Bridge expected influences of PTSD and depressive symptom nodes in the data-driven model (shown as standardized values *z* scores).

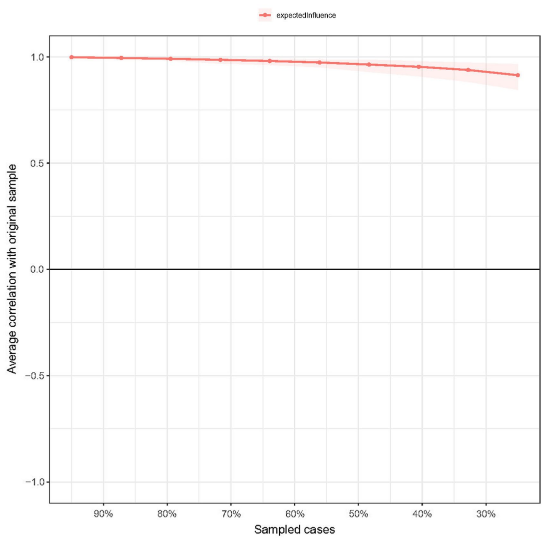

FIGURE 6
Stability of expected influence using case-dropping bootstrap. The *x*-axis represents the percentage of cases in the original sample used at each step. The *y*-axis represents the average of correlations between the expected influence in the original network and the expected influence in the networks that were re-estimated after dropping increasing percentages of cases.

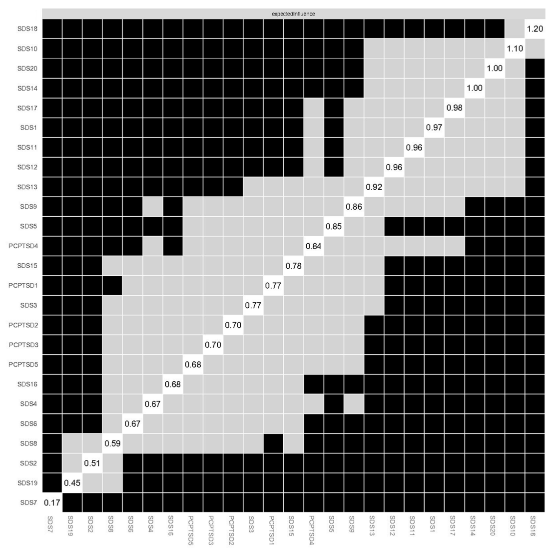

FIGURE 7
Estimation of node expected influence difference by bootstrapped difference test. Gray boxes indicate nodes that do not significantly differ from one another. Black boxes represent nodes that differ significantly from one another. Values in box on the diagonal represent the expected influence of each node.

5. Limitations

Notwithstanding our study firstly demonstrated the PTSD and depression symptom network structure of Chinese firefighters, there are still some limitations need to be clarified. First, the current study was cross-sectional, thus the dynamic alterations and causality among symptom nodes could not be investigated. Second, firefighters recruited in our study were all male, which might limit the promotion of our results among female firefighters. As Cao et al. (67) demonstrated that the sex difference in symptoms connectivity of the PTSD symptom network among adolescents, we speculated that our results need to be further verified in female firefighters. Third, the symptom networks were generated specific to self-reported assessments applied in our study; therefore, the network structure was possibly affected by recall bias and participants' social desirability. Additionally, self-reported assessments were applied rather than clinical interview; thus, atypical clinical features of PTSD and/or depression might be ignored.

6. Conclusion

To the best of our knowledge, the current study firstly demonstrated the network structure of PTSD and depressive symptoms among Chinese firefighters, identifying the central symptoms (i.e., Life emptiness, Fatigue, and Hopeless) and bridge symptoms (i.e., Numb feeling, Sad mood, and Compunction and blame). Meanwhile, the association between two clusters of symptoms was further clarified by the community detection analysis, indicating that core PTSD symptoms were "Flashback" and "Avoidance," whereas "High alertness," "Numb feeling," and "Compunction and blame" were more relevant to depressive symptoms. Our work could act as an impetus for future studies investigating symptom networks of firefighters or other populations with high occupational risk (e.g., policemen, soldiers, etc.) as a method to verify the core symptoms that generalize across various populations with different culture backgrounds and those which are specific for certain populations. Moreover, central and bridge symptoms demonstrated by the current study can be possible targets for clinical intervention to treat firefighters who are suffering from PTSD and depressive symptoms.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethic Committee of the Second Xiangya Hospital of Central South University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

PC and LW: literature review and manuscript drafting. YZ, WM, and GZ: data acquisition. LZ and WL: study design and manuscript revision. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by Natural Science Foundation of China (No. 82171518 to LZ), the Natural Science Foundation of Hunan Province, China (No. 2020JJ5844 to LZ), and Technological Innovation Foundation of Central South University (No. 502801002 to WL).

Acknowledgments

We sincerely thank all participants for their time and patience in this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1096771/full#supplementary-material

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frontiers | Frontiers in Materials

TYPE Original Research
PUBLISHED 11 May 2023
DOI 10.3389/fmats.2023.1142777

OPEN ACCESS

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RECEIVED 12 January 2023
ACCEPTED 25 April 2023
PUBLISHED 11 May 2023

CITATION
Hossain MT, Girase AG and Ormond RB (2023), Evaluating the performance of surfactant and charcoal-based cleaning products to effectively remove PAHs from firefighter gear.
Front. Mater. 10:1142777.
doi: 10.3389/fmats.2023.1142777

Evaluating the performance of surfactant and charcoal-based cleaning products to effectively remove PAHs from firefighter gear

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Firefighters regularly respond to fire scenes where a mixture of chemicals including volatile, semi-volatile, and nonvolatile compounds are present in smoke and soot. Polycyclic aromatic hydrocarbons (PAHs) are common contaminants at fire scenes that may be deposited on the gear and the individual firefighter. Laundering is a common approach for the decontamination of contaminated gear. Surfactants are widely used by firefighters during laundering to remove PAHs as they are generally non-toxic and biodegradable. The removal of PAHs depends on the surfactant types, chemistries, and concentrations. This study evaluated the effect of surfactant concentrations to remove persistent contaminants like PAHs from turnout gear. The cleaning performance of different types of surfactants was also evaluated. Outer shell fabrics were contaminated with a standard mixture of 16 PAH compounds, and two commercial detergents were used at different concentrations. Additionally, the cleaning efficacy of eight commercially available regular and charcoal-based cleaning products was also determined against PAHs at a single surfactant concentration. For the decontamination method, a bench-scale washing procedure simulating the National Fire Protection Assocation 1851 laundering process was used. The removal efficacy of high molecular weight (HMW) PAHs were found to be lower compared to the low molecular weight PAHs for any type or any concentration of detergent. Our research also showed that the recommended surfactant concentrations provided by detergent manufacturers can be ineffective at removing the HMW PAHs from heavily contaminated fabric. With 1 mL of detergent in a 100-mL bath, which is multiple times higher than recommended amount, only 40% of HMW PAHs were removed. The cleaning efficacy can be increased to above 90% by using higher concentrations of detergents. This research shows that firefighters may need to use a higher concentration of detergent than the recommended amount to effectively remove PAHs from the gear. All the regular and charcoal-based detergents were able to remove PAHs effectively from contaminated fabrics when a higher concentration of detergent was used.

KEYWORDS

PAHs, detergent, surfactant, charcoal, decontamination, firefighters, turnout gear, aromatic hydrocarbons

1 Introduction

Firefighting is one of the most hazardous occupations in the world. The chance of death, fatal injuries, skin burns, and heat stress-related casualties is common among firefighters (Mandal et al., 2022; Mandal et al., 2021; Mazumder et al., 2022). Apart from heat-related injuries, firefighting is also associated with several health hazards for firefighters owing to chemical exposure. The International Agency for Research on Cancer (IARC), an agency of the World Health Organization (WHO), reclassified the firefighting occupation as “carcinogenic to humans” (Group 1) in 2022 due to the carcinogenicity involved in occupational exposure as a firefighter during and after firefighting activities (Demers et al., 2022). Previous research showed that the chance of developing prostate cancer and mesothelioma are double among firefighters compared to general population (LeMasters et al., 2006; Kang et al., 2008; Daniels et al., 2014; Tsai et al., 2015). An increased risk of lung, bladder, and colorectal cancers is also observed among firefighters (Daniels et al., 2015; Jalilian et al., 2019; Soteriades et al., 2019; Casjens et al., 2020). Besides cancers, firefighters also suffer from respiratory diseases, reproductive system problems, skeletal, and lymphatic diseases (LeMasters et al., 2006; Daniels et al., 2015; 2014). The U.S. Forest Service reported a higher possibility of death associated with cardiovascular disease and a higher risk of lung cancer among firefighters for long exposure duration in fire scenes.

Firefighters are exposed to a wide range of chemicals and particulates while performing their tasks. Chronic exposure to these contaminants is linked to this increased risk of cancer and other health complexities (Fent and Evans, 2011; Kirk et al., 2011; Tsai et al., 2015; Mazumder et al., 2023). PAHs, phenols, phthalates, benzene, heavy metals, etc. are common carcinogenic substances that might be present in the smoke (Heus, 2015). PAHs are potential carcinogens that are generated from the incomplete combustion of organic fuels or substances like coal, wood, oil, and gas, among others. The United States Environmental Protection Agency (EPA) classified 16 PAHs as known, possibly, or probably carcinogenic for human health (EPA, 1982; Zheng et al., 2018). Exposure to these PAHs may have severe health impacts on firefighters. PAH exposure may cause acute toxicity including leukemia in humans (Akash et al., 2022). PAHs mixtures can link to cell damage and biochemical disruptions associated with cancer and other chronic diseases. Inhalation of PAHs may have the most severe impact on the wellbeing of human as respiratory exposure to PAHs may cause lung cancer (Kim et al., 2013). Gastrointestinal and bladder cancers can be developed in human beings due to the long-term exposure to PAHs. Some PAHs become geno-toxic after metabolized to the diol epoxides which are associated with carcinogenicity and toxicity process (Lewtas, 2007; Gamboa et al., 2008). Long-term exposure to PAHs may reduce immune function, hamper kidney and liver function, respiratory problems, skin, etc. (Abdel-Shafy and Mansour, 2016). A high level of exposure to PAHs mixture may cause different short-term health conditions including eye irritation, skin irritation, diarrhea, and nausea (Unwin et al., 2006).

Among the EPA classified 16 PAHs, many PAHs are identified on the turnout gear of firefighters after participating at the fire scene (Kirk and Logan, 2015; Mayer et al., 2020). Contaminated ensembles act as a source of exposure to contaminants for firefighters as the toxic compounds generated by combustion during a fire deposit on the outer surface of ensembles. Kirk et al. measured the concentration of PAHs from turnout gear of instructors who participated in structural live-fire training sessions (Kirk and Logan, 2015). They found that the concentration of PAHs outside the turnout gear was 69–290 ng/cm^2 (Kirk and Logan, 2015). PAHs are common contaminants in the wildland fire scene also. Cherry et al. (2021) measured an increased concentration of PAHs using skin wipes from hands and neck of wildland firefighters after attending the fire site. Dermal absorption of these contaminants may occur if these transfer and deposit on the skin during the removal of gear (Sousa et al., 2022). Two types of cleanings are recommended by the National Fire Protection Assocation (NFPA) to decontaminate ensembles: routine cleaning and advanced cleaning. On-scene gross decontamination, also referred to as preliminary exposure reduction, is a part of routine cleaning that is performed without taking off the turnout gear before returning to the fire station. On-site decontamination is performed to remove contaminants from the surface of the gear without compromising the functional ability of gear (Calvillo et al., 2019). Fent et al. (2017) used soap and water along with a scrub brush to perform on-scene decontamination. They scrubbed the turnout gear using water and dish soap which reduce the PAH level by 85%. They also found 24% and 0.5% efficiency against PAH contaminants when using dry brush decontamination and air-based decontamination methods, respectively (Fent et al., 2017). Calvillo et al. (2019) evaluated the performance of the water-only decontamination method against PAHs. The authors concluded that the water-only method is ineffective in removing PAHs. Advanced cleaning means hands or machine cleaning by applying cleaning agents. NFPA recommended performing advanced cleaning such as laundering twice a year, once every 6 months, or in case any major issues are observed with the gear after performing routine inspections.

The use of detergent has been proven as an effective technique to remove PAHs from contaminated soil by increasing the solubility of the hydrophobic organic compounds (HOCs) (Paria and Yuet, 2006; Laha et al., 2009; Peng et al., 2011). Removal of hydrophobic organic compounds like PAHs depends on the desorption of contaminants from the fabric surface as the contaminants need to be incorporated into the bulk aqueous phase when washed with water (Edwards et al., 1991). When surfactants are used to remove hydrophobic compounds from contaminated fabrics, these compounds are portioned into hydrophobic cores of surfactant micelles (Peng et al., 2011). Also, enzymes present in the surfactant improve the reactivity of the fibers besides increasing the efficacy of surfactants (Olsen and Falholt, 1998; Parajuli et al., 2021). Different detergents are used by independent service providers (ISP) and fire departments to remove contaminants generated at fire scenes. Mild detergent, dish soap, and regular laundry detergent are used in the industry to perform laundering or on-scene decontamination. Some commercially available detergents in the market are specially formulated for the fire service application such as Citrosqueeze® (Solutions Safety), Doff ‘n DECON™ (Intelagard), and Turnout Gear Wash (Gear Wash). Some charcoal-based soaps and body washes including Sootsoap™ and Responder Wash (Responder Wipes) are also being formulated for use in the fire service for decontaminating skin and hair to take advantage of charcoal’s ability to adsorb chemicals. The chemistry of the cleaning products plays an important role in the cleaning performance. Stolpman et al. (2021) compared the cleaning efficacy of two cleaning solutions, Decon7 and a standard detergent to remove heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and antimony (Sb) while performing laundering. They used the manufacturers' recommended amount for both surfactants and found that Decon7 performed better to reduce metal content compared to the standard laundry detergent.

NFPA 1851: *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* does not provide any instruction regarding the amount of detergent that needs to be used during the laundry or on-scene decontamination process. Many detergent manufacturers also do not provide any guidelines in this regard. In that case, firefighters and fire services need to depend on their own judgment to decide how much detergent needs to be used. Although some manufacturers provide instructions regarding the amount of detergent that needs to be used during laundering, very few research studies have been conducted to determine how effectively their recommended amount of detergent can remove PAHs from turnout gear. Banks et al. (2021) assessed the effect of laundering on semi-volatile organic compounds: PAHs, polybrominated diphenyl ethers (PBDEs), and organophosphate flame retardants (OPFRs). The concentration of PBDEs and OPFRs was found almost similar before and after laundering. They also observed very small successes to remove some PAH compounds from contaminated gear and concluded that current laundering systems are not effective enough against semi-volatile organic compounds (SVOCs). Similarly, Girase et al. (2022) found very low removal efficiency against PAH compounds after performing laundry. Another concern is that firefighters follow the manufacturer-recommended concentration of detergent without considering the concentration of contaminants deposited on gear. Most surfactant manufacturers recommend using surfactants according to load size during the laundry process. However, previous research already showed that maximum surfactant sorption capacity is constant and does not depend on the soil/water weight-to-volume ratio (Liu et al., 1992; Zheng and Obbard, 2002)· The sorption of surfactant on soil largely depends on surfactant concentration (Adeel and Luthy, 1995). A higher concentration of surfactant might be required against highly contaminated soil with persistent compounds like PAHs. The concentration of contaminants that deposit on the turnout gear is hard to predict and contamination levels could be different on the turnout gear of firefighters depending on the work assignment at the fire scene. Fent et al. (2017) observed the highest PAH contamination on the skin of firefighters who were responsible for the search and attack during fire extinguishment. PAHs are hard to remove from fabric due to low water solubility, and the higher concentration of these contaminants may make it more difficult to remove. In that case, the effectiveness of recommended concentration of detergent may reduce further. Therefore, a thorough investigation is required to determine whether the recommended concentration of detergent is effective enough to remove PAHs from the gear and what approach should be followed to gain the utmost cleaning efficacy against these persistent contaminants.

This study aims to evaluate the effect of the concentrations of detergents to remove PAHs from turnout gear. This will give an idea of whether the manufacturers' recommended amount of detergents should be enough to remove PAHs effectively. The removal percentage of PAHs is determined using only water to show the contribution of detergent in removing PAHs. The cleaning efficacy is evaluated of some standard detergents (nonionic or the combination of nonionic and anionic surfactants) and charcoal-based products (soaps and body wash) which could be used by firefighters to clean turnout gear and/or contaminated skin. The study used 16 different PAHs to understand how different chemical structures of PAHs act as contaminants. To our best knowledge, this is the first paper specifically exploring the performance of a wide range of detergents, including those with a charcoal component, regarding the impact of concentration on the ability to remove PAHs from firefighters' gear. This will help in gaining a comprehensive understanding of the removal of PAHs which may help in modifying the approach to the removal of contaminants.

2 Materials and methods

2.1 Materials

2.1.1 Fabric

For this study, a flame-resistant fabric commonly used in wildland firefighting ensembles was selected as the contamination substrate for all cleaning experiments. The Sigma™ fabric (Safety Components) was comprised of 5% meta-aramid/17% polyamide/6% para-aramid/32% Lenzing® FR and had a silicone-based water-repellent finish. This material is similar to many structural firefighter outer shell materials and is certified to NFPA 1977, 1975, and 1951 standards.

2.1.2 Chemical contaminants

A QTM PAH Standard Mix containing 16 PAH compounds shown in Table 1 was already prepared in methylene chloride. This standard mix was purchased from Sigma-Aldrich Inc. (CRM47930). The concentration of each PAH compound in the stock solution was 2,000 ng/μL. The standard mix was packaged in 2-mL amber vials and kept in the refrigerator at 4°C. Dilutions of the standard mix were made for calibration of analytical instrumentation which is explained in 2.2.4.

2.1.3 Detergents

To assess the impact of detergent concentration, two commercially available detergents (CD-1 and CD-2) were used at different concentrations to decontaminate the fabric. CD-1 contains a nonionic surfactant (4-Nonylphenyl-polyethylene glycol), D-limonene, mackamide C, and glycol ether. CD-2 contains non-ionic and anionic surfactants (alkyl ethoxy sulfate and alkyl sulfate, linear alkylbenzene sulfonate), amide oxide, hydrogen peroxide, and percarbonate. Although both are commercial detergents, CD-1 is developed specifically for turnout gear whereas CD-2 is a common consumer laundry detergent.

Cleaning efficacy was also determined for four regular detergents (laundry and dish soaps) (CD-1, CD-2, CD-3, CD-4)

TABLE 1 Chemical and physical properties of 16 targeted PAHs (ATSDR, 2005; Bojes and Pope, 2007; Patel et al., 2020).

PAH compound	Molecular weight (g/mol)	Number of benzene rings	Boiling point (°C)	Octanol-water partitioning coefficient log K_{OW}	Solubility in water (mg/L)	LOD (ng/μL)	LOQ (ng/μL)
Naphthalene (Nap)	128.17	2	218	3.29	31	0.10	0.33
Acenaphthylene (Acy)	152.2	3	280	4.07	3.8	0.03	0.10
2-Bromo naphthalene (2-Br)	207	2	281	No data	3.4	0.03	0.09
Acenaphthene (Ace)	154.21	3	279	3.98	0.045	0.03	0.12
Fluorene (Fle)	166.22	3	295	4.18	1.9	0.03	0.11
Phenanthrene (PHE)	178.23	3	340	4.45	1.1	0.04	0.12
Anthracene (An)	178.23	3	340	4.45	0.045	0.03	0.10
Fluoranthene (Fla)	202.25	4	404	4.9	0.26	0.03	0.09
Pyrene (Py)	202.26	4	400	4.88	0.132	0.02	0.07
Benz a anthracene B[a]A	228.29	4	438	5.61	0.011	0.03	0.11
Chrysene (Chr)	228.29	4	448	5.9	0.0015	0.02	0.05
Benzo b fluoranthene B[b]F	252.32	5	481	6.04	0.0015	0.03	0.09
Benzo a pyrene B[a]P	252.32	5	495	6.06	0.0038	0.03	0.09
Indeno 1,2,3-cd pyrene (Ind)	276.33	6	530	6.58	0.062	0.03	0.10
Dibenz a,h anthracene D[ah]A	278.35	6	524	6.84	0.0005	0.06	0.19
Benzo g,h,i perylene B[ghi]P	276.33	6	550	6.5	0.00026	0.07	0.22

and four charcoal-based products (CD-5, CD-6, CD-7, CD-8). For that, 10 mL of each was added with 90 mL of water to perform the decontamination. CD-3 and CD-4 both contain a blend of non-ionic and anionic surfactants. The four latter products are mainly targeted for skin or hair decontamination and not necessarily for use on fabrics. However, they were included in this study to determine how soaps formulations containing charcoal compared to other surfactants. Supplementary Table S1 shows the list of cleaning products used in this experiment.

2.2 Method

2.2.1 Bench-scale washing for decontamination

Fabric swatches (5 cm × 4 cm) were prepared from the roll of fabric. A repeater pipette (Eppendorf) was used to dispense six 5-μL droplets of the reference mix (60,000 ng of each PAH compound) on the fabric swatch. Fabric swatches were kept for 30 min in ambient conditions so that contaminants could penetrate the fabric surface and the solvent could evaporate. Contaminated swatches were then transferred into 250-mL Erlenmeyer flasks containing water, detergent, and glass beads. The combined volume of detergent and water in each flask was 100 mL. The amounts of surfactants were 0 mL (water only), 1 mL, 10 mL, 20 mL, and 50 mL which were added with 100 mL, 99 mL, 90 mL, 80 mL, and 50 mL of water, respectively. Three replicates were used for each condition. In each flask, 5 g of 4-mm glass beads were added to provide some mechanical agitation during washing. The flasks were placed in an LSE Corning® bench-top shaking incubator to perform bench-scale washing of contaminated fabric swatches. All the samples were washed for 60 min at 40°C and 300 RPM which was the maximum RPM available on the shaker bath. This high RPM would provide mechanical agitation during the washing process. The temperature 40°C was used to perform washing according to the NFPA 1851 standard (NFPA, 1851). After 1 h of washing, contaminated water was drained, and samples were rinsed with 100 mL of clean water at room temperature for 10 min. In each batch, nine samples were washed using the bench-scale washer-extractor. Then, samples were placed in a rack for 24 h for air drying.

2.2.2 Pressurized solvent extraction

The Buchi Speed Extractor E–916 was used to perform the extraction of each fabric. Extraction was completed for one cycle which consists of a 1-min heat up, a 5-min hold, and a 2-min discharge. Temperature and pressure were held at 100°C and 100 bar, respectively. The extraction solvent was n-hexane (95% Millipore Sigma). Fabric swatches were inserted into a 10-mL stainless steel extraction cell and the rest of the volume of the

TABLE 2 Calibration standard preparation for chromatography method.

Calibration standard	Target concentration (ng/μL)	The volume injected from the stock solution (μL)	Mass per unit fabric area (ng/cm^2)
1	0.2	1	100
2	0.8	4	400
3	2	10	1000
4	4	20	2000
5	6	30	3000
6	8	40	4000

cell was filled with glass beads to reduce the consumed amount of solvent during extraction. Top and bottom cellulose filters were used to cap the 10-mL extraction cell. This will trap the particulate present in the fabric samples so that extracted solution is contamination free. One positive control (known quantity of contaminants without wash) was used during each extraction cycle to monitor and ensure that extraction cycles were working properly. It took 18 min to complete the extraction process. After the extraction, n-hexane was added to the extracted solution and then the solution was diluted to volume in a 10-mL volumetric flask. The diluted extract was then transferred into a 2-mL amber autosampler vial using a 3-mL Luer-lock syringe with 0.2 μm PTFE filters.

2.2.3 Gas chromatography-mass spectrometry (GC-MS) analysis

Samples were analyzed using Agilent 7890B gas chromatographic system connected with Agilent 5977B mass spectrometer equipped with electron ionization (EI). The splitless mode was used for the chromatographic analysis with a 100 mL/min purge flow at 1 min. Samples were analyzed using an Agilent EPA 8270D fused silica capillary column (30 m × 0.25 mm × 0.25 μm). Helium was used as the carrier gas with a 1.2 mL/min flow rate. The Agilent Ultra Inert liner (5190–3136) was used in the GC inlet. The injection temperature and injection volume were 250°C and 1 μL, respectively. Initially, the oven temperature was 40°C and raised to 200°C at 10°C/min followed by a 1-min hold. Then, the temperature was again increased to 300°C at 25°C/min and held for one more minute. The total run time for each sample was 30 min. Samples were analyzed in scan mode (35–550 amu) and 70 eV ionization energy was used in EI mode. Throughout the run, the MS transfer line, MS quad, and ion source temperatures were 280°C, 300°C, and 200°C, respectively.

2.2.4 Calibration curve preparation

The instrument was calibrated for each compound. Calibration solutions were prepared in six concentrations: 0.2 ng/μL, 0.8 ng/μL, 2 ng/μL, 4 ng/μL, 6 ng/μL, and 8 ng/μL. To prepare calibration solution, shown in Table 2, PAHs mixture was injected into 10-mL volumetric flasks and diluted using n-hexane. Each concentration was analyzed three times and the average was taken to minimize error. The minimum R-square coefficient was 0.997 among all the calibration curves from each compound. The lowest concentration (0.2 ng/μL) was run seven times consecutively to get the limit of detection (LOD) and limit of quantitation (LOQ) for each compound. Equations 1 and 2 were used respectively to calculate the LOD and LOQ:

$$LOD = \frac{3\sigma}{m} \tag{1}$$

$$LOQ = \frac{10\sigma}{m} \tag{2}$$

Here, σ = standard deviation of the peak area of seven consecutive runs and *m* is the slope of the calibration curve for each compound. LOD represents the minimum value at which the instrument can confidently identify instrument noise and peak area. LOQ represents the minimum value at which the instrument can quantify the peak area of a compound.

2.2.5 Determination of extraction efficiency

Two fabric swatches were spiked with 60,000 ng using the same procedure described as above and were extracted. These swatches were considered as positive controls. The peak area obtained for each compound was used to obtain the concentration using the calibration curve. The spiked amount of contaminant was compared with the extracted amount of contaminant to calculate the extraction efficiency. Uncontaminated fabric washed with surfactant is considered as the negative control.

2.2.6 Determination of cleaning efficacy

Cleaning efficacy represents the concentration of contaminant removed by the washing process. Unwashed contaminated fabric samples were compared to uncontaminated negative samples to calculate cleaning efficacy. Eq. 3 was used to calculate cleaning efficacy which was taken from NFPA 1851 standard after some modification.

$$Cleaning\ efficacy = \frac{(Cc - Cm) - (Cw - Cp)}{(Cc - Cm)} \times 100 \tag{3}$$

Cc = Original concentration of contaminant dosed on the fabric.
Cm = Amount of contaminant on the unwashed uncontaminated fabric.
Cw = Amount of contaminant on washed fabric.
Cp = Amount of contaminant on uncontaminated washed fabric.

3 Result

PAHs are classified into two groups depending on the number of rings present in the structure of the compounds: high molecular

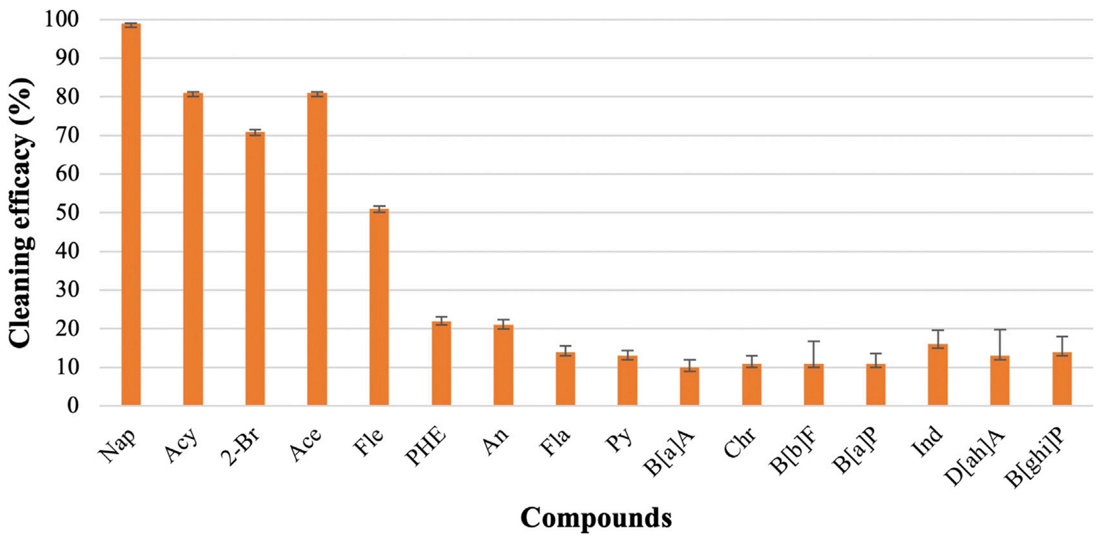

FIGURE 1
Cleaning efficacy of water against 16 PAHs [range = mean ± standard error (SE)].

weight (HMW) PAHs and low molecular weight (LMW) PAHs. In this analysis, HMW PAHs contain four or more aromatic rings in the structure whereas LMW PAHs contain two or three aromatic rings (Lee, 2010). The concentration of each compound was considered zero in unwashed uncontaminated fabric (Cw) and uncontaminated washed fabric (Cp) if no value was obtained after GC analysis. If no chromatograms are detected in GC-MS in the washed sample, then LOQ/2 values were used to calculate cleaning efficacy. The error bars in all the graphs represent the standard errors.

3.1 Cleaning efficacy of only water

Among the 16 PAHs, seven LMW PAHs are naphthalene (Nap), acenaphthylene (Acy), 2-bromo naphthalene (2-Br), acenaphthene (Ace), fluorene (Fle), phenanthrene (PHE), and anthracene (An). Other eight are HMW PAHs: fluoranthene (Fla), pyrene (Py), benz-a-anthracene B[a]A, chrysene (Chr), benzo-b-fluoranthene (B[b]F), Benzo-a-pyrene (B[a]P), Indeno-1,2,3-cd pyrene (Ind), Dibenz-a,h-anthracene (D[ah]A), and Benzo-g,h,i-perylene (B[ghi]P). Figure 1 shows the effectiveness of cleaning the fabrics with only water. Nap and 2-Br contain two rings in the structure, and the Cleaning efficacies of water were 95% and 75% against these compounds, respectively. Acy, Ace, Fle, Phe, and An contains three rings in their structures. The water-only removals for Acy, Ace, Fle were 81%, 81%, and 51%, respectively whereas approximately 20% cleaning efficacy was observed for both PHE and An. The average cleaning efficacy of Σ7 LMW PAHs was 70%. As for HMW PAHs, water-only process showed low effectiveness and the cleaning efficacy of water for Fla, Py, B[a]A, and Chr were 14%, 13%, 10%, and 11%, respectively. B[b]F, B[a]P contain five rings in their structure, and the water-only process removed 11% of both compounds. Ind, D[ah]A, and B[ghi]P contain six rings, and the cleaning efficacies of water against these compounds were 16%, 13%, and 14%, respectively. The cleaning efficacy of water decreases significantly against HMW PAHs, and the average cleaning efficacy of Σ9 HMW PAHs is 12.55%.

3.2 Effect of different concentrations of surfactants

CD-1 is usually used to wash turnout gear and CD-2 is a popular consumer laundry detergent that is also commonly used by fire departments. According to the safety data sheet (SDS) of CD-1, 6 oz of detergent needs to be used for a 45-lbs washing load. The weight of each fabric swatch was 0.5 g. By scaling to the recommended amount, 10 μL of CD-1 needs to be added during the bench-scale washing. However, 1 mL of detergent was used as the lowest concentration of CD-1 for this experiment which is 100 times higher than the recommended amount. CD-2 does not have any specific recommendations like CD-1. Therefore, both detergents were used at the same ratios for the washing. Figure 2 and Figure 3 show the cleaning efficacy of different concentrations of CD-1 against LMW PAHs and HMW PAHs respectively.

Figure 2 shows that cleaning efficacy increased significantly for LMW PAHs with 1 mL of surfactant was used compared to the water-only process. Among the LMW PAHs, the lowest cleaning efficacies were obtained for PHE and An (22% and 21%) using only water. Cleaning efficacy against both compounds increased to 68% when 1 mL of CD-1 was used. Cleaning efficacies of other LMW PAHs also increased significantly. With the 1 mL of CD-1, Acy (91%), 2-Br (84%), Ace (90%), and Fle (78%) were all removed at high levels. For PAHs containing four rings a significant increase in removal was also observed with the 1 mL of surfactant (increased from 10% to 14% to around 50%–60%). However, very poor

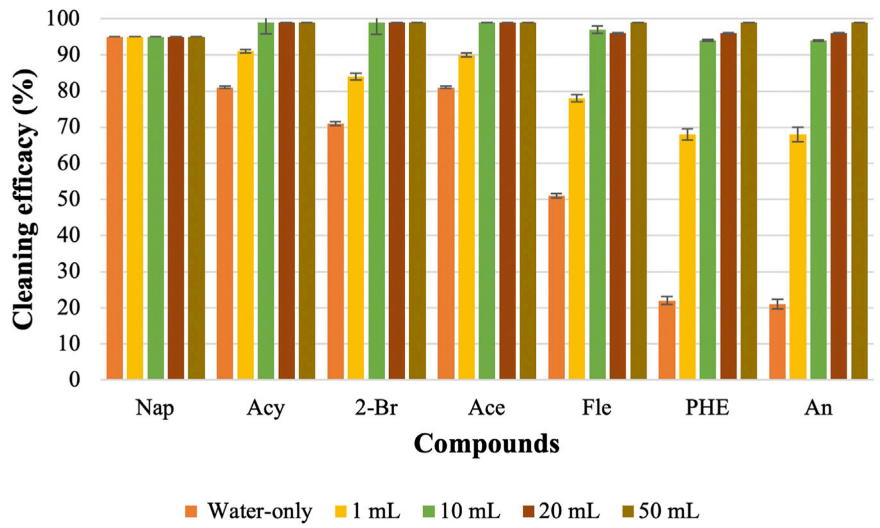

FIGURE 2
Cleaning efficacy of CD-1 against LMW PAHs [range = mean ± SE].

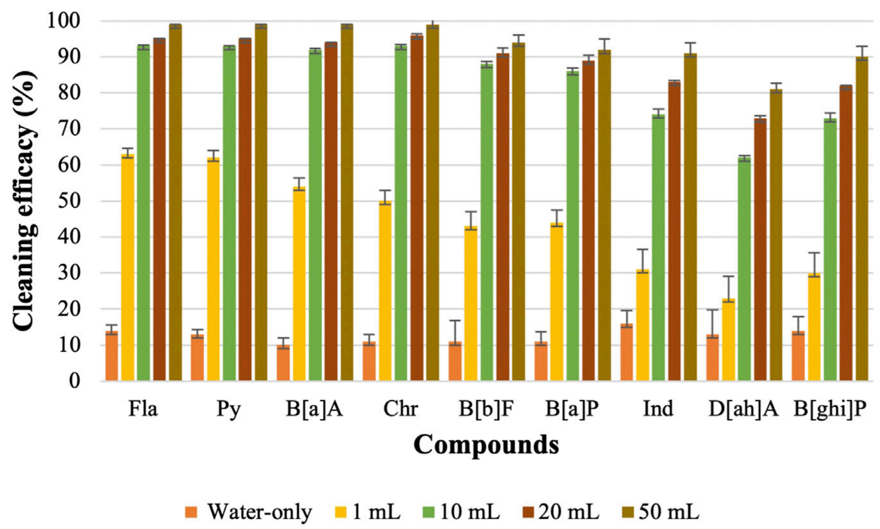

FIGURE 3
Cleaning efficacy of CD-1 against HMW PAHs [range = mean ± SE].

cleaning performance was obtained for PAHs with five or six rings in the structure. Around 30% or less cleaning efficacy was observed for Ind, D[ah]A, and B[ghi]P which are the largest structures and contain six rings.

Increasing to 10 mL of CD-1 showed a drastic improvement in cleaning efficacy against all the PAH compounds. Above 90% cleaning efficacy was measured for all the LMW PAHs and HMW PAHs containing four rings. Cleaning efficacy against all the PAH compounds increased further with 20 mL and 50 mL of CD-1. However, using even 50 mL of surfactant was not able to remove 100% of PAHs containing six rings. Using 20 mL of CD-1 removed 83%, 73%, and 82% of Ind, D[ah]A, and B[ghi]P, respectively, whereas 50 mL of CD-1 removed 91%, 81%, and 90% of those PAH compounds. With the increase of surfactant's concentrations, the solubility of each PAH compound also increases which contributes to enhanced desorption of these PAH compounds (Edwards et al., 1991; Zhou and Zhu, 2007; Zhu and Zhou, 2008; Peng et al., 2011). This might be the reason for the increased removal of PAHs with higher concentrations of surfactants.

Like CD-1, the same concentrations of CD-2 were used against all the PAH compounds (shown in Supplementary Table S2). A similar trend in cleaning efficacy was obtained for different concentrations of CD-2. Like CD-1, 1 mL of CD-2 did not remove HMW PAHs containing five or six rings. Using 10 mL of

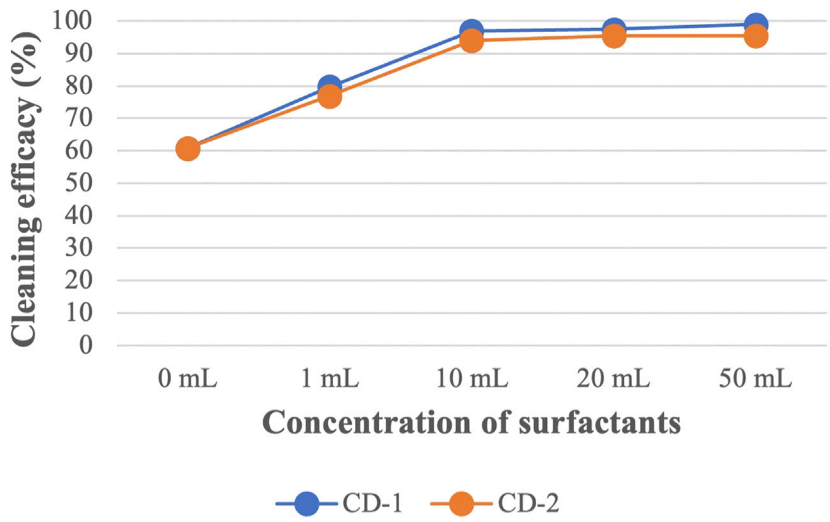

FIGURE 4
The average cleaning efficacy of ∑7 LMW PAHs using different concentrations of CD-1 and CD-2.

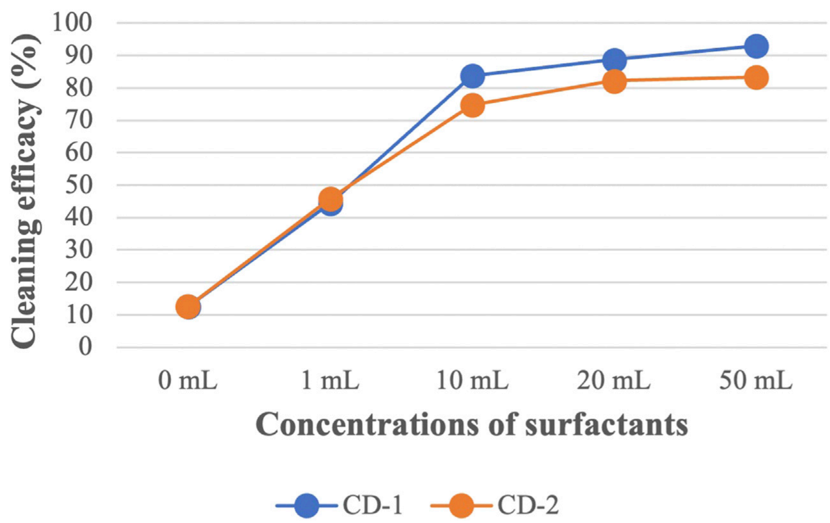

FIGURE 5
The average cleaning efficacy of ∑9 HMW PAHs using different concentrations of CD-1 and CD-2.

CD-2 shows very good cleaning efficacy against all PAHs compounds although cleaning efficacy is low against D[ah]A (53%). Using 20 and 50 mL of CD-2 increased cleaning efficacy further and the highest cleaning efficacy of D[ah]A is around 69% when 50 mL of CD-2 was used. Figure 4; Figure 5 show the average cleaning efficacy of Σ7 LMW PAHs and Σ9 HMW PAHs using CD-1 and CD-2, respectively; Figure 4 shows that 83% of LMW PAHs are removed by 1 mL of CD-1 and 80% of Σ7 LMW PAHs are removed by 1 mL of CD-2. Using 10 mL or higher concentrations of CD-1 and CD-2 showed near 100% cleaning efficacy against Σ7 LMW PAHs. Using 1 mL, 10 mL, 20 mL, and 50 mL of CD-1 show 44%, 84%, 89%, and 93% cleaning efficacy against Σ9 HMW PAHs whereas 1 mL, 10 mL, 20 mL, and 50 mL of CD-2 show 46%, 75%, 82%, and 83% cleaning efficacies against Σ9 HMW PAHs (Figure 5).

3.3 Evaluate the cleaning efficacy of regular and charcoal-based cleaning products

The previous part of the experiment shows that the cleaning efficacy of detergents increases with the increase in

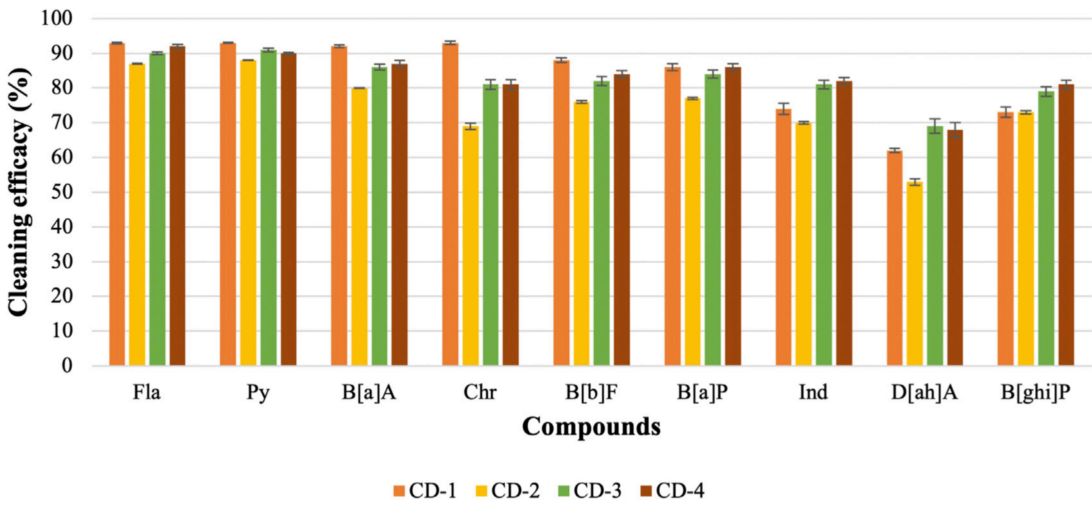

FIGURE 6
Cleaning efficacy of regular detergents against HMW PAHs [range = mean ± SE].

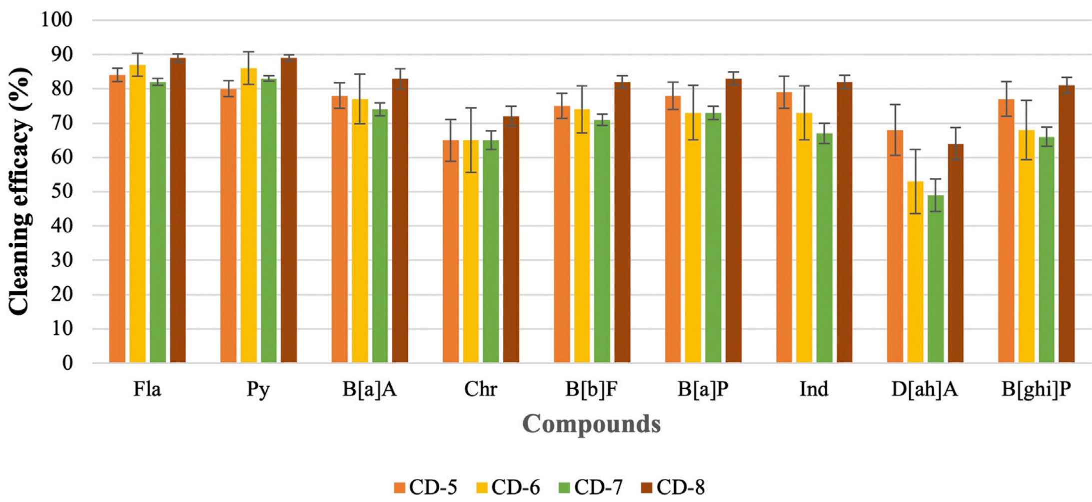

FIGURE 7
Cleaning efficacy of charcoal-based detergents against HMW PAHs [range = mean ± SE].

concentration. Therefore, it is hard to compare among detergents as one detergent may show lower or similar cleaning efficacy depending on which concentration is used. As 10 mL of detergents with 90 mL of water shows good cleaning efficacy against most of the PAHs, this concentration of detergent is used to evaluate the cleaning efficacy of regular detergent (anionic, nonionic, or cationic surfactant) and charcoal-based products. Figure 6; Figure 7 show the cleaning efficacy against HMW PAHs using regular detergents and charcoal-based products, respectively. Cleaning efficacy has been determined against all the 16 PAH compounds and removal efficacy of LMW PAHs has been shown in the Supplementary Figures S1, S2 respectively when regular and charcoal-based detergents were used. Around 90% or higher cleaning efficacy is obtained against Σ7 LMW PAHs for each regular detergent and charcoal-based product. As expected, the removal of PAH compounds decreases with the increase of molecular weight and octanol-water partition coefficient (K_{OW}) values. The removal of PAHs containing four aromatic rings is higher compared to those with five or six rings. The regular surfactants CD-1, CD-2, CD-3, and CD-4 show 84%, 75%, 83%, and 83% cleaning efficacy against Σ9 HMW PAHs. Regular surfactants and charcoal-based surfactants showed similar cleaning performance. The charcoal-based products CD-5, CD-6, CD-7, and CD-8 showed 76%, 72%, 70% and 81% cleaning efficacy respectively against Σ9 HMW PAHs. Charcoal-based surfactants are developed to clean body parts like hair and hands. Higher removal of PAHs from outer shell fabrics by using these products may also indicate that these products would be able to remove PAHs from the body parts of firefighters. Each detergent showed the lowest cleaning efficacy against D[ah]A which contains six aromatic rings in its structure.

4 Discussion

In most of the prior research works, wipes were used to collect PAHs from the outer surface of fabrics to calculate the cleaning efficacy although the efficacy of wipes to collect PAHs from ensembles was unknown. Therefore, pressurized solvent extraction of contaminated fabric was done in this research to collect contaminants from both the fabric surface and in-between the fibers. Besides that, contaminants deposit on the turnout gear unevenly at the fire scene, making it harder to compare pre and post-cleaning concentrations of contaminants. To avoid such issues, a known concentration of contaminants was pipetted on the fabric. Moreover, using the full-scale washer extractor increases the chance of cross-contamination during the washing process. Therefore, a bench scale washing method was used in this experiment to evaluate the cleaning performance. The removal of PAHs during the cleaning process largely depend on the physico-chemical properties of these compounds like octanol-water partition coefficients (K_{OW}) and solubility. The ratio of a chemical's concentration in the octanol phase and the aqueous phase is expressed as K_{OW} which can be used to estimate the solubility of that chemical both in the aqueous and organic phases.

4.1 PAHs removal by water

Among the 16 targeted PAHs, seven are LMW PAHs containing two to three fused rings and the other nine PAHs are HMW PAHs containing four to six fused rings. The range of K_{OW} values of LMW PAHs and HMW PAHs is 3.29–4.45 and 4.9 to 6.50. Generally, K_{OW} is expressed in logarithmic form. Compounds are lipophilic or hydrophobic when K_{OW} is greater than 1 and compounds are hydrophilic if K_{OW} is below 1. K_{OW} is inversely proportional to solubility and directly proportional to the molecular weight of any compound. Therefore, the water solubility of HWM PAHs is low compared to LMW PAHs. This is responsible for better removal efficacy of LMW PAHs compared to HMW PAHs when water or any concentrations of surfactant were used. Usually, increased temperatures during the extraction process increase the solubility of PAHs in the solvent used for extraction and accelerate the desorption of PAHs from a solid matrix (Lau et al., 2010). LMW PAHs, such as naphthalene, could be evaporated due to their higher volatile nature. Therefore, low extraction efficiency was observed among LMW PAHs compared to HMW PAHs compounds. Especially, the extraction efficiency of naphthalene (28%) was very low due to its low molecular weight, high solubility, and low boiling point. The low extraction efficiency of naphthalene was considered during the calculation of cleaning efficacy, and LOQ/2 was used to measure the concentration of naphthalene as no peaks were detected after washing with water. Considering the low extraction efficiency, the cleaning efficacy of naphthalene is around 95% with water. The cleaning efficacy of water against other LMW PAHs decreases with the increase of molecular weight and K_{OW} values. However, around 61% of $\sum 7$ LMW PAHs are removed by water only. This indicates that a significant amount of lighter and high volatile PAHs can be removed by using only water. HMW PAHs have low solubility and high K_{OW} values which make them less mobile in the soil-water system compared to LMW PAHs (Sabljić et al., 1995; Lu et al., 2008). Due to the higher K_{OW} values, HMW PAHs become more non-polar which indicates these compounds show more affinity toward fabrics. Therefore, the cleaning efficacy of water and other cleaning materials is low against HMW PAHs compared to LMW PAHs and the average cleaning efficacy is around 12.5% against $\sum 9$ HMW PAHs when only water was used for the washing.

4.2 Effect of detergent concentration to remove PAHs

It is very important for firefighters to select appropriate detergents and concentrations to remove persistent contaminants like PAHs from turnout gear. According to the safety data sheet of CD-1, 10 µL should be used considering the weight of the fabric (0.5 g) used in the experiment. However, as the fabric is heavily contaminated, the minimum amount of CD-1 was selected as 1 mL to remove PAHs from the fabric. The same concentration of CD-2 was used as it does not have any specific guideline regarding the concentration of surfactant that needs to be used during the laundry process. To select the amount of detergents during the washing, both detergents focused on the load size without considering the concentration of contaminants in the turnout gear.

Cleaning efficacy against PAHs increased significantly using 1 mL of surfactant compared to using only water and cleaning efficacy is further increased with the increase of surfactant concentrations. Surfactants are sorbed as monomers at lower concentrations and form a monolayer on the fabric surface. Therefore, low partition of PAHs is observed from fabric surface at lower concentrations. Sorption of surfactant increases drastically when micelles are formed. The desorption of PAH compounds occurs when the concentration of surfactant is significantly higher than the critical micelle concentration (CMC) (Grasso et al., 2001). If the concentration of surfactant is lower than the CMC value, the surfactant fails to desorb PAHs from the fabric as the surfactant tends to sorb onto the fabric itself until it reaches the CMC (Grasso et al., 2001). Therefore, the solubility of most of the PAHs improves dramatically when the concentration of surfactant is above the CMC value. Surfactants are amphiphilic in nature and a higher concentration of surfactant needs to be used to form micelles in the presence of soil due to the sorption of surfactant on the fabric. The CMC of a surfactant in a soil-water system is high compared to an aqueous solution without soil (Laha et al., 2009). This higher dose of surfactant in the soil-water system is called elevated CMC or effective CMC (CMC_{eff}). Above the CMC, a sharp increase in solubility is observed for that compound and the relationship between the solubility and concentration of surfactant above CMC is linear (Edwards et al., 1991). This indicates the excess amount of surfactant, the difference between the used amount of surfactant and the amount required to attain the CMC, creates increased micelle volume in the bulk solution that contributes to solubilizing higher concentrations of PAHs. Therefore, cleaning efficacy increases against all the PAH compounds when increased concentrations of CD-1 and CD-2 were used. The cleaning efficacy of both surfactants is very good against LMW PAHs when 1 mL of surfactant was applied. However, 1 mL of surfactant was not effective enough to solubilize HMW PAHs. Only 44% and 46% of

HMW PAHs are removed by CD-1 and CD-2, respectively. Considering the low cleaning efficacy of 1 mL of surfactant, it can be assumed that 10 μL of CD-1 or CD-2 would not be able to solubilize or remove HMW PAHs from fabrics that are contaminated at the 60,000 ng level required by the NFPA 1851 standard for cleaning validation.

The cleaning efficacy of CD-1 and CD-2 increases sharply when 10 mL of surfactant is used. Almost all the LMW PAHs are removed with this concentration of both surfactants. Cleaning efficacies are around 84% and 75% against HMW PAHs for CD-1 and CD-2, respectively. Although 1 mL of CD-1 and CD-2 show similar cleaning efficacy, 10 mL of CD-1 shows better performance against HMW PAHs compared to CD-2. This indicates comparison among different surfactants is difficult as each surfactant has a different CMC value, contains different ingredients and is formulated differently by the manufacturer, which may or may not be optimized for a firefighter contamination application. Each surfactant requires a different concentration of surfactants to show optimum cleaning efficacy. Further increase of concentration (20 mL or 50 mL) of both surfactants does not show a sharp increase in cleaning efficacy against most of the HMW PAHs. Using 10 mL of surfactant was able to remove a high portion of the PAH compound. Therefore, cleaning efficacy did not increase sharply when 20 and 50 mL of surfactants were used. This also indicates the fabric's surface is saturated with the micelle or bilayers with 10 mL of surfactants as the sorption of surfactants reaches the saturation point. As sorption reaches a plateau against most of the HMW PAHs, a nonlinear sorption isotherm is obtained against most of the HMW PAHs above 10 mL of surfactant in the fabric-surfactant-HOCs system (Zhou and Zhu, 2007). Although cleaning efficacy increased slowly above 10 mL of surfactants, even 50 mL of surfactant could not remove some of the HMW PAHs like Ind, D[ah]A, B[ghi]P (K_{OW} value is above 6.5). PAHs with 6.5 or higher K_{OW} value are strongly hydrophobic in nature, capable to be readily adsorbed on the fabric surface, and show a very high affinity to fabrics. If any surfactant can remove these three contaminants during washing, then it can be assumed that other PAH compounds will also be removed effectively. If the turnout gear is heavily contaminated with HMW PAHs, then firefighters may need to use a significantly high concentration of surfactants or a pre-soak step to effectively remove the contamination. The reported findings related to the cleaning of turnout gear from PAHs can be expected for other organic compounds like phenols and phthalates that are released during fires.

4.3 Cleaning efficacy of different cleaning products

In the aqueous solution, surfactants change the hydrophobicity of PAHs, which contributes to moving PAHs from fabric to hydrophobic micelle cores. The hydrophobicity of HOCs correlates with molecular weight and the number of aromatic rings present in the structure. Increasing the number of micelles in the aqueous solution will increase the washing performance. The previous section shows that hydrophobic factors, like K_{OW} and solubility, play a significant role in removing PAHs from contaminated fabric. CD-2, CD-3, and CD-4 contain a blend of nonionic and anionic surfactants, and all three surfactants were found effective against PAHs when 10 mL of surfactant was used with 90 mL of water. Generally, synergism is observed when nonionic and anionic surfactants are mixed in the aqueous solution meaning that mixed micelles show improvement in some crucial properties including surface tension, solubility, and wettability compared to single micelles (Mohamed and Mahfoodh, 2006). Due to the synergism, mixed surfactants show lower surface/interfacial tensions, better micellar partition coefficients (K_m), and require low concentration to reach CMC compared to single surfactants. The combined use of anionic and non-ionic surfactants reduces the polarity of micelles and increases the aggregation number (Shi et al., 2013). This contributes to higher solubilization of PAHs and more PAHs are transferred into the micelles of surfactant. The average cleaning efficacy of CD-2, CD-3, and CD-4 against Σ9 HMW PAHs are around 75%, 83%, and 83%, respectively. CD-1 contains nonionic surfactant and D-limonene. The repulsion force between the head groups of nonionic surfactants is relatively weak, enabling them to form large micelles in the aqueous solution. Therefore, nonionic surfactants showed better solubilization power to PAH compared to ionic surfactants (Liang et al., 2017). Besides that, the desorption of PAHs from the soil reached equilibrium at low CMC of nonionic surfactants compared to anionic surfactants. Therefore, the solubilization power of nonionic surfactant is also better compared to anionic surfactant (Shih et al., 2020). The cleaning performance of CD-1 is also boosted by the hydrophobic ingredient D-limonene to remove non-polar PAHs from fabrics. The average cleaning efficacy of CD-1 against Σ9 HMW PAHs is around 84%. All these surfactants removed more than 90% of Σ7 LMW PAHs.

CD-5, CD-6, CD-7, and CD-8 are charcoal-based shampoo or body wash. In this experiment, these products were used to decontaminate fabrics to investigate the cleaning efficacy of these products against PAHs. The high removal efficacy of PAHs from contaminated fabrics would indicate that these are capable of removing PAHs from body parts as well. Charcoal is a popular adsorbent due to its microporous structure, large specific surface area, higher surface activities, and high adsorption capacity (Gürses et al., 2016). One teaspoon of charcoal powder may have the same surface area as a football field (between 950 m^2/g to 2000 m^2/g) (Azmi et al., 2022). Therefore, charcoal acts like a magnet to grab contaminants from a contaminated surface. The average cleaning efficacy of CD-5, CD-6, CD-7, and CD-8 against Σ7 LMW PAHs is around 90% or higher. Above 70% cleaning efficacy is observed against Σ9 HMW PAHs for each of the cleaning products. All the cleaning products showed the lowest removal efficacy against D[ah]A due to having the highest K_{OW} value among other PAHs. Results show that cleaning performance of charcoal-based products is similar to regular detergents in removing PAH compounds. The charcoal-based products also have a surfactant formulation in the structure, so it is hard to conclude whether the charcoal is removing PAHs from fabrics or it is the surfactants in the products that are removing the PAH compounds. Besides that, these charcoal-based products are developed to decontaminate the body parts of firefighters rather than fabric or turnout gear. Human skin can be divided into layers and each layer has different functions (Honari, 2017). PAHs that are generated at the fire scene can be adsorbed on the particles and deposited on the skin of firefighters. Human skin is prone to breakage and small particles or contaminants like PAHs can penetrate through the skin (Liyanage et al., 2021). Considering the complexities of skin, it is hard to predict the cleaning efficacy of charcoal-based products against PAHs deposited on the skin. Therefore, it is important to conduct further research to investigate whether the high removal efficacy of PAHs using charcoal-based cleaning products is also reflected when used to decontaminate the skin or body parts of firefighters.

5 Limitations

The laboratory-based washing method was used in this experiment as large numbers of samples needed to be washed separately. This bench-scale washing method may have some limitations including the sample size, and G-force applied during washing. The load size in the washing extractor during the laundry process is not comparable to the load size used in this laboratory-based washing method. Therefore, using the same ratio of detergents in washing extractors and laboratory-based washing methods may not provide the same results in cleaning performance. However, a similar trend should be observed in both washing processes. Girase et al. (2022) contaminated fabrics using some hydrophobic organic compounds (HOCs) including Py, and B[a]P. Then laundering of the contaminated gear was performed according to the current NFPA 1851 washing procedures using UNIMAC® 45 lbs. washing extractor. The CD-1 was used during the washing process according to the manufacturer's recommendation (120 mL CD-1 per 45 lbs load). The cleaning efficacies of these two HMW PAHs were 57.62% and 35.73%, respectively. This indicates cleaning efficacy against PAHs containing six aromatic rings would be much lower. Therefore, we can assume that performing laundry in a washing extractor and laboratory-based washing methods will show similar cleaning performance. This research showed that higher concentrations of detergent would be able to remove PAHs effectively. However, further research is required to investigate whether higher concentrations of surfactant would affect the functional or physical properties of turnout gear.

6 Conclusion

The molecular weight of PAHs is proportional to the solubility of PAHs and inversely proportional K_{OW} values. PAHs with lower solubility and high K_{OW} values show higher affinity to the fabric. Therefore, the removal efficacy of PAH compounds decreases with the increase of K_{OW} values. HMW PAHs have higher K_{OW} values compared to LMW PAHs. Therefore, HMW PAHs are difficult to remove compared to LMW PAHs. Water can remove a significant amount (around 61%) of LMW PAHs. However, detergents are critical to remove HMW PAHs from turnout gear. The observation indicates that surfactant-enhanced cleaning of PAH-contaminated gear largely depends on the concentrations of detergent during the washing process. The results indicate that the HMW-PAHs are the compounds that we need to focus on. The NFPA 1851 contains a list of contaminants in subsection 12.6. The PAHs in the list are LMW PAHs which are not much of a concern and do not represent the entire spectrum of PAHs. Thus, it is of crucial importance to modify the cleaning approach of the contaminants. This also includes in categorizing the compounds based on Kow values which will help in developing more targeted approach towards verifying the independent service providers (ISP)s. Using detergents based on the load size may not remove PAHs from turnout gear effectively if the gear is highly contaminated with organic compounds like PAHs. This research will help firefighters and fire services understand that they may need to use a higher concentration of surfactant than the recommended quantity by detergent manufacturers to effectively remove PAHs from turnout gear. Although the study highlighted that the concentration of the surfactants plays a vital role in removing PAHs, the effect of these concentrations on the PPE need to be studied. Since the high Kow values indicate the high affinity of the compounds towards the organic matter than the water then these compounds will partition more towards particulate matter. At such times, the on-site decontamination technique if used with high concentration of surfactant and brushing of the particulate matter that can help in achieving the maximum decontamination of HMW-PAHs. Evaluation of the cleaning performance of regular detergents showed that using only nonionic or the combined use of nonionic and anionic surfactants can remove PAHs from turnout gear effectively. Charcoal-based cleaning products are also found effective to remove PAHs from turnout gear. Therefore, it can be assumed that using charcoal-based products might be a useful technique to remove PAHs from the body parts of firefighters if the skin of firefighters is contaminated by PAHs.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

MH: Experiment methodology, data acquisition, data analysis, data interpretation, and drafting of the manuscript; AG: Experiment methodology, reviewing and editing the manuscript; RO: Conception and design of the study, supervising the experiment and writing, reviewing the manuscript, and editing.

Funding

Financial support was provided by the US Department of Homeland Security (Fire Investigator grant EMW-2019-FP-

00392) and Wildfire Conservancy (PRIME FEMA Fire Prevention and Safety EMW-2019-FP-00944).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2023.1142777/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Cleaning efficacy of regular detergents against LMW PAHs [range=mean ± SE].

SUPPLEMENTARY FIGURE S2
Cleaning efficacy of charcoal-based detergents against LMW PAHs [range=mean ± SE].

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frontiers | Frontiers in Oncology

TYPE Original Research
PUBLISHED 12 May 2023
DOI 10.3389/fonc.2023.1130754

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OPEN ACCESS

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RECEIVED 10 January 2023
ACCEPTED 26 April 2023
PUBLISHED 12 May 2023

CITATION
Lee DJ, Ahn S, McClure LA, Caban-Martinez AJ, Kobetz EN, Ukani H, Boga DJ, Hernandez D and Pinheiro PS (2023) Cancer risk and mortality among firefighters: a meta-analytic review. *Front. Oncol.* 13:1130754. doi: 10.3389/fonc.2023.1130754

Cancer risk and mortality among firefighters: a meta-analytic review

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Background: Firefighting is a hazardous occupation that is associated with an increased risk of select cancers. The number of studies has grown in recent years allowing for a synthesis of findings.

Methods: Following PRISMA guidelines, multiple electronic databases were searched to identify studies on firefighter cancer risk and mortality. We computed pooled standardized incidence risk (SIRE) and standardized mortality estimates (SMRE), tested for publication bias, and conducted moderator analyses.

Results: Thirty-eight studies published between 1978 and March 2022 were included for final meta-analysis. Overall, cancer incidence and mortality were significantly lower for firefighters (SIRE = 0.93; 95% CI: 0.91-0.95; SMRE = 0.93; 95% CI: 0.92 - 0.95) compared to the general population. Incident cancer risks were significantly higher for skin melanoma (SIRE = 1.14; 95% CI:1.08 - 1.21), other skin cancers (SIRE = 1.24; 95% CI:1.16-1.32), and prostate cancer (SIRE = 1.09; 95% CI: 1.04-1.14). Firefighters showed higher mortality for rectum (SMRE = 1.18; 95% CI: 1.02-1.36), testis (SMRE = 1.64; 95% CI: 1.00-2.67), and non-Hodgkin lymphoma (SMRE = 1.20; 95% CI: 1.02-1.40). There was evidence of publication bias for SIRE and SMRE estimates. Some moderators explained variations in study effects, including study quality scores.

Conclusion: Firefighters are at higher risk for several cancers; to the extent that some (e.g., melanoma and prostate) are screening amenable, more study into firefighter-specific recommendations for cancer surveillance is needed. Moreover, longitudinal studies with more detailed data on the specific length and types of exposures are necessary, as well as on unstudied subtypes of cancers (e.g., subtypes of brain cancer and leukemias) are needed.

KEYWORDS
firefighters, meta-analysis, cancer incidence, cancer mortality, occupational research, review

Introduction

Firefighting is a hazardous occupation that is associated with an increase in the risk of select cancers. Hazards include direct and indirect exposure to known and suspected carcinogens. Firefighters may inhale, ingest, or have skin contact with known carcinogens such as polycyclic aromatic hydrocarbons (PAH) and benzene (1). Exposure to firefighting activities leads to increased urinary levels of a variety of chemicals including PAHs, benzene, organo-chlorine and -phosphorus compounds, phenols, phthalates and heavy metals and metalloids (2). Changes in DNA methylation have been documented in firefighters 2-3 years relative to pre-fire school training levels (3). Select methylated sites with pathways associated with cancer risk were identified providing one potential mechanistic pathway linking occupational exposures to cancer risks in firefighters. The International Agency for Research on Cancer (IARC) is working on a comprehensive update of a previous report issued on cancer risks in firefighters (4). The final report has not yet been released but an initial summary of findings indicates that there is strong mechanistic evidence that occupational exposures documented in firefighters exhibit carcinogenic characteristics (5). On the basis of this comprehensive review the Working Group has concluded that the occupational exposures of firefighters are "carcinogenic to humans (Group 1) based on 'sufficient' evidence for cancer in humans".

Although numerous studies have been conducted, generalizable and comparative assessments are complicated by considerable variations in study design, time period, geographic location, measurement of exposure, definition of firefighter roles, and classification of cancer diagnoses, among other study characteristics. Further complications may arise from small sample sizes and time-related variables such as changes in safety regulations and types of firefighter exposures. Due to these challenges faced by primary researchers, meta-analysis has been used as a valuable tool for understanding the overall relationship between firefighting and cancer and further delineates the differential (or moderating) effects.

However, previous meta-analyses on this topic reveal mixed findings. For example, LeMasters et al. (6) found firefighters are at probable higher risk for multiple myeloma, non-Hodgkin lymphoma, prostate, and testicular cancers. The earlier IARC report on occupational exposures in firefighters included a meta-analysis which found increased risks for prostate, testicular, and non-Hodgkin lymphoma cancers (4). A more recent meta-analysis by Jalilian et al. (7) found firefighters to be at greater risk for colorectal, prostate, testicular, bladder, thyroid, and pleural cancers and malignant melanoma, and increased mortality for rectal cancer and non-Hodgkin lymphoma. Similarly, Soteriades et al. (8) found firefighting to be associated with incident colon, prostate, and testicular cancers. Firefighter mortality was elevated for a larger number of cancer subtypes including brain and central nervous system, non-Hodgkin lymphoma, melanoma, rectal, bladder, prostate, testicular, Hodgkin's disease, lymphosarcoma and reticulosarcoma, multiple myeloma, pancreatic, and kidney cancer. However, a more restrictive analysis conducted by Soteriades et al. (8) based on a subset of studies judged to be high quality found significantly higher risks only for testicular incident cancers and mortality due to rectal (and colorectal) cancer. Finally, a recent examination of eleven systematic reviews examining firefighter cancer incidence and mortality concluded that relative to the general population, firefighters are at higher risk of bladder cancer, melanoma, mesothelioma, prostate cancer, and rectal cancer (9). Excess mortality due to rectal cancer and non-Hodgkin lymphoma was also consistently reported to be elevated in firefighters. Such large variations in individual studies and mixed findings from previous meta-analyses demonstrated a need for further research.

Additionally, chronological and geographical overlap in participants was found across firefighter cancer studies, demonstrating the dependency issues in study effects when conducting meta-analysis. The Jalilian et al.'s (7) meta-analysis did not take this into consideration while the Soteriades et al.'s (8) meta-analysis did exclude papers which covered similar geographic areas. Included in the Jalilian et al.'s (7) and Soteriades et al.'s (8) meta-analyses were studies which employed less common study designs (e.g., case-control), which when combined with the more common designs, can introduce heterogeneity complicating interpretation of study findings. With our careful inspection of study design, we only included studies that do not have substantial geographical and chronological overlap a potential dependency that would inflate type I error rates. In addition, we performed a variety of moderator analyses such that the sources of the variations in effects (i.e., study quality, gender, type of effect size) can be identified.

Lastly, a number of new studies examining firefighter cancer risk and mortality have been published since the Jalilian et al.'s (7) and Soteriades et al.'s (8) meta-analyses were completed (10–16) which have been incorporated into the present analysis (n=7). Therefore, the present meta-analysis provides an updated review of worldwide cancer risk among firefighters. Details of the protocol for this meta-analysis were registered on PROSPERO (17) and can be accessed at www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42019110520.

Materials and methods

Search strategy

Relevant studies were located by searching multiple sources. First, a series of comprehensive electronic searches were conducted using multiple databases including ERIC, PsychINFO, ProQuest Dissertation & Theses, PUBMED, and MEDLINE *via* EBSCO. Second, we performed citation searches using various online search engines including Embase, Web of Science Core collection, Google Scholar, and SCOPUS. Third, we searched multiple websites including government, cancer registries, and the Cochrane Library. Keywords being used in all our searches are a combination of the following terms: (Cancer OR tumor OR malignancy OR neoplasm OR mutation) & (fire inspector OR fire inspectors OR fire rescue OR fire-rescue OR firefighter OR firefighters OR "fire fighter" OR "fire fighters" OR paramedic OR paramedics OR emergency medical technician OR “first responder”). All Mesh terms used in our searches can be found in Appendix 1. Two independent reviewers were responsible for determining if studies were eligible with a third author confirming any discrepancies in whether a study met eligibility criteria.

Inclusion and exclusion criteria

To be included in the current meta-analysis, a study must meet the following inclusion and exclusion criteria, including:

1. A study must be empirical and quantitative;
2. A study must be based on human research;
3. A study population must be firefighters;
4. A study must be related to firefighters’ cancer incidence or mortality;
5. A study must be written in English;
6. A study must provide cancer incidence and/or mortality from firefighters that are largely geographically and chronologically independent from those included other studies;
7. The study comparison group must be the general population (e.g., multi-national, national, regional, or local)
8. A study must report sufficient statistics that enable us to compute effect size and its associated standard error.

Figure 1 displays a PRISMA flow chart that summarizes the comprehensive search process based on inclusion and exclusion criteria.

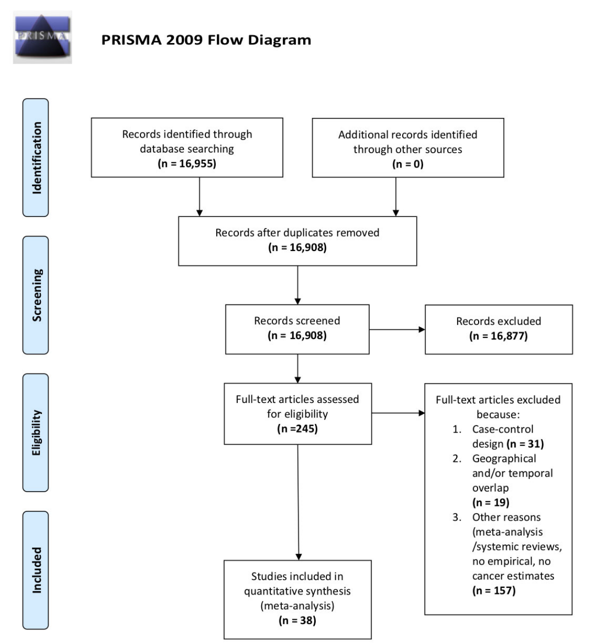

FIGURE 1
Flow diagram.

Coding of study characteristics

Each study initially considered for the present meta-analysis was reviewed and coded, including (1) design characteristics (i.e., cohort, cross-sectional, longitudinal, mixed, and other) (2), outcome type (i.e., incidence and mortality) (3), cancer coding system (i.e., International Classification of Diseases (ICD) ICD-8, ICD-9, ICD-10, International Classification of Disease for Oncology (ICD-O), ICD-O-2, ICD-O-3, Surveillance, Epidemiology, End Results (SEER) codes, and others) (4), cancer sites (5), whether *in situ* cases were excluded in data analyses (6), source of occupation designations (i.e., employment, certification, cancer, registry, death certificate, and other) (7), type of incident that firefighters attended (8), sample characteristics (i.e., age, employment duration, employment status, gender, race/ethnicity, and smoking status), and (9) study characteristics (i.e., location, publication type, and publication year). The two coders independently read the included studies and extracted study information from the 38 studies included in the meta-analysis based on the final coding instrument through REDCap (see Appendix 2 for REDCap coding sheet). Intraclass correlation (ICC) calculated for each category indicated good to excellent level of inter-coder reliability, yielding a range from .73 (type of research design) to 1.00 (study location). Any discrepancies discovered in the coding stage were corrected based on the additional review by the first author before data analysis.

Effect sizes and standard errors

The primary effect size measures used in the current meta-analysis were (1) standardized incidence ratio (SIR) and (2) standardized mortality ratio (SMR) depending on study designs used in the primary studies. We calculated pooled incidence risk estimates (SIRE) and mortality risk estimates (SMRE) as described below.

First, the reported SIR value was directly extracted from each study. When it was not reported, the SIR value was computed by dividing the observed number of firefighters with cancer by the expected number of the reference population with cancer. The computed SIR value was transformed to its logarithm by taking the log of the computed SIR value, whose standard error value was computed by taking a square root of $1/E1 + 1/E2$, where E1 and E2 are the expected frequencies of firefighters and reference population with cancer. If only 95% confidence intervals around the reported SIR value are given, the standard error was computed using: $(UL - SIR)/1.96$, where UL is an upper level of 95% confidence interval and SIR is the reported SIR value.

Second, the reported SMR value and its associated standard error were directly extracted from each study. When it was not reported, the SMR value was computed by dividing the observed number of firefighters’ mortality due to cancer by the expected number of the reference population’s mortality due to cancer. The computed SMR value was transformed to its logarithm by taking the log of the computed SMR value, whose standard error value was computed by taking a square root of $1/O$, where O is the observed number of firefighters' mortality due to cancer. If only 95% confidence intervals around the reported SMR value are given, the standard error was computed using: (UL – SMR)/1.96, where UL is an upper level of 95% confidence interval and SMR is the reported SMR value.

All the parameter estimates (i.e., pooled SIRE and SMRE) computed in the meta-analysis were transformed back to the original scale by taking exponential (e) to the power of the estimates.

Publication bias

The potential for publication bias, which might occur due to the possibility that studies demonstrating a significant effect in a favorable direction are more likely to be published, was assessed using multiple indicators. These included (1): Begg and Mazumdar's rank correlation test (18) for funnel plot asymmetry (2), Egger's regression test of intercept (19), and (3) funnel plots. When the null hypothesis stating no relationship between effect sizes and their associated precision measures is accepted, we can conclude that there is no sufficient evidence supporting publication bias in the included studies.

Handling dependency in effect sizes

As many studies reported effect sizes in relation to multiple cancer sites, more than one effect sizes were extracted from a single study, leading to the violation of independence assumption for the meta-analysis (20). Before any analysis, we first excluded studies that were geographically overlapping with others. Of several available methods that deal with dependency issues (21), effect sizes were first separated by outcome type (i.e., SMR vs. SIR). We performed statistical analysis separated by type of outcome variables. Second, within each cancer site, we checked whether effect sizes from the same study are independent of one another. When effect sizes were based on independent samples (i.e., effects reported separated by gender (22), firefighters exposed to 9/11 vs. those not exposed to 9/11 (23), FDNY vs. CFHS (15), low, medium, vs. high risk (24), they were treated as independent effects.

Study quality assessment

Two content experts (first and last authors) independently rated 38 studies using the Risk of Bias and Precision of Observational Studies (RTI) item banks and Newcastle-Ottawa Quality Assessment Scale (Newcastle-Ottawa). These scales were examined by the independent reviewers on a sample of studies not included in the final analysis to ensure consistent assumptions and criteria were employed. Slight modifications were then made to the original quality assessments to better align with the methods of the studies evaluated, and some items were removed that were not relevant. Then, the Many-facet Rasch Measurement Model (MFRM) was used to estimate the latent quality score of each assessment, which is expressed on a standard score (z-score) with a mean of 0 (25).

Statistical analysis

The metaphor package (26) in R version 4.0.2 (R Development Core Team, 2021) was used to analyze the data, which was based on the meta-analytic methods proposed by Hedges and Olkin (27). First, the overall homogeneity was assessed using Q_{total} under the assumption that all total number of effects (k) were from the sample population. If Q_{total} was found to be statistically significant, the overall effect was estimated under the random-effects model, where between-study variance was estimated using Restricted Maximum Likelihood (REML) estimation method (28). Otherwise, the fixed-effects model was used to estimate the overall effect (i.e., pooled SIRE and SMRE). All main analyses were performed separately by cancer sites. Second, when Q_{total} was found to be significant, a series of moderator analyses with a categorical predictor (i.e., weighted Analysis of Variance [ANOVA]) were performed to identify source of variability in SIRs or SMRs. In particular, the mixed-effects model with a categorical predictor was adopted when a within-study variation (Q_{within}) is found to be statistically significant after controlling for the moderator. When the mixed-effects model was used, the additional between-study variance after controlling for moderator was estimated using the REML method and then incorporated. Otherwise, the fixed-effects analysis with a categorical predictor was performed. In these moderator analyses, the significant Q_{model} suggests that study effects (i.e., SIRs or SMRs) significantly differ depending on subgroups. Moderators used in the current meta-analysis include (1): cancer sites (2), whether *in situ* cases were excluded in data analyses (3), participant characteristics (i.e., employment status, gender, race/ethnicity, and smoking status), and (4) study characteristics (i.e., location, publication type). More details about random-effects or mixed-effects model can be found in Raudenbush (28).

Results

Description of studies

A total of 38 independent studies published between 1978 and 2022 were coded in a number of study characteristics including (1): outcome type (i.e., k_{study} = 17, reporting SIR, k_{study} = 26, reporting SMR; with 5 studies reporting both SIR and SMR) (2), cancer coding system (3), cancer sites (4), whether *in situ* cases were excluded in data analyses (k_{study} = 1 *in situ* cases were included, k_{study} = 3 *in situ* cases were excluded, k_{study} = 34 not reported) (5), source of occupation designations (i.e., employment, certification, cancer, registry, death certificate, and other) (6), type of incident that firefighters attended (e.g., 9-11) (7), participant characteristics (e.g., age, employment status, gender, race/ethnicity, and smoking status), and (8) study characteristics (i.e., location [k_{study} = 13 for US studies, k_{study} = 25 for non-US studies], publication type [k_{study} = 2 for unpublished, k_{study} = 36 for published]).

Assessing publication bias

Figures 2, 3 display funnel plots that visually display the relationship between effect sizes (SIRE for Figure 2 and SMRE for Figure 3) and their associated standard errors as measure of precision. Results from (1) Begg and Mazumdar's rank correlation test for funnel plot asymmetry (2), Egger's regression test of intercept, and (3) funnel plot suggest that there might be some evidence for publication bias for SIRE (z = -13.07, p <.01 by Egger's regression test; Kendall's tau = -.21, p <.01) and SMR (z = -13.11, p <.01 by Egger's regression test; Kendall's tau = .03, p = .52). Therefore, we have some evidence supporting the potential publication bias in the included studies for both SIRE and SMRE.

Overall analyses

Standardized incidence risk estimates

Table 1 and Figure 4 summarize the pooled effects of standardized incidence risk estimates by cancer site. Results showed that firefighters had significantly higher incidence rates for skin melanoma (SIRE = 1.14, k = 20, 95% CI: 1.08 - 1.21), other skin cancers (SIRE = 1.24, k = 8, 95% CI: 1.16 – 1.32), and prostate cancer (SIRE = 1.09, k = 14, 95% CI: 1.04 - 1.14) when compared to the reference population. However, no significant differences in standardized incidence rates were found for other cancer sites between firefighters and the reference population. Also, incidence rates were significantly lower among firefighters for esophagus (SIRE = 0.73, k = 14, 95% CI: 0.60 – 0.88), liver (SIRE = 0.62, k = 9, 95% CI: 0.51 – 0.75), larynx (SIRE = 0.65, k = 12, 95% CI: 0.52 – 0.81), lung (SIRE = 0.67, k = 21, 95% CI: 0.63 – 0.73), colorectal (SIRE = 0.86, k = 7, 95% CI: 0.80 – 0.93), lymphatic and hematopoietic tissue (SIRE = 0.82, k = 10, 95% CI: 0.75 – 0.89), and all cancers (SIRE = 0.93, k = 25, 95% CI: 0.91 – 0.95). No other significant differences in standardized incidence rates were found for other areas of cancer site between firefighters and reference groups.

Standardized mortality risk estimates

Table 2 and Figure 5 summarize the estimated overall effects of SMR by cancer site. Results showed firefighters with significantly higher mortality rates for rectum (SMRE = 1.18, k = 10, 95% CI: 1.02-1.36), testis (SMRE = 1.64, k = 11, 95% CI: 1.00-2.67) and non-Hodgkin lymphoma (SMRE = 1.20, k = 2, 95% CI: 1.02-1.40), when compared to the reference population. Also, mortality rates were significantly lower among firefighters for all cancers (SMRE = 0.93, k = 36, 95% CI: 0.92-0.95), stomach (SMRE = 0.77, k = 11, 95% CI: 0.68-0.87), colon (SMRE = 0.78, k = 9, 95% CI: 0.66-0.91), liver (SMRE = 0.60, k = 7, 95% CI: 0.51-0.72), larynx (SMRE = 0.49, k = 7, 95% CI: 0.37-0.65), bone (SMRE = 0.52, k = 2, 95% CI: 0.13-2.10), brain (SMRE = 0.64, k = 4, 95% CI: 0.53-0.78), Hodgkin's disease (SMRE = 0.17, k = 6, 95% CI: 0.08-0.37), lip, oral cavity, and pharynx (SMRE = 0.65, k = 7, 95% CI: 0.53-0.78), lymphatic and hematopoietic tissue (SMRE = 0.82, k = 12, 95% CI: 0.71-0.95). However, no significant differences in standardized mortality rates were found for other cancer sites between firefighters and reference groups.

Moderator analyses

Standardized incidence risk estimates

Results from the mixed-effects model suggest that several moderators were found to explain variations in SIREs. Significant moderators include: 1) quality score rated using Newcastle-Ottawa Quality Assessment Scale (Q_{model}(1) = 27.91, p <.01), 2) whether studies included female participants or not (Q_{model} (1) = 19.61, p <.01), 3) whether patients with non-malignant tumors were included or not (Q_{model} (1) = 37.61, p <.01). First, the pooled estimate of SIRE was found to be significantly increased by 29% when quality score rated using Newcastle-Ottawa Quality Assessment Scale was increased by 1 (b = 1.29, p <.01). Second, the pooled SIRE for males was significantly lower than those for females (SIRE = 0.61, p = .05 for male firefighters vs. SIRE = 1.07, p <.01 for female firefighters). Third, SIRE was significantly lower when participants with non-malignant tumors (e.g., benign brain tumors and *in situ*) were included (SIRE = 0.97, p = .70).

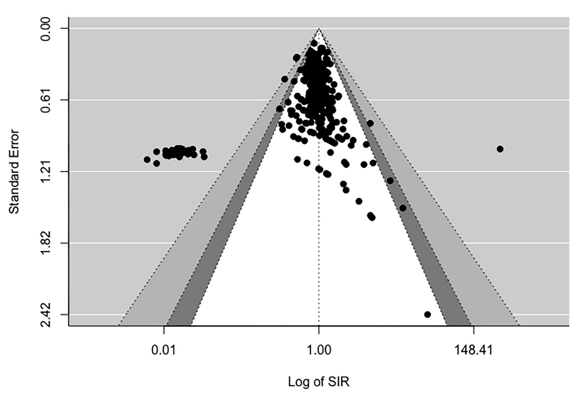

FIGURE 2
Funnel plot for Standardized Incidence Rate (SIR).

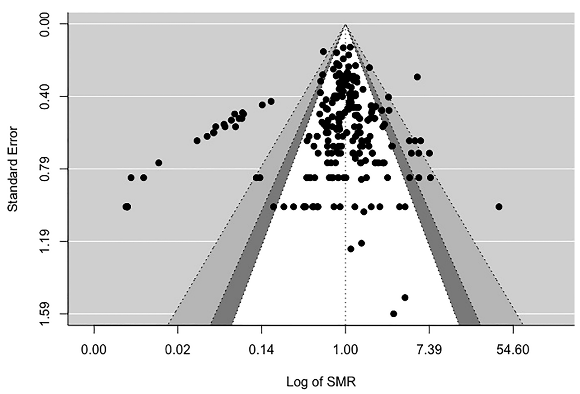

FIGURE 3
Funnel plot for Standardized Mortality Rate (SMR).

TABLE 1 Standardized incidence ratio by cancer site.

Cancer sites	SIRE	*k*	95%CI
All cancers (140–209)	0.93**	25	[0.91, 0.95]
Lip, oral cavity, pharynx (140–149)	0.80	3	[0.52, 1.24]
Esophagus (150)	0.73**	14	[0.60, 0.88]
Stomach (151)	0.91	14	[0.81, 1.03]
Small intestine (152)	1.33	3	[0.65, 2.73]
Colon (153)	0.96	14	[0.89, 1.04]
Rectum (154)	0.97	13	[0.87, 1.08]
Colorectal (153, 154)	0.86**	7	[0.80, 0.93]
Liver (155)	0.62**	9	[0.51, 0.75]
Gallbladder (156)	1.15	3	[0.68, 1.96]
Pancreas (157)	0.88	17	[0.76, 1.02]
Nasal cavities, ear, and accessory sinuses (160)	1.49	2	[0.37, 5.93]
Larynx (161)	0.65**	12	[0.52, 0.81]
Lung (162)	0.67**	21	[0.63, 0.73]
Pleura (163)	0.82	10	[0.62, 1.08]
Bone (170)	1.31	4	[0.53, 3.25]
Connective and other soft tissue (171)	1.02	3	[0.50, 2.05]
Malignant melanoma of skin (172)	1.14**	20	[1.08, 1.21]
Other skin (173)	1.24**	8	[1.16, 1.32]
Female Breast (174)	>0.84	2	[0.39, 1.83]
Male breast (175)	1.06	4	[0.55, 2.05]
Cervix uteri (180)	1.30	3	[0.57, 2.94]
Uterus (179,182)	0.90	2	[0.74, 1.10]
Prostate (185)	1.09**	14	[1.04, 1.14]
Testis (186)	1.01	12	[0.83, 1.21]
Bladder (188)	0.91	8	[0.78, 1.07]
Kidney (189)	0.93	15	[0.81, 1.06]
Brain & nervous system (191-192)	0.88	11	[0.74, 1.04]
Thyroid (193)	0.95	11	[0.76, 1.19]
Endocrine (193-194)	0.86	4	[0.65, 1.13]
Non-Hodgkin lymphoma (200, 202)	0.91	12	[0.81, 1.02]
Hodgkin's disease (201)	0.94	7	[0.66, 1.33]
Multiple myeloma (203)	0.90	10	[0.73, 1.12]
Leukemia (204-208)	0.87	18	[0.76, 1.00]
Broader combinations:			
Digestive system (150-159)	0.81**	11	[0.76, 0.86]
Respiratory (160-165)	0.62**	15	[0.58, 0.67]
Male genital (185-187)	1.07**	9	[1.02, 1.12]

(Continued)

TABLE 1 Continued

Cancer sites	SIRE	*k*	95%CI
Kidney & Bladder (188-189)	0.85**	13	[0.77, 0.93]
Endocrine (193-194)	0.86	4	[0.65, 1.13]
Lymphatic and Hematopoietic Tissue (200-208)	0.82**	10	[0.75, 0.89]

k = # of effect sizes; **p <.01.

Standardized mortality risk estimates

Results from the mixed-effects model suggest that several moderators were found to explain variations in SMREs. Significant moderators include: 1) quality score rated using Newcastle-Ottawa Quality Assessment Scale (Q_{model} (1) = 66.70, p <.01), 2) whether studies included female participants or not (Q_{model}(1) = 11.58, p <.01) and 3) study location (Q_{model}(1) = 11.16, p <.01). First, the pooled estimate of SMRE was found to be significantly increased by 55% when quality score rated using Newcastle-Ottawa Quality Assessment Scale was increased (b = 1.55, p <.01). Second, the pooled SMRE for males was significantly higher than those for females when compared to general population (SMRE = 1.48, p = .05 for male firefighters vs. SMRE = 0.71, p <.01 for female firefighters). Third, the pooled SMRE extracted from non-US studies (SMRE = 1.10, p <.01) was significantly higher than those from US studies (SMRE = 0.65, p = .43).

Discussion

Summary of study findings

Overall, this meta-analysis demonstrated that the risk of incident cancers was significantly higher for skin melanoma, other skin cancers, prostate cancer, with higher mortality for rectal, testicular, brain and nervous system cancers, and non-Hodgkin lymphoma, among firefighters when compared to reference populations. Below we discuss in greater detail these significant findings including the possible firefighting exposures which could be implicated in these increased risks.

Skin cancers

In the present meta-analysis, firefighters had a 14% higher risk of melanoma compared to the general population. A similar pattern was found for mortality, although not statistically significant (SMRE = 1.12, 95% CI: 0.87, 1.44). Other skin cancer incidence rate was also significantly higher in firefighters (SIRE = 1.24, 95% CI: 1.16 – 1.32). Firefighters are exposed to a number of carcinogens associated with melanoma and/or other skin cancers including polycyclic aromatic hydrocarbons (PAHs), Polychlorinated Biphenyls (PCBs), and benzene (29). Often working outside firefighters are exposed to ultraviolent radiation, a known risk factor for melanoma (30). As reviewed previously by Guidotti et al., there may be a causal association between firefighting exposures and risk of melanoma in firefighters although non-occupational ultraviolent radiation and firefighter lifestyle factors cannot be ruled out as a contributing factor (31).

Prostate cancer

In the present meta-analysis, incident prostate cancer was significantly higher in firefighters (SIRE = 1.09, 95% CI: 1.04 – 1.14) while mortality was similar to that of the general population (SMRE = 1.03, 95% CI: 0.93 – 1.13). Of note, studies in other populations have documented associations with PAH, PCB, and heavy metal exposures with prostate cancer risk (32). Moreover, shiftwork has been associated with prostate cancer risk in other worker groups (33). Additional research is needed to determine if firefighter-specific carcinogenic exposures can be causally linked to any increased risks for prostate cancer that are independent of possible detection bias due to the different prevalence of PSA testing in firefighters versus other populations.

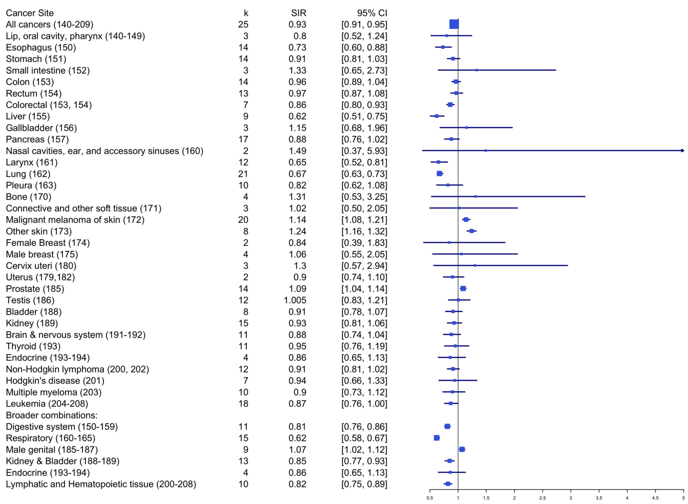

FIGURE 4
Standardized incidence ratio by cancer site.

Rectal cancer

In the present meta-analysis, incident rectal cancer was not significantly higher in firefighters (SIRE = 0.97, 95% CI: 0.87 – 1.08) while there was significantly increased risk of death due to rectal cancer (SMRE = 1.18, 95% CI: 1.02 – 1.36). Other investigators have suggested that there is a possible association between rectal cancer mortality and firefighting (6, 34), however, the lack of known carcinogenic exposures linked to this cancer in firefighters should be considered when assessing causality.

Testicular cancer

In the present meta-analysis, incident testicular cancer was not significantly higher in firefighters (SIRE = 0.97, 95% CI: 0.87 – 1.08) while there was a significantly higher risk of death due to

TABLE 2 Standardized mortality ratio by cancer site.

Cancer site	SMRE	k	95%CI
All cancers (140-209)	0.93**	36	[0.92, 0.95]
Lip, oral cavity, pharynx (140-149)	0.65**	7	[0.53, 0.78]
Esophagus (150)	0.96	8	[0.84, 1.10]
Stomach (151)	0.77**	11	[0.68, 0.87]
Colon (153)	0.78**	9	[0.66, 0.91]
Rectum (154)	1.18**	10	[1.02, 1.36]
Liver (155)	0.60**	7	[0.51, 0.72]
Pancreas (157)	0.86	8	[0.70, 1.05]
Larynx (161)	0.49**	7	[0.37, 0.65]
Lung (162)	0.98	11	[0.94, 1.03]
Pleura (163)	1.37	2	[0.87, 2.15]
Bone (170)	0.52	4	[0.13, 2.10]
Malignant melanoma of skin (172)	1.12	14	[0.87, 1.44]
Male breast (175)	1.34	4	[0.82, 2.19]
Prostate (185)	1.03	11	[0.93, 1.13]
Testis (186)	1.64**	11	[1.00, 2.67]
Bladder (188)	0.92	11	[0.79, 1.07]
Kidney (189)	0.91	8	[0.77, 1.07]
Brain & nervous system (191-192)	1.90**	13	[1.48, 2.45]
Thyroid (193)	0.8	5	[0.47, 1.35]
Non-Hodgkin lymphoma (200, 202)	1.20**	2	[1.02, 1.40]
Hodgkin's disease (201)	0.17**	6	[0.08, 0.37]
Multiple myeloma (203)	0.98	3	[0.75, 1.27]
Lymphoid leukemia (204)	1.90	2	[0.95, 3.79]
Myeloid Leukemia (205)	1.11	3	[0.95, 1.30]
Leukemia (204-208)	0.41**	5	[0.29, 0.58]
Broader combinations:			
Digestive system (150-159)	1.10**	5	[1.02, 1.19]
Respiratory (160-163)	0.91	9	[0.82, 1.01]
Male genital (185-187)	1.85	2	[0.26,13.13]
Lymphatic and Hematopoietic Tissue (200-208)	0.82**	12	[0.71, 0.95]

k = # of effect size; **p <.01.

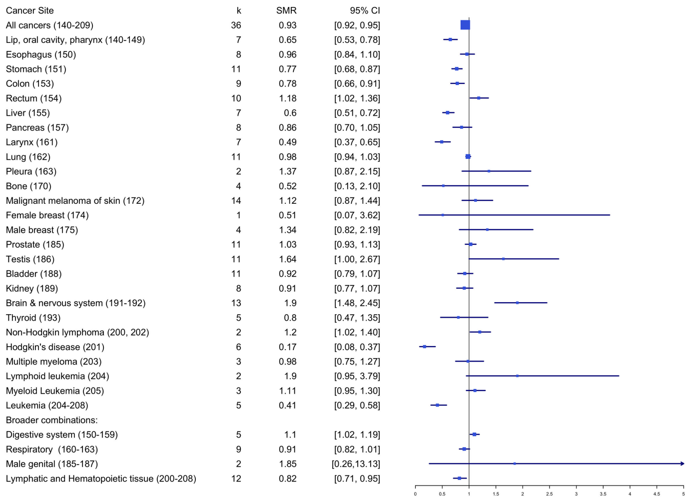

FIGURE 5
Standardized mortality ratio by cancer site.

testicular cancer (SMRE = 1.64, 95% CI: 1.02- 2.67). Firefighters are exposed to Polychlorinated Biphenyls and Polybrominated Biphenyls (PCBs) (4), which is an IARC- verified carcinogen (35); however, studies conducted in other occupational groups are limited (36–38). Caution is required to interpret our finding given the considerable discrepancy in the pooled effects for incidence and mortality.

Non-hodgkin lymphoma

The present meta-analysis suggests lower risk (albeit non-significant) for non-Hodgkin lymphoma among firefighters (SIRE = 0.91, 95% CI: 0.81 – 1.02) while a significant increased risk of death was observed on the basis of just two pooled studies (SMRE = 1.20, 95% CI: 1.02 – 1.40). Again, some caution is required to interpret our findings given discrepancies in the pooled effects for incidence and mortality. There is "limited" evidence from studies of non-Hodgkin lymphoma risk to support the Group 1 designation (5), in line with conclusions from IARC (4) and supported by a subsequent meta-analysis completed by LeMasters et al. (6), conducted in approximately the same time period. Of note, non-Hodgkin lymphoma has many distinct sub-types (>30), not all of which have been shown to associated with occupational exposures (39, 40). According to the IARC, exposure to formaldehyde, a known firefighter exposure (4), as well as lindane and pentachlorophenol, both of which can be used to treat wood products, are associated with an increased risk of non-Hodgkin lymphoma (41).

Brain and central nervous system cancers

In the present meta-analysis incident brain and central nervous system cancers were not significantly higher in firefighters (SIRE = 0.88, 95% CI: 0.74 – 1.04) while there was a significant increased risk of death due to this heterogeneous group of cancers (SMRE = 1.90, 95% CI: 1.48 – 2.45). This cancer grouping is characterized by a large number of histologically distinct subtypes, only a subset of which may be associated with firefighting-related occupational exposures (39, 42). Lead exposures are associated with firefighting activities (4), and associations between lead exposure and increased brain cancer risk have been documented in other occupational groups as well (43–47).

The role of moderator analyses in the interpretation of meta-analytic findings

Previous meta-analytic studies of firefighter cancer risk either did not complete formal moderator analyses or conducted analysis with a limited number of variables. Uncovering sources of variability in study effects (i.e., cancer incidence or mortality) can be useful for researchers in that it will enhance the interpretability and generalizability of meta-analytic results, which is estimated based on more consistent study effects. In this meta-analysis, we identified several moderators that explained considerable amount of between-study variability in effects. Jalilian et al.'s documented evidence of moderate to strong heterogeneity for several site-specific cancers including buccal cavity and pharynx, brain and nervous system, esophagus, larynx, lung, melanoma, skin, prostate, and kidney (7).

Not only have we expanded the number of moderator variables examined, but also, we undertook a comprehensive assessment of study quality as a moderator using two quality assessment tools. Soteriades et al.'s meta-analysis included a smaller number of studies and did analyses categorized by level of study quality (i.e., "good and adequate" and "good studies only"). Such subgrouping presumably reduced heterogeneity in effects, but at the expense of the number of studies included in their subgroup analyses across specific cancer sites. For analyses based on "good studies", the number of studies ranged from 1 to 14 for cancer incidence, and from 2 to 24 for cancer mortality. We found that study quality ratings using the Newcastle-Ottawa Quality Assessment Scale explained variations in SIRE and SMRE estimates, suggesting that SIRE and SMRE estimates are likely to be higher as study quality score is increased. Careful consideration of optimal future study designs examining firefighter cancer risk is needed to capture risk levels more accurately in this occupational group.

The identification of other important moderators helps researchers to give careful consideration to the optimal design of future firefighter cancer studies (i.e., sample characteristics, design characteristics) as well as help to contextualize the present meta-analysis findings. For instance, our moderator analyses also found significantly lower pooled cancer incidence effects for males than females, while pooled cancer mortality was higher for males than females, when compared to general population. One possible explanation for these differential effects is that the proportionately smaller number of female firefighters, when included in select individual studies, resulted in large, but unstable effect size estimates in incidence studies, while lower pooled effects in female mortality studies could reflect differences in aggregate lifetime carcinogenic exposures since women started joining the workforce only in recent decades in the US and elsewhere (48). Caution is therefore warranted when interpreting possible cancer risks in female versus male firefighters given the relative sparseness of the number of observed incident and mortality cases in females as well as differences in the likely average career carcinogenic exposure profiles experienced in male and female fighters in the studies included in the present meta-analysis.

Comparison with previous meta-analytic findings

Two meta-analyses conducted by independent research teams were published in 2019 (7, 8). There was substantial overlap in the papers selected for these two meta-analyses which, in the case of Jalilian et al. included studies published through 2017. However, Soteriades et al. limited their original searches for articles to papers published between 1960 and 2007, and ultimately did not include any firefighter's cancer studies that were published between 2010 and 2017. Of the three meta-analyses, Soteriades et al. consistently included the smallest number of studies in their meta-analysis, especially when they restricted their analyses to those that were judged to be of high quality. For this reason, a list of studies included in our meta-analysis more closely resembles that the Jalilian et al.'s meta-analysis, but also included additional papers published after 2017 (10, 12, 49–55). However, not all studies were included in our meta-analysis given that we eliminated data from studies with substantial geographic and chronological overlaps. In such cases we extracted data from studies that covered the greatest number of years and/or conducted in the largest geographic catchment area. Given the potential biases that might arise from the dependence in study effects, we carefully investigated study design and included study effects that are largely independent of one another. Thus, in some cases the number of independent study estimates differ from the number of studies that contributed to the study estimates.

Overall, there was some agreement for an increased risk of several cancers across the two meta-analyses as well as findings from the present analysis. For example, pooled SIRE estimates for incident prostate cancer were significantly higher in previous two meta-analyses, which ranged from 1.09 and 1.20. The range of pooled SMRE estimates for non-Hodgkin lymphoma mortality was significantly higher than general population in all three meta-analyses, which ranged from 1.20 to 1.44. Finally, the range of pooled SMRE estimates for rectal cancer mortality were significantly higher in all three analyses, which ranged from 1.16 to 1.36. Except for the pooled estimate of rectal cancer mortality found in the Soteriades et al.'s meta-analysis (SMR = 1.18 95% CI: 1.02-1.36), our estimates were lowest.

Both the present (SIR = 1.14, 95% CI: 1.08-1.21) and Jalilian et al.'s meta-analyses (95% CI: 1.21-1.45) demonstrated significantly higher risk for incident melanoma; Soteriades et al.'s finding was not statistically significant (SIR = 1.10, 95% CI: 0.77-1.58). In contrast, testicular mortality estimate was significantly higher in the present meta-analysis (SIR = 1.64, 95% CI: 1.00-2.67), but not in the Soteriades et al.'s (SIR = 1.63, 95% CI: 0.60-4.40), although the pooled estimates were similar in magnitude. Jalilian et al. did not report a summary estimate for testicular mortality. Brain and central nervous system cancer mortality rates were significantly higher in the present (SMR = 1.90, 95% CI: 1.48-2.45) and in the Soteriades et al.'s meta-analyses (SMR = 1.26, 95% CI: 1.02-1.55), while they were not in the Jalilian et al.'s (SMR = 1.25, 95% CI: 0.96-1.63), although similar in magnitude.

Risk of testicular cancer incidence was not found to be significant in the present analysis (SIR = 1.01, 95% CI: 0.83-1.21) whereas both the Jalilian et al. (SIR = 1.34, 95% CI: 1.08-1.68) and the Soteriades et al. found significantly higher risk (SIR = 1.63, 95% CI: 0.60-4.40). Reasons for such discrepancy are uncertain. No study has considered differences between seminomas and non-seminoma types of testicular cancer. However, more estimates were used in the present meta-analysis (k = 12), but fewer in both Jalilian et al.'s (k = 9) and Soteriades et al.'s (k = 7). Also, some of more recent studies that were included in the present meta-analysis showed lower risk testicular cancer incidence.

Evaluating causality

Determining if elevations in cancer risk documented *via* meta-analytic reviews are causally related to the occupation of firefighting is a complex process. The IARC has developed a systematic process for determining if certain chemical, biological, and occupational exposures may be causally linked to a specific cancer *via* assessment of available cancer studies and meta-analytic synthesis, experimental animal studies, exposure studies and assessment of other relevant mechanistic data (e.g., toxicokinetic, metabolomic and genetic effects) (41, 56). In its most recent assessment, it has upgraded a previous designation of firefighter as possibly carcinogenic occupational exposure (Group 2B designation) (4) to the Group 1 designation of firefighting as carcinogenic (5). Part of the evidence in support of this elevated designation included a meta-analysis of seven studies which found an increased risk of incident mesothelioma (reported 58% increased risk; 95% CI=14%–120%) as well as a pooled increased risk of incident bladder cancer in based on the inclusion of "several" bladder cancer cohort studies (reported 16% increased risk; 95% CI=8%–26%). We did not find similar increased pooled estimates for either incident cancer (pleura [mesothelioma] 0.82; [0.62-1.08]; bladder 0.91; [0.78-1.07]) although we did find a non-significantly increased risk of pleura mortality SMRE= (1.37, 95% CI: 0.87-2.15). The forthcoming full IARC report will likely provide more details on the methods employed and the list of studies that were included in their meta-analysis for these and other cancers.

Other investigators have proposed and applied different frameworks for evaluating the causality or likelihood of cancer risks associated with firefighting that includes some of the following features: 1) consistency of reported epidemiologic findings, 2) assessment of study quality, confounders, misclassification and bias, and 3) consideration of the biologic plausibility of carcinogenic and other chemical exposures as drivers of increased cancer risk (6, 34, 39).

It is therefore important to note that completion of meta-analytic analysis of study findings is just one element of a comprehensive assessment of cancer risk that may be determined to be causally linked to exposures associated with firefighting.

Prevention and screening opportunities in the fire service

Results of the present analysis, combined with the other recent meta-analytic reviews and the recent IARC review clearly document elevated cancer risk in firefighters, supporting the need for additional work identifying and implementing best practices to reduce the carcinogenic exposures which occur during and after fire suppression activities (57–60). Additional work on educating firefighters on strategies to reduce overall cancer risk reduction is also needed (61–63). Finally, workplace policies for more aggressive early detection of skin and prostate cancers should be considered given the noted elevated risks seen in firefighters (61, 64).

Limitations

There are study limitations that require some caution for interpretation. First, our analysis included only a small number of studies that estimated the amount of carcinogenic exposure firefighters faced (65); but because this information is not available for virtually all studies, we have no method of correlating amount or type of exposure with cancer risk. Rather, most studies included in this meta-analysis use job title as the exposure indicator. Through a variety of sources, the general population is also exposed, to some degree, to carcinogens commonly attributed to firefighters' activities. Healthy worker effects are likely present in studies of firefighters and may lead to a systematic underestimate of cancer risks in firefighters (66). Another limitation is the small number of cases for some cancer sites which does not allow for the calculation of stable risk estimates. This is particularly true for cancers of the bone, specific leukemias and brain cancers, and mesothelioma among others. An additional limitation is that out of 38 studies, we have only 8 studies reporting the descriptive statistics of participants by age. Seven studies reported participant mean age, between 30 to 39.4. One study reported a mean age of 57. Given that the lack of reported information and (when reported) its homogeneous nature of participants in terms of their mean age (30 – 39), we decided not to run the moderator analysis using age as a continuous predictor on SIR and SMR. Finally, the process to minimize study overlap *via* careful selection of papers with respect to geographic region and years covered was imprecise as we balanced the need for inclusion of otherwise eligible studies against avoiding the inclusion of effect sizes drawn for similar cohorts of firefighters. It was not possible to completely eliminate study overlap so some dependency effects may remain in our analysis.

Despite these limitations, we were able to minimize the inflation of type I error rates that might arise from dependency in effects by undertaking careful inspection of individual study designs for the possibility of dependency in effect sizes. In addition, we performed a variety of moderator analyses to better understand sources of the observed variations (i.e., gender, study quality scores, type of effect size). Finally, we carefully investigated all included studies and selected the most independent study effects to avoid overlap with respect to geographic region and years covered by each study.

Conclusion

Despite differences between our study and others, our results reinforce the associations between firefighting and cancer. This occupational group faces many unique hazards and exposures, and more research employing high-quality study designs, such as the ongoing National Firefighter Registry (67) and the Career Firefighter Health Study (68), is needed to investigate how these exposures impact cancer risk. Moreover, future cohort studies that account for important confounders and employ longitudinal exposure to document the frequency, duration, and intensity, of exposures are needed. Continued improvements to personal protective equipment, adherence to safety measures in the fire service, and protective policies and legislation are imperative to keeping firefighters safe (68).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

This study was supported by funds from Florida State Appropriation #2382A (https://umiamihealth.org/sylvester-comprehensive-cancer-center/research/firefighter-cancer-initiative). Research reported in this publication was also supported by the National Cancer Institute of the National Institutes of Health under Award Number P30CA240139. The funder had no role in the developing the protocol for the study. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The data used in this report were collected by The Florida State Fire Marshal's Office and the Florida Cancer Data System (FCDS), the statewide cancer registry funded by the Florida Department of Health (DOH), and the Centers for Disease Control and Prevention's National Program of Cancer Registries (CDC-NPCR).

Acknowledgments

The authors wish to acknowledge the State of Florida and their Firefighter colleagues for their continued support and ongoing contributions to the Firefighter Cancer Initiative at Sylvester Comprehensive Cancer Center. We also wish to thank Steven Peace at the Florida Cancer Data System for his expert guidance on cancer coding and changes over time.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fonc.2023.1130754/full#supplementary-material

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frontiers | Frontiers in Materials

TYPE Original Research
PUBLISHED 07 July 2023
DOI 10.3389/fmats.2023.1138652

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OPEN ACCESS

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RECEIVED 05 January 2023
ACCEPTED 26 June 2023
PUBLISHED 07 July 2023

CITATION
Girase A, Thompson DB and Ormond RB (2023), Impact of conventional and advanced cleaning techniques on the durability of firefighter turnout ensembles.
Front. Mater. 10:1138652.
doi: 10.3389/fmats.2023.1138652

Impact of conventional and advanced cleaning techniques on the durability of firefighter turnout ensembles

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The concern for firefighters' occupational exposure to harmful contaminants is growing due to the increase in health issues in the firefighting community. At such times, effective decontamination of personnel and equipment is an essential component of a hazard mitigation strategy. The current decontamination practices used for firefighter protective clothing have been shown to not be very effective. Hence, the scientific community is looking for several alternatives to conventional washing procedures. Liquid carbon dioxide (CO_2) has been used in laundering and has distinct advantages over conventional dry-cleaning solvents such as perchloroethylene. The following study is aimed to assess how different washing procedures affect the durability of the turnout material. The study includes using three washing procedures on different samples: 1) conventional washing procedure, 2) liquid CO_2 washing procedure, and 3) a high-temperature washing procedure. Samples for durability testing were constructed from a common aramid fabric used in firefighter turnout ensembles. These swatches were subjected to different washing techniques. The durability assessment was performed for physical testing of the samples, visual inspection, water repellency, and quantifying color changes using spectrophotometric analysis. The conventional wash and high-temperature washing affected the durability of the outer shell material in a significant manner. The liquid CO_2 process did not affect the samples' water repellency or physical strength. In contrast, conventional and high-temperature washing significantly affected the durability of the outer shell material. However, all samples met the criteria for tearing strength outlined in the NFPA 1971 standard subsection 7.1.11.

KEYWORDS

decontamination, liquid CO_2, NFPA 1851, turnout, carcinogenic

1 Introduction

Firefighting is a challenging profession that includes working in a hazardous and dynamic environment. Protective clothing is the firefighter's last line of defense to reduce the risk of injury in this environment. The coats and pants, which are referred to as turnout or bunker gear, are typically constructed from three layers of materials: an outer shell, a moisture barrier, and a thermal liner. The design and performance requirements for these materials are specified in the NFPA 1971 *Standard on Protective Ensembles for Structural Firefighting and Proximity Firefighting* (NFPA, 1971; 2020). The outer shell protects firefighters from abrasion, cuts, and thermal threats. The most common fabrics used in turnouts include blends of polybenzimidazole (PBI), meta-aramid, and para-aramid fibers. To provide protection from splashes/sprays of water and flammable liquids, durable water and oil repellents finishes are applied to the outer shell materials. The moisture barrier, which offers protection from penetration of water, some chemicals, and bodily fluids, is made of polytetrafluoroethylene (PTFE) and polyurethane (PU) attached or laminated to a support fabric. The thermal liner is the innermost layer that provides thermal protection from heat (NFPA, 1971; 2020). The supplementary accessories include reflective trims, product labels, zippers, buckles, and hook-and-loop attachment points. The trim is an important element of the turnout gear as it aids the wearer's ability to be noticed by fellow firefighters during fire suppression activities as well as roadside visibility when responding to motor vehicle accidents. The product label provides instructions to help firefighters take care of the turnout suits. Thus, the elements enhance the functionality of the turnout gear.

The NFPA 1851 *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* (referred to as the SCAM document) requires the retirement of the ensembles and elements no more than 10 years from the manufacturing date (NFPA, 2020; 2020). Thus, the turnout gear's durability and continued performance is a critical parameter. The NFPA 1851 standard recommends washing guidelines from the durability perspective. The guidelines included in the standard for washing are: 1) temperature of the washing should not be greater than 40°C (105°F), 2) the G-force should be less than 100 G and the pH of the detergent should be between 6 and 10.5, and 3) the surfactant should not contain chlorine or oxidizing agents since oxidation can damage the aramid fibers of the outer shell. The standard has added a requirement for the turnout to receive at least two advanced cleaning per year (NFPA, 2020; 2020). All these guidelines make washing procedures less damaging to the gear but can also result in less effective cleaning processes.

The interim report of Research Foundation, NFPA in 2018 was based on research project to understand the cleaning practices. The report indicated shortcomings of the current turnout laundering practices (Research Foundation, 2018). Since then, a limited number of studies have been performed to assess the decontamination efficacy of the current the practices (Fent et al., 2017; Mayer et al., 2019; Mayer et al., 2020; Banks et al., 2021). Most of these studies marked the presence of polycyclic aromatic hydrocarbons (PAH)s and phthalates. These studies showed that decontamination of the turnout suits using current laundering practices is inefficient. The inefficiency is basically an incomplete removal of the foreground contaminants.

The NFPA 1851 standard has added cleaning validation of the laundering practices for independent service providers (ISP)s. The cleaning efficiency is calculated by measuring the differences of the pre-wash and post-wash concentration of the selected contaminants (NFPA, 2020; 2020). The sole purpose of any laundering practice is to maximize the removal of the contaminants. These findings led to investigations into alternative cleaning solutions such as modifying parameters including temperature and time, developing improved surfactants, and assessments of specialized cleaning such as liquid CO_2 (Girase et al., 2022).

Along with chemical exposures, firefighters are also exposed to biological contamination when responding to fires as well as emergency medical situations. Along with chemical exposures, firefighters are also exposed to biological contamination. Bacterial contamination such as *Staphylococcus aureus* and *Enterococcus faecalis* has been reported in the occupational environment (Roberts, 2014; Farcas et al., 2019; McGuire-Wolfe, 2020). These bacteria can pose a risk to the health of firefighters, and it is essential to remove them from PPE during the cleaning process. However, removing contaminants from the personal protective ensemble (PPE) can be challenging, and several factors affect the removal of contaminants: temperature, time, chemistry, and mechanical action. Temperature is one of the important parameters that significantly impact cleaning and has shown a significant increase in the logarithmic reduction of microorganisms on fabric surfaces (Wiksell et al., 1973). So higher temperatures might seem a viable option to improve biological decontamination. But its impact on the physical properties of the turnout suits needs to be considered first.

Dry cleaning is a process of removing soil from textiles using a non-aqueous solvent. Perchloroethylene (PER) has been used conventionally in dry cleaning, but it is highly toxic to the human body (Sutanto et al., 2013). The environmental and health hazards due to PER led to producing "clean" technologies with fewer environmental concerns like low toxicity and low energy consumption. Carbon dioxide (CO_2) gas is abundantly available in nature and at high pressure and low temperature, it turns into a supercritical liquid which offers several advantages, such as low viscosity surface tension that facilitates its penetration into the interstices of the fabric and improves cleaning efficiency (Dutschk et al., 2013). Liquid CO_2 has been shown to effectively remove targeted foreground contamination from the outer shell material compared to the conventional washing method (Girase et al., 2022).

None of the above studies have assessed the impact of these laundering practices on the life of the PPE. Several questions remain unanswered, such as.

(1) What happens to the physical properties of the outer shell material after repeated laundering?
(2) What happens to the turnout suit if washed at a higher temperature?
(3) How durable are the water-repellent finishes applied on the outer shell material?
(4) How do specialized cleaning practices such as liquid CO_2 affect the turnout suits?

Our previous research evaluated the comparative cleaning efficacy of conventional laundering and a liquid CO_2 process (Girase et al., 2022). This follow on study aimed to assess the impact of multiple washing cycles of various techniques on the durability of the turnout suits. The comparative analysis of conventional and liquid CO_2 to assess the cleaning efficiency was done; hence both these methods were kept consistent with the study described in (Girase et al., 2022). The outer shell material is accessorized with reflective trims and product labels to ensure the firefighters' complete safety and instructions to maintain their turnout suits. The turnout suits need to last more than 5 years since they are very expensive. Thus, before incorporating any changes in the cleaning procedure, its impact on durability needs to be investigated.

1.1 Materials and methods

To study the impact of various washing methods on the durability of the turnout suits and their accessories, outer shell swatches (26-inch × 26-inch) were constructed from a common PBI/aramid-based firefighter protective clothing material (7 oz) with a fluorinated durable water and oil repellent finish. These swatches were used to simulate the turnout suits in a controlled manner. The yellow-silver reflective trims were given by a major manufacturer and stitched to the outer shell material. An example of a finished swatch is shown in Figures 1A. The product labels were heat-pressed on the trim's opposite side (assumed as an inner side) at 400°F for 10 s, as shown in Figures 1B. Every set contained five swatches, all accessorized with trims, and four of those were accessorized with product labels due to the limited availability of the product labels.

The swatches in every set were subjected to 30 washes for the respective method. It was decided that if there were any significant damage for 30 washes, another set of fabrics would be subjected to 15 washes using the same method to compare the results. Ballast material was used to make up the volume of 30 lbs. The ballast material for conventional and modified washing included outer shell material jackets. All ballast material was washed and air-dried before using them in the process. For liquid CO_2, information about ballast material was not available. The objective was to assess the impact of the washing on the garment, and the assumption was that the turnout suits receive washing once every month. A separate set of four swatches was prepared, kept unwashed, and used as a controlled sample for future measurements. The sampling distribution is provided in Table 1.

The washing methods were as follows.

1.1.1 Conventional

The conventional method was set up according to the NFPA 1851 guidelines (Table 2). A 45 lb capacity washer extractor (UNIMAC) was set to 40°C with a 60-min wash duration. A d-limonene-based commercial detergent (CD-1) was chosen due to its popularity in the firefighting community. The volume of the detergent used in each cycle was 120 mL based on the weight of the material washed. The amount of detergent was decided based on manufacturer's recommendation. The cycle included

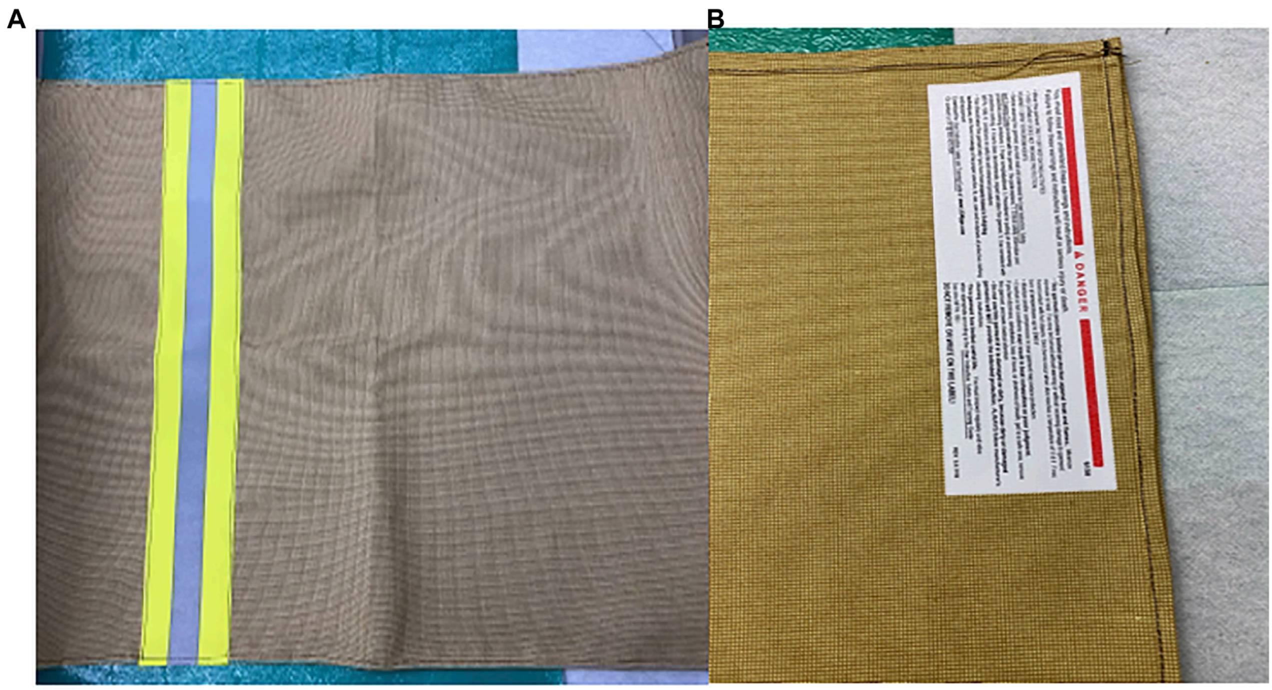

FIGURE 1
(A) Outershell swatch with reflective trims **(B)** Product Label heat sealed.

TABLE 1 Sampling distribution.

	Set A	Set B	Set C	Set D	Set E
Washing method used	None (Control)	Conventional	Modified High temperature	Liquid CO_2	Liquid CO_2
Number of washes	0	30	30	30	15
Number of swatches	5	5	5	5	5

TABLE 2 Details of the aqueous methods.

Details	Conventional washing	Modified washing
Washing temperature	40°C	65°C
Washing duration	60 min	60 min
Rinsing	10 min	10 min
Detergent amount	120 mL	120 mL

TABLE 3 Liquid CO_2 details.

Step	Details
Duration of cycle	50 min
Wash bath: Single wash	8 min
Rinse: Two cycles	4 min each
Pressure range	600–850 psi
Total load	50 lbs
Detergent	Proprietary
CO_2 grade	Beverage

60 min of washing followed by 10 min of rinsing. This meant that the surfactant solution was in contact with the garment for a total of 60 min. In practice, the surfactant solution contact time experienced in cleaning by turnout cleaners or fire departments can vary from 20 to 40 min, and then rinsing with fresh water is followed. The period of contact was kept at 60 min to be consistent with our previous cleaning efficacy study (Girase et al., 2022) and to eliminate the variations in the volume of water during rinsing cycles.

1.1.2 Modified washing

The modified conventional method was added to assess the impact of higher washing temperatures on outer shell material. Hence, the washer extractor cycle was set to 65°C for 60 min. This was a significant increase in the temperature from the conventional washing technique. All other parameters were kept consistent with the conventional washing method (Table 2).

1.1.3 Liquid CO_2

For liquid CO_2 cleaning, two sets of swatches were shipped to Tersus Solutions (Denver, CO). One set was subjected to 15 washes, and other was subjected to 30 washes. Post-washing, all the samples were sent back for analysis. All the samples were stored in brown zip-lock bags and in the box to mitigate light exposure. The details of the method are provided in Table 3.

1.2 Physical testing of the samples

1.2.1 Tearing strength

The outer shell material is the primary line of defense for firefighters. The outer shell material protects the firefighters from cuts, abrasion, *etc.* Thus, it is important to assess the tearing and breaking strength of the outer shell material. The test method covered the measurement of the tearing strength of the fabric by the trapezoid procedure. For tearing strength, the ASTM D5587 method was used (ASTM International, 2019). Ten swatches (5 in the warp direction and 5 in the weft direction) of size 3-inch × 6-inch were cut randomly from every set.

1.2.1.1 Breaking strength

For breaking strength, the ASTM D5034 method was used (ASTM International, 2021). The test method determined the breaking force for the fabric. Ten swatches (5 in the warp direction and 5 in the weft direction) of size 4-inch × 6-inch were cut randomly from every set.

1.2.1.2 Goniometer

Contact angle measurements were used to study the impact of different washing procedures when subjected multiple times to the water-repellent finish. The Analytical Services Laboratory at Wilson College of Textiles was contracted for this testing. The Goniometer FDS Corporation Data physics optical contact angle system (Charlotte, NC) was used. For every set, 18 replicates of the fabrics were used of 1 cm diameter.

1.2.1.3 Spectrophotometer L*, a*, b* values

The working conditions of the firefighters are very harsh. The conspicuity of the firefighter is very important during fire rescue operations. The fluorescence of reflective trims enhances the conspicuity, which is important during partial light, night time work. The color measurement of the samples was performed on a spectrophotometer: Spectro-Guide sphere gloss S (Model 68-15-10) (BYK instruments, Chester, NY). For every set, the ΔE values were measured for the outer shell material, the reflective trim (yellow and silver strip), and the whiteness of the product label measured using L*. Every measurement was an average of measurements taken from random places on the sample. Due to limited availability of the resources, the retroreflectivity and the fluorescence testing was not performed on the trims.

1.3 Data analysis

Microsoft Excel was used to plot the bar graphs for all the testing data. The statistical analysis was done using JMP Pro® statistical software (15.2.0, SAS Institute Inc., Cary, NC) to perform the Shapiro-Wilks test to check the data's normal distribution. Once the normality was confirmed, the singled tail t-test was done at a p-value of 0.05, assuming unequal variances. The tearing force was measured in Newtons, and to have a comprehensive analysis, the average of warp and weft directions were taken for statistical analysis.

2 Results and discussion

2.1 Tearing strength

The testing results are illustrated in Figure 2 (mean values with error bars representing standard errors). All the results were

TABLE 4 Statistical test results for tearing strength (average of warp and weft direction) (*p*-values).

Washing method used	None (control)	Conventional	Modified	Liquid CO_2	Liquid CO_2
Number of washes	0	30	30	15	30
Shapiro-Wilks	0.5756	0.2121	0.4317	0.9162	0.8788
t-test Single tail	-	0.0001[a]	0.0008[a]	0.1351	0.5925

[a]= statistically significant.

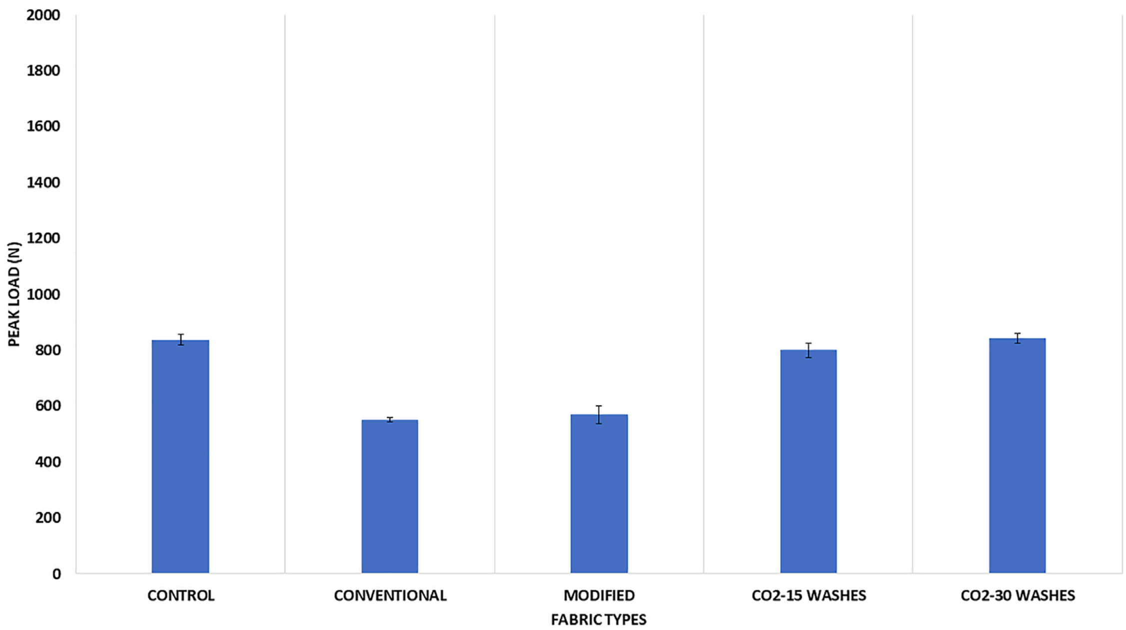

FIGURE 2
Tearing strength results.

compared with the unwashed (control) samples. There was a significant drop in the tearing strength of the samples washed with conventional and modified methods. The Shapiro-Wilks test showed that the data was normally distributed. The *p*-values are shown in Table 4. The *t*-test results shown in Table 4 showed that the conventional and modified wash results were statistically significant. The results indicated that the surfactant solution could damage the fabric when kept for a longer period in contact with the fabric. The tearing strength decreased by 34.22% for conventionally washed samples and 32.04% for modified-washed samples. Generally, the conventional aqueous wash would have less than 60 min of contact time with the fabric. These results indicated the worst-case scenario for a conventional wash. For liquid CO_2, there was no significant damage in the tearing strength. The liquid CO_2 set washed 15 times did show a loss (4.44%) in the tearing strength compared to the 30 washes set that showed a 0.59% increase, which was inconsistent and was attributed to a research artifact. According to the criteria described in NFPA 1971 subsection 7.1.11 for the tearing strength (strength >100 N), all the fabrics passed the test (NFPA, 1971; 2020).

2.2 Breaking strength

The peak load for the breaking strength testing was calculated in Newtons, and the results are illustrated in Figure 3 (arithmetic mean values with error bars representing standard errors). All the fabrics exceeded the performance requirements for breaking strength (>623 N) according to subsection 7.1.5 in NFPA 1971 (NFPA, 1971; 2020). For the grab test, the major hindrance was calculating peak load because the machine kept measuring the load even after the fabric was torn apart since some of the filaments were still intact. For conventionally washed samples, the breaking strength did not decrease much (0.08%), while the modified washed samples showed a significant decrease (29.28%) in the breaking strength. When the modified wash was considered, the only difference between the modified wash and conventional wash parameters was the higher washing temperature (65°C) in the modified wash. Thus, the higher temperature has an adverse effect on the breaking strength of the outer shell material. The results were statistically significant ($p < 0.05$) compared to control samples. The liquid CO_2-washed samples showed a 6.47% decrease for 15-wash and a 6.97% decrease for 30

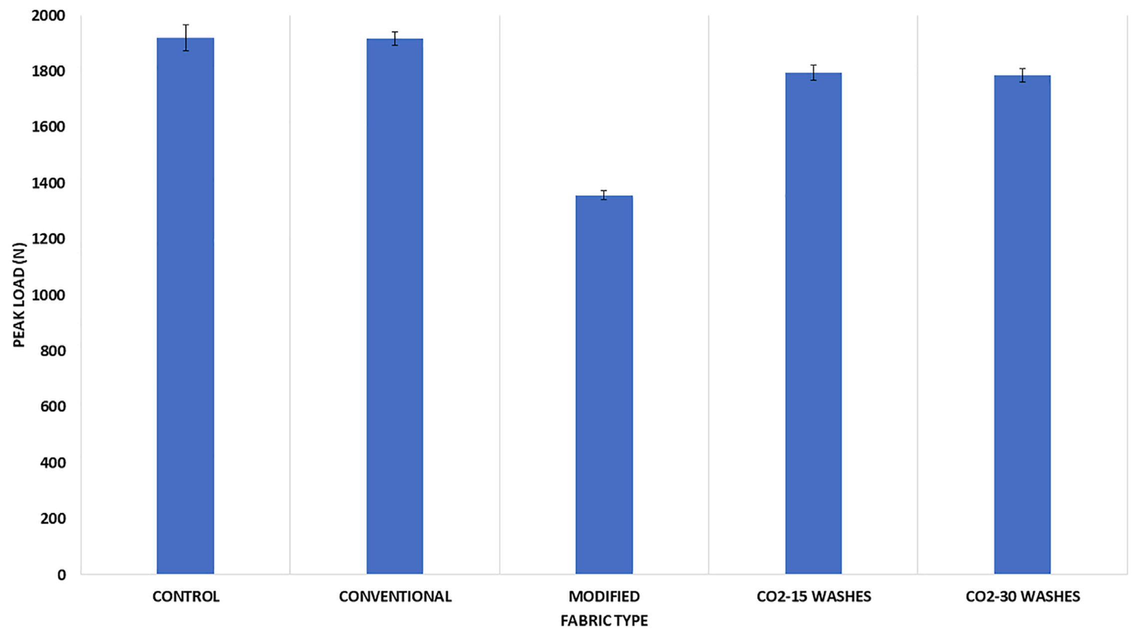

FIGURE 3
Breaking strength.

TABLE 5 Statistical test results for breaking strength (average of warp and weft direction) (*p*-values).

Washing method used	None (control)	Conventional	Modified	Liquid CO_2	Liquid CO_2
Number of washes	0	30	30	15	30
Shapiro-Wilks	0.6183	0.1099	0.3184	0.4794	0.7980
t-test Single tail	-	0.4931	0.0063[a]	0.1124	0.1002

[a]= statistically significant.

washes. This indicates that after a significant initial drop, liquid CO_2 did not affect much subsequent washing. The *p*-values in Table 5 showed that results for modified washed samples are statistically significant.

2.3 Goniometer

The results from the contact angle measurements are illustrated in Figure 4. The water droplet schematics are shown in Figure 5. The control (unwashed) samples demonstrated high levels of water repellency. The fabrics washed multiple times using conventional and modified wash demonstrated hydrophilicity hence there were no measurements available. This showed that the washing process removed or damaged the water-repellent finish after multiple cycles. The important point to consider here is that this was longer than the usual-contact period of surfactant with the fabric for the conventional wash, demonstrating an extreme case for a conventional wash. This loss in repellency may be due to the adsorption of surfactants onto the surface of the fiber or the fabric's abrasion also may have caused fragmentation of the fibers that can cause a loss in finishes (Arunyadej et al., 1998; Abdullah et al., 2006). It also meant that the conventional wash could affect the water-repellent finish over the years. The liquid CO_2-washed fabrics demonstrated comparable results with the control samples. The water droplet did not absorb on the fabric surfaces washed with liquid CO_2. Thus, the liquid CO_2 wash used in this process did not impact the water-repellant finish applied to the outershell material. The goniometer results shown in Figure 4 for liquid CO_2-15 washes and 30 washes indicate a very insignificant decline as the number of washes increased.

2.4 Visual comparison

The effect of the different washes on the outer shell and reflective trim is shown in Figure 6. After 30 washes of the conventional wash method, the color of the outer shell faded, and the reflective trim peeled off. The peeling started after the 22nd wash, to be specific. The modified wash had a more severe effect on the reflective trim as more peeling was observed. Thus, temperatures as high as 65°C can damage the accessories of the outer shell material. There was no damage to the writing on the product labels, and they were legible

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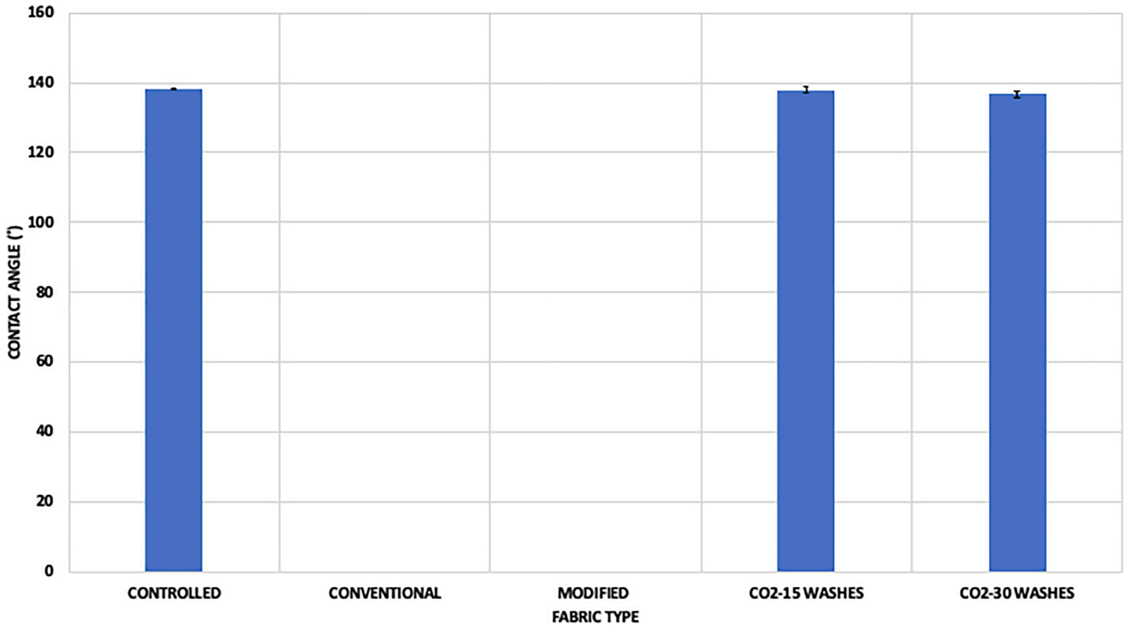

FIGURE 4
Goniometer testing results.

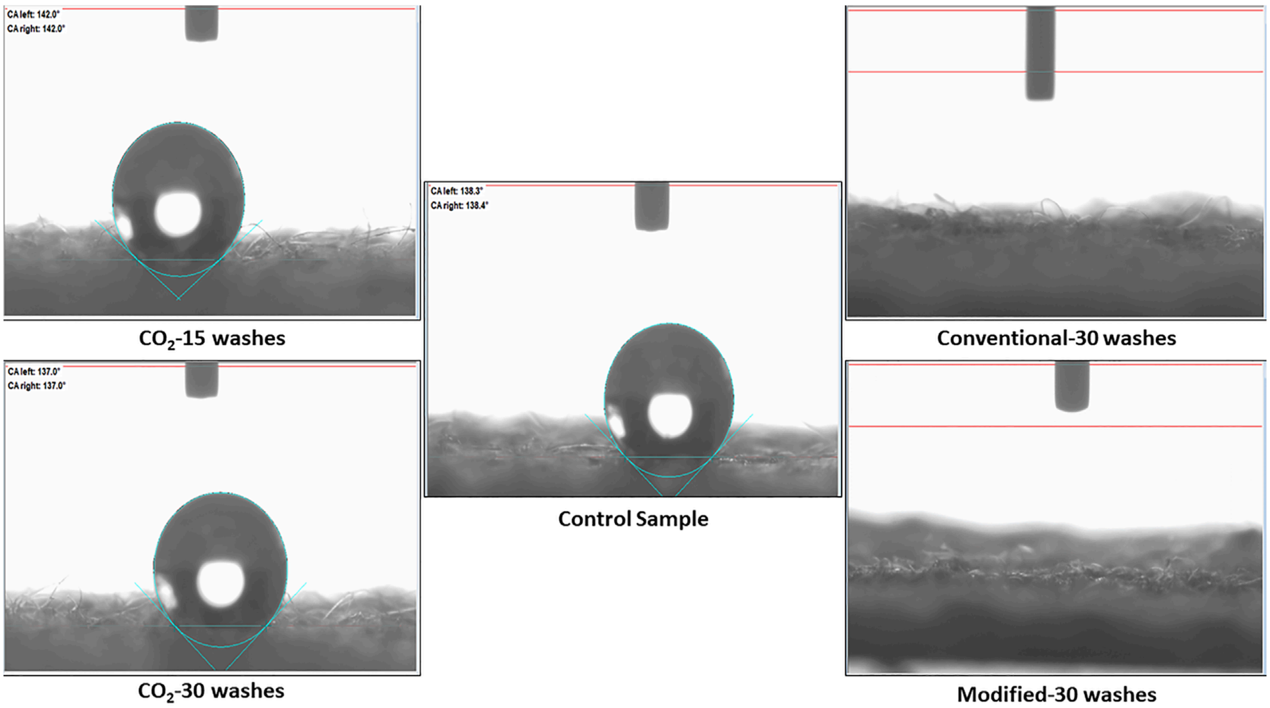

FIGURE 5
Contact angle measurements for fabrics washed with different techniques.

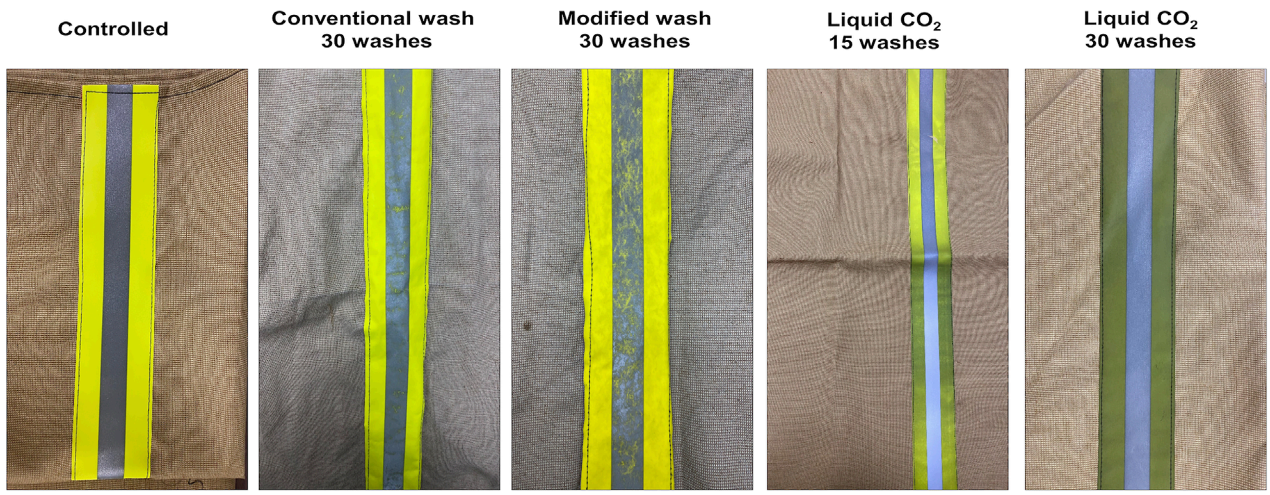

FIGURE 6
Effect of different washes on outershell and reflective trims.

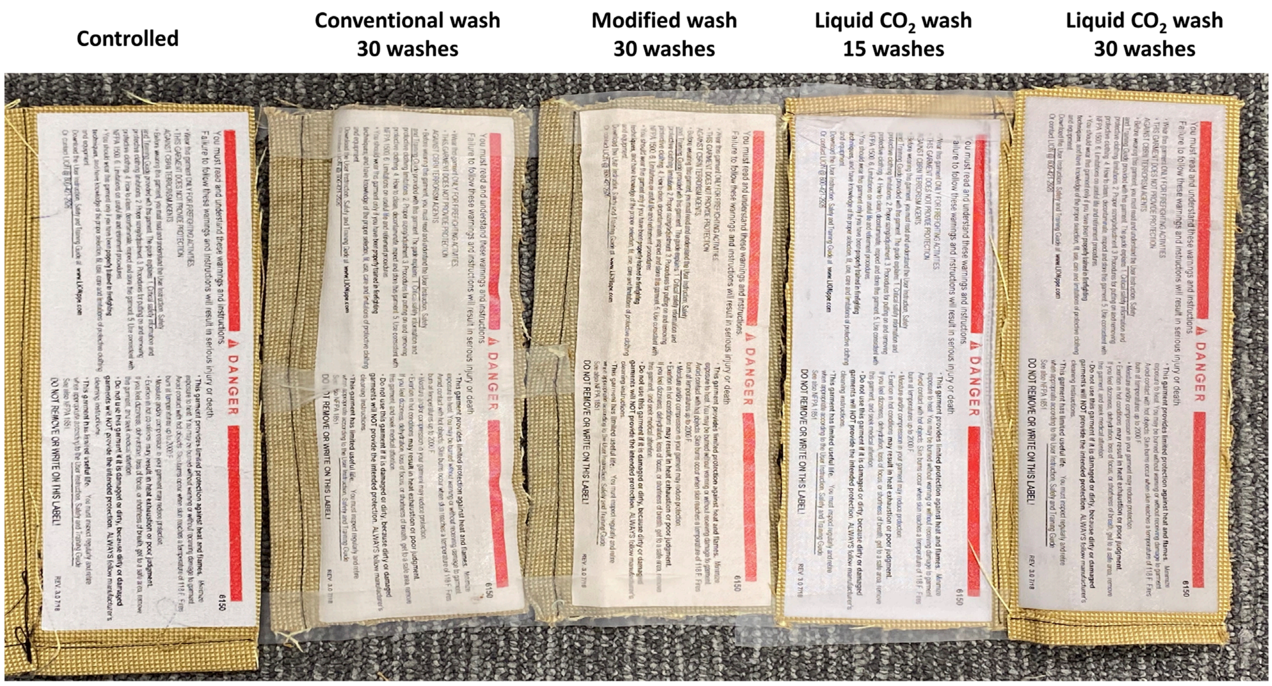

FIGURE 7
Effect of different washing techniques on product labels.

from a 12-inch distance which is a requirement according to the NFPA 1971 standard subsection 8.41.4.2.2 (NFPA, 1971; 2020).

There was no damage to the product label due to conventional washing. Out of the four product labels, two of the product labels started to detach from the outer shell garment washed using a modified washing technique (Figure 7). This was at the end of the 27th washing cycle, to be specific. The instructions on the product labels were clear and easy to read for all the product labels.

For liquid CO_2 washing, there was no significant color change in the outer shell material. The lack of mechanical agitation in the process can be a probable cause in the lack of physical damage to the accessories. However, the yellow color of the reflective trim was darkened. Even for 15 washes, the effect was visible. The whiteness of the product label was also lost somewhat for liquid CO_2 washing, although the instructions were still discernible from a 12-inch distance.

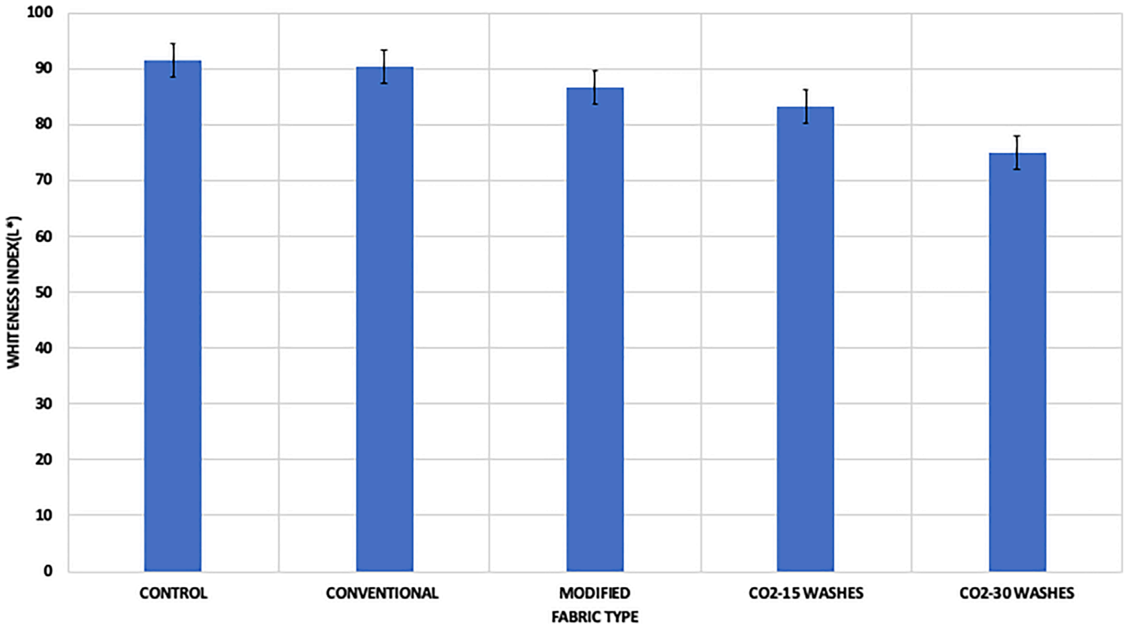

FIGURE 8
Whiteness index of the product labels.

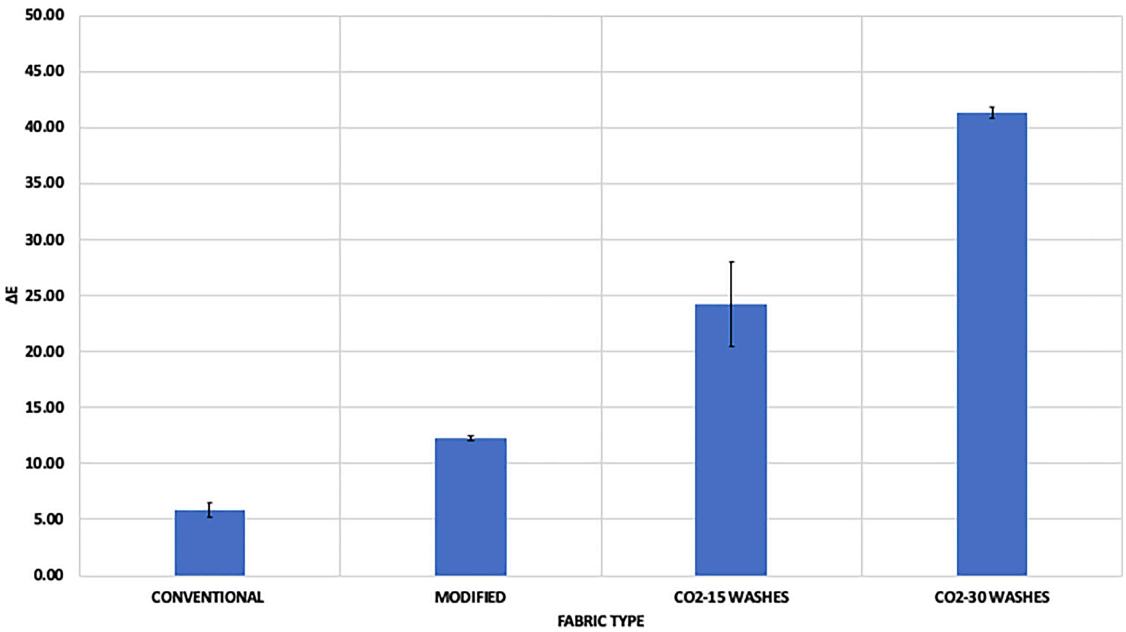

FIGURE 9
Delta-E values for yellow stripe of reflective trim.

2.5 Spectrophotometer L*, a*, b* values

The lightness index of the product labels is shown in Figure 8. The values for the conventional wash were comparable with control samples which illustrated that the conventional wash did not affect the whiteness of the product labels. Higher temperature affected the product label adversely, the lightness index was lost, and two out of four labels were detached from the outer shell. The lightness index of the product labels washed with the liquid CO_2 technique was decreased, and there was a decreasing trend as the number of washes increased from 15 to 30 washes. There are two probable reasons for this: 1) An impurity was present either in the machine's drum

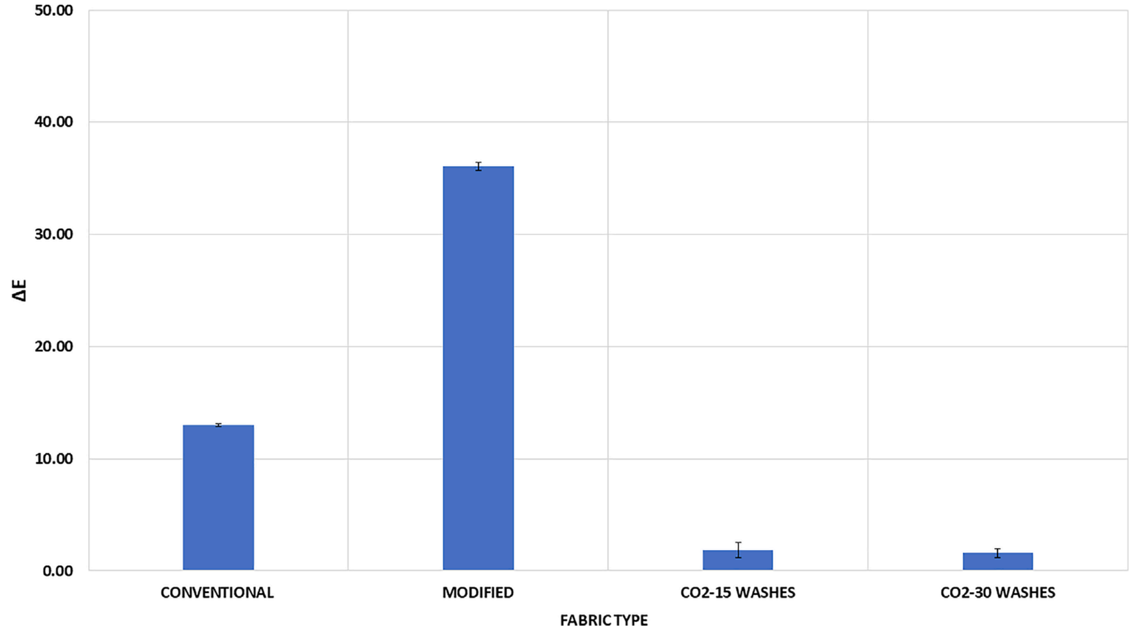

FIGURE 10
Delta-E values for outershell materials.

or in the particular batch of CO_2 used for the washing cycle that was not filtered out efficiently. The point to ponder here is that if there was redeposition of a certain impurity, it was localized on trims and labels only since the outershell material did not show any color change. 2) The primary reason might be that the white dye used in the product label and the dyes in the product labels may be dissolved in the liquid CO_2. Similarly, for the reflective trims (Figure 9), the color change was significant when washed with liquid CO_2. The probable reasons are similar. The color change for the yellow stripe of the reflective trim was quantified using ΔE values relative to the control (unwashed) reflective trim. As seen from Figure 9, the ΔE values for the liquid CO_2-washed reflective trim were higher as compared to the aqueous washes, which was evident from the visual comparisons as well. Further investigation into this matter is needed since only one kind of liquid CO_2 process was used in the study. This change in the colors can also be situational.

The color change (ΔE) in the outershell materials for conventional and modified washing was higher (Figure 10). The mechanical agitation, longer surfactant contact time, and higher temperature all contributed to the color change. This might be because the agitation contributed to the fragmentation of the fibers that peeled off the dye and the finishes together. The inter-fabric friction, as well as continuous abrasion between the fabric and the drum part for a significantly longer duration, may have contributed to the color change of the fabric. For liquid CO_2, there was no significant color change even after 30 washes. However, for the outer shell material, color change in the modified washed samples was higher. Thus, the aqueous wash with higher temperatures can adversely impact the outer shell material.

3 Conclusion

The durability study of the outer shell and its accessories showed that different washing techniques affect the outer shell and its accessories differently. The important outcome of this study was that repeated laundering has a significant impact on the physical properties of the PPE. In aqueous-based washing, the higher temperature both have an adverse effect on PPE. The mechanical agitation such as the frictional and abrasion among the fabrics and walls of the washing basket can contribute to degradation in the laundering process (Slater, 1991). The conventional wash used in this study was the representation of the effect of the surfactant solution on the garment if used for longer durations. If the duration for the contact of the surfactant solution to the conventional wash is considered an average of 30 min, then every single conventional wash represented in this study can be counted as double. Thus, the conventional wash of 30 times represents washing over 5 years if we consider the turnout suit receiving washing once every month. So, after 60 washes, the conventional wash can have an impact on the turnout suit and its accessories. Although the aqueous-based cleaning method showed decrease in the tearing strength, all the samples demonstrated tearing strength higher than the criteria set by the NFPA 1971 standard (tearing strength >100 N) (NFPA, 1971; 2020).

The only difference between the aqueous washes was modified wash used a higher temperature, Thus, the study showed the effects of higher temperatures on the turnout suits and their accessories. This answered the question of using the higher temperature to wash out the turnout suits. The breaking, tearing strength, and hydrophobicity of the outer shell material was lost after 30 washes of the modified washing technique. This could happen when it is washed frequently at higher temperatures. The modified wash used in the study includes a high temperature of 65°C. Hence, further investigation of the optimization of the number of washes, higher optimized temperature, and its effects need to be studied.

The liquid CO_2 washing technique used in this study showed that it did not have any significant effect on the tearing strength, breaking strength, or water-repellent finish applied to the outer shell material. However, it had an impact on the reflective trim and product labels. The color change can be attributed to localized cross-contamination or the dissolving of the dye. This might be the only drawback of the liquid CO_2 technique.

Limitations of this study are centered on the single sample type used. Only one type of outer shell material, reflective trim, and product label were used. A further study comprising various outer shell materials, moisture barriers, thermal liners, and accessories from different manufacturers needs to be completed to gain a more comprehensive understanding of the effects of different washing techniques on turnout suits. The flame retardant (FR) properties need to be tested to study the effect of different washing techniques. Given the limitations of this study and considering the previously demonstrated cleaning performance (Girase et al., 2022) and minimal impacts on the PPE durability, cleaning turnout gear in a liquid CO_2 process is a potential option that can be incorporated as specialized cleaning into the NFPA 1851.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization, DT and RO; methodology, AG; software, AG; validation, DT, RO, and AG; writing—original draft preparation, AG; writing—review and editing, AG, RO; project administration, RO; funding acquisition, RO and DT. All authors contributed to the article and approved the submitted version.

Funding

The following project is funded by the Assistance to Firefighters Grant Program (AFG)—Fire Prevention and Safety (FP&S) Research and Development Grants (EMW-2017-FP-00601).

Acknowledgments

The author acknowledges the support of Steve Madsen from Tersus Solutions and Bill Brooks from Unimac.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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TYPE Original Research
PUBLISHED 27 July 2023
DOI 10.3389/fmats.2023.1162730

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RECEIVED 09 February 2023
ACCEPTED 13 July 2023
PUBLISHED 27 July 2023

CITATION
Williams DN, El Hay F, Wijesinghe A, Pulluri S, Sturdivant RX, Barr KL and Harris DD (2023), Chemical compounds associated with increased risk for cancer incidence found in environmental samples obtained from two fire departments.
Front. Mater. 10:1162730.
doi: 10.3389/fmats.2023.1162730

Chemical compounds associated with increased risk for cancer incidence found in environmental samples obtained from two fire departments

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Firefighters are exposed to many different biological and chemical contaminants while conducting their work duties, including polyaromatic hydrocarbons or PAHs. PAH compounds are of particular interest in investigations of firefighter health as they have been linked to detrimental health outcomes, including respiratory illnesses and cancers, and are found in high concentrations after fires. Thus, they are quantified in several studies on the occupational exposure of firefighters, and they are the focus of several protocols and technologies aiming to mitigate occupational exposures. Fire departments use standard operation protocols for limiting exposure to occupational health hazards, including exposure to chemical compounds such as PAHs. However, observations of firefighter workflows reveal the potential for major contamination of fire station work-live areas. Herein we make an initial report on the PAHs that firefighters continue to be exposed to after they have finished responding to calls and have potentially doffed their protective gear. The sampling of environmental surfaces in fire apparatus and stations was used as data. This study found that PAHs identified on turnout gear were found in the fire station, suggesting that turnout gear may be vectors of toxic chemicals. Therefore, protocols for decontamination of turnout gear and fire stations should be evaluated to remove PAHs and other chemicals known to impair health. This and further surface sampling studies are needed to better understand the full occupational exposures of firefighters to hazardous chemicals.

KEYWORDS

polycyclic aromatic hydrocarbons, PAH, cancer, environmental surfaces, turnout gear, chemical contaminants, occupational exposures, vector of transmission

1 Introduction

Firefighters are exposed to a wide range of chemical contaminants during active fire suppression operations (Bolstad-Johnson et al., 2000; Blomqvist et al., 2012; Environmental Protection Agency, 2013; Fent et al., 2015; Easter et al., 2016; Fent et al., 2018; Beitel et al., 2020; Banks et al., 2021a). Thus, firefighter contaminated turnout gear may be a vector of toxic chemical transmission to the fire station, from structure and ground fires as well as other non-fire related service calls with chemical exposures. Limited research on fire apparatus environments and exposures to occupants suggests a gap in the research. Engelsman et al. (2019) collected samples from apparatus cabins and was able to detect polycyclic aromatic hydrocarbons (PAHs) in a minimal number of samples. In addition, this study (Engelsman et al., 2019) analyzed samples across fifteen fire stations. It focused on air and wipe samples from the interior and exterior of the fire stations, personal protective equipment (PPE) including clothing, and from within the cabins of fire apparatus. Engelsman et al. (2019) found that elevated concentrations in these environments are associated with the transfer of chemicals from fire suppression operations, increasing exposure risks and increased risk of adverse health effects. Other studies (Sparer et al., 2017; Stec et al., 2018; Shen et al., 2018; Young et al., 2021) support these findings across a spectrum of toxic chemicals, where elevated levels of toxic chemicals were found in fire station dust compared to other occupational and residential settings.

PAH are of particular concern in firefighter occupational exposure studies because they are ubiquitous pollutants that are found in high concentrations during and after fire suppression operations (Keir et al., 2020; Thai et al., 2020; Hoppe-Jones et al., 2021). PAHs are referred to as carcinogens, mutagens, and teratogens. They therefore are known to present a significant risk to human health and wellness (Mallah et al., 2022). PAHs are formed through incomplete combustion of organic materials and are pervasive pollutants on surfaces and in air (Kim et al., 2013). During and after fire suppression operations, firefighters may be exposed to PAHs by absorption through the skin, from cross-transfer of contaminants on PPE to the skin, and through inhalation (Fent et al., 2017). In a pre- and post-exposure study evaluating PAH concentrations, PAH levels were elevated after the fire training scenario on the front of the neck, back of the neck, jaw, and hands of the participating firefighters (Stec et al., 2018). The same study found that PPE items assessed also had elevated PAH levels, including the self-containing breathing apparatus (SCBA), zipflap, shoulder of the turnout gear, gloves, and hood. Whether evaluating ambient air of fire stations, PPE of firefighters, or surface samples found associated with the transmission of PAHs across environments, PAHs and other known chemical contaminants need to be further investigated to identify, quantify, assess risk, and develop protocols to protect firefighters.

Common PAHs produced during structure fires are classified by the International Agency for Research on Cancer (IARC) at various levels of potential carcinogenicity. For examples, there are the classification of benzo [a]pyrene as carcinogenic to humans (Group 1), classification of dibenz (a,h)anthracene, chrysene, and anthracene as probably or possibly carcinogenic to humans (Group 2A or 2B), and acenaphthene, fluorene, phenanthrene, and pyrene as chemicals of concern but current evidence is inadequate in humans or limited in experimental animals (Group 3) (Palmer, 2011). Nearly all fires will produce other potentially carcinogenic aromatic hydrocarbons, such as benzene and chrysene. Regardless of the IARC classifications, acute health effects of PAHs depend on the length of time of exposure, the concentration of PAHs during exposure, the toxicity of the PAHs, and the route of exposure (inhalation, ingestion, or skin absorption). For chronic occupational exposures, mixtures of PAHs and other workplace chemicals are associated with a series of health problems including increased risk of skin, lung, bladder, and gastrointestinal cancers (Kim et al., 2013). Additionally, external factors may affect health impacts such as pre-existing health conditions and age. For instance, PAHs have been reported to impair lung function in asthmatics and thrombotic effects in those affected by coronary heart disease (ACGIH, 2005). Occupational exposures to high levels of chemical pollutant mixtures containing PAHs are known to result in symptoms such as eye irritation, nausea and vomiting, and inflammation (Unwin et al., 2006; Kim et al., 2013). PAHs also have the potential to interfere with the hormone systems, effecting reproductive and immune function, cataracts, kidney, and liver damage, and gene mutation cell damage (García-Suástegui et al., 2011; Yang et al., 2021). Unfortunately, most studies of PAHs are focused on chemical mixtures and not isolated PAH, making it difficult to isolate the effect of individual PAHs (Kim et al., 2013). It is still widely accepted that PAHs have carcinogenic potential based on evidence from epidemiological studies identified in a meta-analysis focused on cancer risk after exposure to PAHs (Armstrong et al., 2003).

With some of the highest rates of injuries and illnesses across all occupations, firefighters are at elevated risk for cancers and incidences of respiratory, digestive, lymphatic, skeletal, and reproductive health problems (Lemasters et al., 2006; Daniels et al., 2014; Daniels et al., 2015). Thus the evolution of protocols to protect firefighters from these contaminants continues (McGuire-Wolfe, 2020). Currently, firefighters rely heavily on PPE to protect them during fire suppression operations and other service calls, and to mitigate direct exposures to toxic chemical compounds. However, firefighters are continually at risk of cross-contamination through donning and doffing PPE, handling turnout gear during decontamination protocols, and passively off-gassing in fire stations. While firefighters expect the risk of exposure while responding to service calls, they are vulnerable in their fire station where they work, sleep, cook, and live while on duty. This study aims to investigate, through surveillance, fire station contamination of environmental surfaces. This study will evaluate PAH chemicals known to be found at structure fire sites and on firefighter PPE to discern their potential transmission to fire stations, increasing risk of exposure of firefighters.

2 Materials and methods

2.1 Materials

Dichloromethane (DCM), disposable sampling templates (10 cm × 10 cm), n-hexane, sterile cellulosic gauze pads (3 in x 3 in), and syringe filters (PTFE, 0.45 µm) were purchased through Fisher Scientific. CLPS-B PAH Mix (2,000 µg/mL in DCM:benzene), anthracene-d10 (1,000 µg/mL in DCM), benzo(a)pyrene-d12 (1,000 µg/mL in DCM), and phenanthrene-d10 (1,000 µg/mL in DCM) from Spex® CertiPrep were purchased through Fisher Scientific. Acenaphthene-d10 (2,000 µg/mL in DCM) and naphthalene-d8 (2,000 µg/mL in DCM) from MilliporeSigma™ Supelco™ were also purchased through Fisher Scientific.

2.2 Environmental sampling

Two fire departments located in the southern region of the United States provided access for environmental sampling of polycyclic aromatic hydrocarbons (PAHs). This sampling was conducted parallel to microbial sampling detailed in a previous report (Barr et al., 2021). Fire Department 1 (FD1) provided access to one fire station for repeated sampling over 4 weeks. Fire Department 2 (FD2) provided access to four fire stations for incidental sampling on 1 day.

The following surfaces were sampled: medical bag (nylon), back seat (unknown synthetic woven textile) and console (unknown polymer) in the fire engine; extractor (stainless steel & glass) and contaminated turnout gear outer shell (Kevlar®/Nomex®) in the fire station garage; and the computer keyboard (acrylonitrile butadiene styrene) and entryway floor (PVC safety sheet flooring) in the live-work area of the fire station. These surfaces were chosen because they were either high-touch or high-use objects within the fire station. In total there were 159 samples collected.

A wipe protocol (Figure 1) was used to collect samples. Wipes—Sterile cellulosic gauze pads wet with 2 mL of n-hexane—Were used with a disposable sampling template to sample designated areas of each surface. Within the template, the wetted side of the gauze was pressed to wipe down firmly at an upper corner of the textile sample. An "S" shape motion (as many as needed) is made to cover the entire textile (Figure 1A). The gauze wipe was folded in half, keeping dirty side in. Then, the gauze was used to wipe in an "S" shape motion perpendicular to the first wipe ensuring the entire textile sample is covered (Figure 1B). The gauze wipe is folded in half again, keeping dirty side in, and a third wipe focusing on the edges of the specimen is performed (Figure 1C). The wipe was folded again, with the sample side folded in, to place the folded wipe into an extraction vessel while avoiding contact with other surfaces and the upper portion of the extraction vessel. New disposable gloves and tweezers cleaned with solvents were used to handle each new gauze wipe and textile specimen pair, with care to avoid touching anything other than these items. Wipe samples were placed in amber vials, labeled, and stored in a −80°C freezer until the time of extraction.

2.3 Samples analysis

Wipe samples were cut into three portions (triplicates) for PAH extraction. PAHs were extracted from samples following sonication procedures adapted from previously reported methods. Stec et al. (2018), Beitel et al. (2020), Fent et al. (2020), Mayer et al. (2020). Wipes were placed in extraction vessels with 8 mL of DCM. The vessels were screwed closed and then sonicated for 60 min with no heat. Immediately after sonication, the extraction vessels were vented in a hood until they reached room temperature. Extracts were filtered through 0.45 µm PTFE syringe filters into vessels for evaporation. The extraction vessels and filters were rinsed with excess extraction solvent and transferred to the evaporation vessels too. After evaporation, samples are stored in 1 mL DCM in amber chromatography vials to await gas chromatography-mass spectrometry (GC/MS) analysis.

Prior to analysis by GC/MS, five deuterated PAHs were added to each sample at 2 ppm to serve as internal standards: acenaphthene-d10, anthracene-d10, benzo(a)pyrene-d12, naphthalene-d8, and phenanthrene-d10. The internal standards were also added to an external calibration curve prepared from a 2,000 ppm CLSP-B ampule diluted in dichloromethane. Dichloromethane blanks were run regularly between extraction samples to prevent and monitor carry-over.

GC/MS analysis was completed with a Thermo Trace 1310 Gas Chromatograph coupled to an ISQ 7000 single quadrupole mass spectrometer (Thermo Scientific, Austin, TX, United States) and Thermo Scientific Dionex Chromeleon 7 Data System Version 7.3 (60919) using a 60 m column, 1 µL injection volume, and

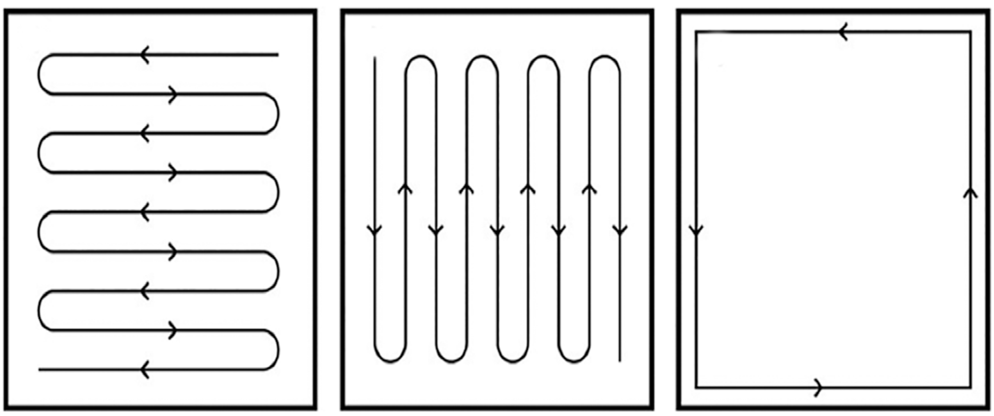

FIGURE 1
Schematic of a side-to-side overlapping "S" wiping pattern.

splitless mode. The inlet temperature of the GC was set to 300°C and the temperature ramped as follows: hold at 50°C for 1 min, ramp 20°C/min up to 250°C, ramp 10°C/min up to 330°C, hold at 330°C for 1 min. MS acquisition ran in positive mode with an electron ionization (EI) source temperature of 300°C. Peaks in the raw data were manually selected for identification and matched against the NIST database of EI spectra. Recorded limits of quantification (LOQ) are: acenaphthene (10 ppb), acenaphthylene (10 ppb), anthracene (100 ppb), benz(a)anthracene (10 ppb), benzo(b)fluoranthene (100 ppb), benzo(k)fluoranthene (5 ppm), benzo (g,h,i)perylene (10 ppm), benzo(a)pyrene (250 ppb), chrysene (25 ppb), dibenz (a,h)anthracene (2 ppm), fluorene (10 ppb), indeno (1,2,3-c,d)pyrene (10 ppm), naphthalene (50 ppb), phenanthrene (50 ppb), and pyrene (10 ppb).

2.4 Data analysis

PAH concentrations were assigned against the external standards for each extraction. Then, the triplicates of each wipe sample were combined with the presence of PAHs being defined as a positive result on at least one of the three samples. FD1 in week 1 had more observed collection sites than the other departments/weeks. The additional observations were from various parts of the same site (e.g., back of drum and drum). So, these samples were combined into a single observation, with presence meaning any of the samples were positive.

ANOVA was utilized to compare average presence of chemicals across sites and departments. Tukey HSD pairwise comparisons were utilized if the result was statistically significant to identify pairs that differed. Logistic regression was performed to model the binary outcome of presence of chemical and odds ratios comparing groups to a reference category reported. In some instances, data sparsity (subgroups with either no chemical present or chemicals present in every sample) made logistic regression infeasible. So, the ANOVA results were the only option.

3 Results

3.1 Fire department 1 (FD1)

Table 1 represents the four discrete sampling events (1, 2, 3, and 4) over time at the same fire station in FD1. All sampled locations at the FD1 station had detectable levels of chrysene at every time point. Several locations had additional PAHs. The sampled console had detected levels of anthracene at week 3, and pyrene at weeks 1 and 3 sampling events. The sampled extractor had detectable levels of fluorene, naphthalene, and pyrene at the week 1 sampling event. Acenaphthene, anthracene, benzo(b)fluoranthene, benzo (g,h,i)perylene, dibenz (a,h)anthracene, fluorene, naphthalene, and pyrene were detected at the week 3 sampling event. Anthracene was also found at this location at the week 4 sampling event. Acenaphthylene, benz(a)anthracene, benzo(k)fluoranthene, benzo(a)pyrene, indeno (1,2,3-c,d)pyrene, and phenanthrene were probed for, but not detected at any surface sampling site of the FD1 station at concentrations above our limits of detection. When comparing all four sampling events, no significance was found.

Table 2 illustrates that the detection of chrysene is statistically different than the detection of all other PAHs ($p < 0.0001$) using Tukey HSD to adjust for multiple comparisons. The next largest differences are between anthracene and pyrene (which were both detected 4 times) and each PAH that was not detected. However, these differences are not statistically significant ($p = 0.186$).

TABLE 1 PAHs found at surface sampling sites by week of collection (1, 2, 3, 4) at FD1.

	Medical bag	Computer keyboard	Fire engine console	Extractor	Live-work floor	Fire engine seat	Contaminated turnout gear
Acenaphthene				3			
Acenaphthylene							
Anthracene			3	1, 3,4			
Benz(a)anthracene							
Benzo(b)fluoranthene				3			
Benzo(k)fluoranthene							
Benzo (g,h,i)perylene				3			
Benzo(a)pyrene							
Chrysene	1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4	1,2,3,4
Dibenz (a,h)anthracene							
Fluorene				1, 3			
Indeno (1,2,3-c,d)pyrene							
Naphthalene				1, 3			
Phenanthrene							
Pyrene			1,3	1, 3			

TABLE 2 PAH detection at FD1.

	diff	lwr	upr	p.adj
Chrysene-Benz(a)anthracene	1.0000	0.8337	1.1663	<0.001
Chrysene-Acenaphthylene	1.0000	0.8337	1.1663	<0.001
Chrysene-Benzo(k)fluoranthene	1.0000	0.8337	1.1663	<0.001
Chrysene-Benzo(a)pyrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Indeno (123cd)pyrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Phenanthrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Dibenz (ah)anthracene	1.0000	0.8337	1.1663	<0.001
Chrysene-Acenaphthene	0.9643	0.7980	1.1306	<0.001
Chrysene-Benzo(b)fluoranthene	0.9643	0.7980	1.1306	<0.001
Chrysene-Benzo (ghi)perylene	0.9643	0.7980	1.1306	<0.001
Chrysene-Naphthalene	0.9286	0.7623	1.0949	<0.001
Chrysene-Fluorene	0.9286	0.7623	1.0949	<0.001
Chrysene-Anthracene	0.8571	0.6909	1.0234	<0.001
Chrysene-Pyrene	0.8571	0.6909	1.0234	<0.001

TABLE 3 Site contamination at FD1.

	diff	lwr	upr	p.adj
Extractor-Flooring	0.2000	0.0390	0.3610	0.0049
Extractor-Turnout Gear	0.2000	0.0390	0.3610	0.0049
Extractor-Medical Bag	0.2000	0.0390	0.3610	0.0049
Extractor-Apparatus Seat	0.2000	0.0390	0.3610	0.0049
Extractor-Computer Keyboard	0.2000	0.0390	0.3610	0.0049
Extractor-Apparatus Console	0.1500	−0.0110	0.3110	0.0865

There are significant differences in observed presences by site (ANOVA F-test, $p = 0.0011$). Table 3 shows pairwise *post hoc* comparisons with p-values < 0.5. All comparisons shown are significant at 0.05 level except the Extractor-Apparatus comparison ($p = 0.086$).

3.2 Fire department FD2

The results of Table 4 represent incidental sampling across four different fire stations (A, B, C, D) of FD2 on the same day. All sampled locations had detectable levels of chrysene at every station of FD2. We also detected additional PAHs at several stations and surface sampling locations of FD2. Anthracene was detected on the computer of FD2-B. Benz(a)anthracene, benzo(b)fluoranthene, benzo (g,h,i)perylene, benzo(a)pyrene, indeno (1,2,3-c,d)pyrene, and pyrene were detected on the fire engine console of FD2-C. Benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo (g,h,i)perylene, benzo(a)pyrene, indeno (1,2,3-c,d)pyrene, and pyrene were detected on FD2-C's entryway floor at significant concentrations. Acenaphthene, acenaphthylene, dibenz (a,h)anthracene, fluorene, naphthalene, and phenanthrene were probed for but not detected at any FD2 station at significant concentrations.

Tukey HSD adjusted pairwise comparisons show significant differences between the incidence of chrysene and all other PAHs detected (Table 5).

There were no significant differences in observed PAH presence by site ($p = 0.1008$), but there was a statistically significant difference within the stations. FD2-C had a statistically higher count of PAH observations ($p = 0.000981$) compared to all other stations as shown in Table 6.

3.3 Comparison across the fire departments

The overall percentage of tests for which any chemical was found by station (and week for FD1) is shown in Figure 2. The station factor is statistically significant ($p = 0.007$) With FD2's Station C as the reference group, all other station/weeks have a statistically significant reduction in odds of a chemical detection except for FD1-3 (Table 7).

4 Discussion

PAH compounds are of particular interest in investigations of firefighter health and occupational exposure studies as they are ubiquitous pollutants which are found in especially high concentrations after fires (McMahon and Tsoukalas, 1978; Vergnoux et al., 2011; Baxter et al., 2014; Mansilha et al., 2014; Keir et al., 2020; Fent et al., 2020; Banks et al., 2021a; Hoppe-Jones et al., 2021). Exposures to PAHs have been linked to detrimental human health outcomes. Generalities about PAH exposure cannot be drawn as the type of PAH, exposure route (dermal absorption, inhalation, and ingestion), length of exposure, amount of exposure and biological susceptibility factors impact the levels of concern; but acute exposures to PAHs—Such as through exhaust gases and food—Have been linked to mucous membrane irritation, skin irritation, vomiting, confusion, and diarrhea (Agency for Toxic Substances and Disease Registry (ATSDR), 2023). Chronic exposures to PAHs have additionally been linked to asthma, chronic obstructive pulmonary disease (COPD), and a variety of cancers (Agency for Toxic Substances and Disease Registry (ATSDR), 2023; Centers for Disease Control and Prevention, 2013). Observations of firefighter protocols and workflow elucidate that their occupation lends them to acute and chronic exposures to PAHs, acute exposures sourced from the fires that they combat. Chronic exposures are sourced from acute exposures throughout a firefighter's career, and from their interaction with contaminated textiles and surfaces.

We previously published our observations of firefighter behaviors at FD1 and FD2 during the time of this surface sampling (Barr et al., 2021). At each station observed, firefighters entered their stations and went immediately to file reports using their station computers prior to washing their hands. When completed, handwashing practices were not consistent between stations or within them. Additionally, we observed one station respond to multiple calls before returning to the station, filing reports on their station computers, and then washing their hands. So, it is

TABLE 4 PAHs found at surface sampling sites by station location (A, B, C, D) at FD2.

	Medical bag	Computer keyboard	Fire engine console	Extractor	Live-work floor	Fire engine Seat*
Acenaphthene						
Acenaphthylene						
Anthracene		B				
Benz(a)anthracene			C		C	
Benzo(b)fluoranthene			C		C	
Benzo(k)fluoranthene					C	
10.3.1 Benzo (g,h,i)perylene			C		C	
Benzo(a)pyrene			C		C	
Chrysene	A, B, C, D	A, B, C, D	A, B, C, D	A, B, C, D	A, B, C, D	B
Dibenz (a,h)anthracene						
Fluorene						
Indeno (1,2,3-c,d)pyrene			C		C	
Naphthalene						
Phenanthrene						
Pyrene			C		C	

* This site was only sampled at location B.

TABLE 5 PAH detection at FD2.

	diff	Lwr	upr	p.adj
Chrysene-Benz(a)anthracene	1.0000	0.8337	1.1663	<0.001
Chrysene-Acenaphthylene	1.0000	0.8337	1.1663	<0.001
Chrysene-Benzo(k)fluoranthene	1.0000	0.8337	1.1663	<0.001
Chrysene-Benzo(a)pyrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Indeno (123cd)pyrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Phenanthrene	1.0000	0.8337	1.1663	<0.001
Chrysene-Dibenz (ah)anthracene	1.0000	0.8337	1.1663	<0.001
Chrysene-Acenaphthene	0.9643	0.7980	1.1306	<0.001
Chrysene-Benzo(b)fluoranthene	0.9643	0.7980	1.1306	<0.001
Chrysene-Benzo (ghi)perylene	0.9643	0.7980	1.1306	<0.001
Chrysene-Naphthalene	0.9286	0.7623	1.0949	<0.001
Chrysene-Fluorene	0.9286	0.7623	1.0949	<0.001
Chrysene-Anthracene	0.8571	0.6909	1.0234	<0.001
Chrysene-Pyrene	0.8571	0.6909	1.0234	<0.001

TABLE 6 PAH detection within the stations for FD2.

	diff	lwr	upr	p.adj
FD2-A—FD2-B	0.1733	0.0423	0.3043	0.0040
FD2-A—FD2-D	0.1733	0.0423	0.3043	0.0040
FD2-A—FD2-C	0.1600	0.0290	0.2910	0.0095

possible that PAHs from each call that this station responded to accumulated on the firefighters until they were deposited on the computer keyboard. The standard operating protocols for exposure control and general cleaning were also inconsistent between the departments or stations. The FD1 station had protocols that included mopping entryway floors daily. Alternatively, the FD2 stations used disinfecting mats on the entryway floors, but each station did not use them correctly. So, it is possible that the entryway floor mats could serve as a vector for PAHs in that environment. In summation, the handwashing behaviors and exposure control procedures observed did not appear sufficient for limiting the contamination of fire station live-work areas.

In this study, the PAH chrysene was found at every sampled site where detectable levels of PAHs were observed at both fire departments. Chrysene's detection was found to be significantly greater than that of the other probed for PAHs (Tables 2 and 5). Since chrysene is one of the most common PAHs and is produced as smoke during incomplete combustion of coal, gasoline, garbage, animal, and plant materials, its presence is not surprising (Biswas and Ghosh, 2014). Chrysene and several of its isomers are classified as "probably carcinogenic" and "reasonably anticipated to be" carcinogenic to humans by several organizations (Gehle, 2009; National Toxicology Program, 2021; American Cancer Society, 2022). Chrysene's significant presence at every site sampled, at every fire station sampled exemplifies the problem of hazardous contamination in the live-work spaces of firefighters. It is important to note that other PAHs used in this study are listed by the Environmental Protection Agency (EPA) as priority chemicals, including acenaphthene, acenaphthylene, anthracene, benzo (g,h,i)perylene, fluorene, phenanthrene, and pyrene. Other studies finding similar combinations of PAHs in smoke exposure (Fabian et al., 2014), PPE and skin (Fent et al., 2017; Stec et al., 2018; Mayer et al., 2019; Mayer et al., 2020), and air and surfaces (Sparer et al., 2017; Fent et al., 2018; Engelsman et al., 2019; Keir et al., 2020; Shinde, 2020; Banks et al., 2021b) begin to indicate the initial ambient exposures, turnout contamination and the transmission to fire stations.

A second concern of hazardous contamination in the live-work spaces elucidated by this study is that the extractor was the most contaminated site sampled at FD1 (Table 1), presenting a concern that the extractor is cross-contaminating turnout sets. Since we observed no significant difference between the contamination in the fire apparatus and the extractor (Table 3), contamination of the extractor most likely came from the firefighter gear worn in the apparatus from fire calls, transferred from the service call site, and placed into the extractor for cleaning. Being able to detect PAHs in the empty extractor is likely due to the regular washing of firefighter uniforms and turnout gear without a standard protocol for decontaminating the extractor after each use. Considering that every firefighter's uniform, turnout gear or clothing may go through a cleaning in the extractor, proper decontamination of the extractor is imperative to break the chain and prevent it from being a vector of hazardous exposure after the cleaning, disinfecting, and decontaminating process is complete.

A third factor of fire station contamination elucidated by this study is the variability of contamination of the station regardless of the frequency of fire calls (Figure 2; Tables 6, 7). FD2-A had significantly more fire service call frequencies than the other FD2 stations as previously reported (Barr et al., 2021). This finding brings into question standard protocols for cleaning and decontamination of fire stations. FD2-C had only 31% of the fire service calls yet was significantly more contaminated with sampled PAHs than the other FD2 stations. Further investigation is needed to determine factors contributing to variability of PAH deposits in the fire station environment.

There are several PAHs that we probed for but did not identify above the limit of our protocols. This does not necessarily mean that the PAHs were not on the sampled locations because our research protocols have limitations. Chemical sampling and analysis are often optimized to the levels/concentrations/amounts of chemicals to be sampled. Unfortunately, we lacked an awareness of the contamination levels before surface sampling. So, our surface sampling and analysis methods may not be well optimized. For example, we sampled the bottom of the medical bag for PAHs but sampling the side or top of the bag may have led to PAH detection. Also, our evaporation process (for the concentration of sample extractions) may have resulted in a loss of PAHs prior to GC/MS analysis. This study also has limited surface sampling sites and number of stations in its data. Despite these limitations, this preliminary study certainly illustrates the need to further surveil chemical contamination levels of the live-work spaces in fire stations.

There are more PAHs and other carcinogenic chemical compounds in fire station live-work areas that are not covered in this or similar studies. Environmental sampling and chemical surveillance should be comprehensive at fire stations to attain a full picture of the current occupational hazard and exposure levels for firefighters. A full assessment can lead to the development and implementation of mitigations and protocols to limit and contain risks to the health of this important population of our society.

In conclusion, the PAHs studied are listed as priority chemicals by the EPA. Combinations are found in fire site smoke and ambient air in fire stations; on PPE, skin, and environmental surfaces, which represents transmission from the source fire to fire stations via firefighters and contaminated turnout gear. Observed protocols for minimizing exposure risks such as including particulate trap mats at entryways, housekeeping, and handwashing, did not appear sufficient for limiting contamination of fire station live-work areas. Consistent facility decisions along with additional training and an informational campaign may increase compliance with processes that will reduce exposure risks. Among the environmental samples collected, the most contaminated site was the extractor. Proper decontamination of the extractor between loads is recommended to break the chain of transmission, preventing potential cross-contamination of turnouts during the decontamination process. The variability of fire station contamination was not dependent on the service call frequency. Variability may be due to the inconsistency of chemical toxicants in different fires, differences in housekeeping, or other factors not considered. Further investigation is needed to determine contributing factors of PAH deposits on surfaces in fire stations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KB and DH contributed to the conceptualization and design of the study. KB, DH, and DW developed the methodology. KB and DH conducted sample collection. FE, DH, SP, AW, and DW contributed to sample analysis. RS and DW performed the formal analysis. KB, FE, DH, RS, AW, and DW contributed to the original draft preparation. All authors contributed to the article and approved the submitted version.

Funding

Funding for this study was provided by Baylor University.

Acknowledgments

We would like to thank the fire departments who participated in this study. We would also like to thank Dr. Alejandro J. Ramirez for training and support for the GC/MS in Baylor's Mass Spectrometry Center.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Original Research
PUBLISHED 18 August 2023
DOI 10.3389/fonc.2023.1155650

OPEN ACCESS

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RECEIVED 31 January 2023
ACCEPTED 27 April 2023
PUBLISHED 18 August 2023

CITATION
Koru-Sengul T, Pinheiro PS, Zhao W, Hernandez MN, Hernandez DR, Maggioni A, Kobetz EN, Caban-Martinez AJ and Lee DJ (2023) Lung cancer survival among Florida male firefighters. *Front. Oncol.* 13:1155650. doi: 10.3389/fonc.2023.1155650

Lung cancer survival among Florida male firefighters

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Introduction: Lung cancer is a leading cause of cancer incidence and death in the United States. Although most firefighters are fit and do not smoke, they are exposed to many known carcinogens during and in the aftermath of firefighting activities. Comprehensive epidemiologic investigations on lung cancer survival for both career and volunteer firefighters have not been undertaken.

Methods: Data from the Florida Cancer Data System (1981–2014) were linked with firefighter certification records from the Florida State Fire Marshal's Office to identify all patients of this occupational group; lung cancer cause-specific survival data were compared with other occupational groups using Cox regression models with occupation as the main effect. Adjusted hazard ratios (aHR) and 95% confidence intervals (95% CI) were calculated.

Results: Out of 210,541 male lung cancer cases diagnosed in Florida (1981–2014), 761 were firefighters (604 career, 157 volunteer). Lung cancer death was similar between volunteer (75.2%) and career firefighters (74.0%) but lower than non-firefighters (80.0%). Survival at 5 years was higher among firefighters (29.7%; career: 30.3%; volunteer: 27.4%) than non-firefighters (23.8%). In a multivariable model, compared with non-firefighters, firefighters have significantly higher cause-specific survival (aHR = 0.84; 95% CI: 0.77–0.91; $p < 0.001$). However, there were no significant survival differences between career and volunteer firefighters (1.14; 0.93–1.39; $p = 0.213$). In a separate multivariable model with firefighters as the comparator, other broad occupational groups had significantly lower cause-specific survival [white collar: 1.11 (1.02–1.21); blue collar: 1.15 (1.05–1.25); service: 1.13 (1.03–1.25); others/unknown: 1.21 (1.12–1.32); all p-values < 0.02].

Conclusion: Lung cancer survival is significantly higher among firefighters compared with non-firefighters, but there is no significant difference between career and volunteer firefighters. Improved survival for firefighters might be due to a healthy worker effect, lower smoking prevalence relative to other worker groups, and possibly superior treatment adherence and compliance. Many firefighters are cross-trained as EMTs/paramedics and possess a level of medical knowledge that may favorably impact treatment engagement and better navigation of complex cancer care.

KEYWORDS

lung cancer, cancer survival, firefighters, Florida, occupational exposure

1 Introduction

Lung cancer is the most predominant cause of cancer-specific death in the United States (US), in addition to being the second leading cause of death overall (1, 2). Lung cancer accounts for 20% of cancer deaths, making it the primary cause of death among all cancers (1). In 2023, it is anticipated that approximately 238,340 new cases of lung cancer (117,550 in men and 120,790 in women) with 127,070 deaths (67,160 in men and 59,910 in women) in the US are expected (1, 3, 4). The age-adjusted lung cancer death rate in the US was 34.8 per 100,000 in 2018 (5). Notably, the age-adjusted incidence and death rate for lung cancer was higher in men than in women (incidence: 75.2 *vs*. 52.3 and death: 46.7 *vs*. 31.9; per 100,000) (6). In the US, the 5-year relative survival rate for lung cancer is 18.6%, which is lower than any other major cancer site (7). The highest age-adjusted lung cancer death rate was reported to be 53.5 per 100,000 (8). The 5-year relative survival rate varies by lung cancer type and tumor stage (8). The rates for non-small cell lung cancer (NSCLC) are substantially higher than the rates for small cell lung cancer (SCLC) (overall 28% *vs*. 7%; localized 65% *vs*. 30%; regional 37% *vs*. 18%; distant 9% *vs*. 3%, respectively) (8). Florida ranks 22nd in the nation for lung cancer incidence with 56 per 100,000 compared with the national 57 per 100,000 (9). Moreover, 25% of all cases are detected at an early stage. Furthermore, Florida's 5-year relative survival rate is 26.5%, which is markedly greater than the nationwide survival rate of 25%, ranking 14th in the nation (9).

The burden of lung cancer incidence and mortality is reflective of the pervasiveness of its risk factors. Approximately 80% of lung cancer cases can be attributed to cigarette smoking (10). However, individuals that do not engage in tobacco use may still develop lung cancer. Risk factors that do not include tobacco usage include secondhand smoke exposure, radon exposure, and exposure to cancer-causing agents in the workplace, among others. Occupational exposures to known carcinogens, which can be classified as preventable causes, have been identified in different areas of work, particularly in firefighting (11, 12).

Firefighters are exposed to various toxic substances by the inhalation of particulate matter and gases. They are susceptible to significant amounts of carbon monoxide, benzene, sulfur dioxide, hydrogen cyanide, acrolein, aldehydes, hydrogen chloride, nitrogen dioxide, chlorinated hydrocarbons, trichloroethylene, toluene, dichlorofluoromethane, and soot. Health surveys have shown that firefighters have an increased prevalence of respiratory symptoms and reduced lung function due to exposure to toxic substances by inhalation of particulate matter and gases. Studies have shown that firefighters have an increased risk of cancer due to occupational prolonged bronchial epithelium exposure to inhaled particles and carcinogens (13, 14). There exists sufficient evidence showing that firefighters are exposed to a range of cancer-causing toxins on the job (15–18). As a result of such evidence, in the summer of 2022, the World Health Organization's International Agency for Research on Cancer (IARC) reclassified firefighting as a carcinogenic profession, and an IARC Group 1 designation was given (19, 20). Furthermore, firefighters are also at increased risk of dying from non-malignant respiratory diseases. While respiratory protection is widely available, the nature of their job makes proper protection difficult to ensure (21).

Despite these exposure risks, firefighters appear not to be at increased risk of lung cancer. Based on a systematic review of case–control studies, there was no increased lung cancer risk overall or by specific cell type among firefighters with and without smoking status adjustment (22). There were also no significant exposure–response relationships in terms of work duration. Other investigators have reported that some lung cancers that develop in never-smoking career firefighters should be considered potentially job-related (23).

There is no known study in the literature on the lung cancer survival experience of firefighters. Comparing the lung cancer characteristics and the survival of firefighters to non-firefighters and of different occupations will help fill this knowledge gap. The current study has two major contributions. First, we aim to assess specific patterns of lung cancer in firefighters including demographics such as smoking status at the time of cancer diagnosis, tumor characteristics such as histology, and cancer treatment. Second, we aim to evaluate cancer survival among a group of Florida male firefighters (career and volunteer), as cancer survivors of the first primary lung cancer compared with the Florida general population of non-firefighters with different occupational histories over a 33-year period (1981–2014). This study will provide the first population-based analysis of the epidemiological analysis of lung cancer survival among male firefighters in Florida.

2 Materials and methods

2.1 Study design

This study is part of a retrospective observational cohort from a broader data linkage project as part of the Firefighters Cancer Initiative (24, 25).

2.2 Data sources

This study uses the Florida Cancer Data System (FCDS) incidence cancer records (1981–2014) as the analytical cohort. This dataset linked data from three additional data sources: 1) firefighter certification records from the Florida State Fire Marshal's Office (FMO) (1972–2012); 2) LexisNexis©, a national dataset of legal, government, business, and high-tech information for identification of missing linkage variables (e.g., date of birth, social security number); and 3) Florida Office of Vital Statistics and the National Death Index (1981–2019) for computation of survival time from cancer diagnosis. The design and methods of the original data linkage with the first three sources of data have been published previously (24).

2.3 Study population

From the linked dataset, male patients in Florida with a diagnosis of primary or first multiple primaries of malignant lung and bronchus cancer (sequence numbers 0 and 1 from the cancer registry) from 1981 to 2014 were included. To be able to allow at least a 5-year follow-up for survival, the follow-up time for determining death due to cancer was extended further into the year 2019. Therefore, the timeframe for analysis includes 1981–2014 for cancer diagnosis but 1981–2019 for survival follow-up. The study flowchart specifically determining the analytical data for lung and bronchus is depicted in Figure 1. It is important to note that male patients diagnosed with incident cases of lung and bronchus cancer are based on the International Classification of Diseases for Oncology, third edition (ICD-O-3) primary site codes C34.0–C34.9 with the corresponding morphology codes for adenocarcinoma (8050, 8140–8147, 8211, 8250–8255, 8260, 8290–8333, 8470–8550, 8570–8574, 8576), squamous cell carcinoma (8052–8078, 8083–8183), large cell carcinoma (8012–8014, 8021, 8082), not otherwise specified (8046), and small cell carcinoma (8002, 8041–8045). Histology was further grouped into NSCLC (adenocarcinoma, squamous cell carcinoma, large cell carcinoma, not otherwise specified), and SCLC (small cell carcinoma) (26). The Surveillance, Epidemiology, and End Results (SEER) cause-specific standards based on the sequence number of lung and bronchus cancer were used to identify whether the death was due to lung and bronchus cancer (27, 28). For the purpose of this study, we will refer to lung and bronchus cancer as lung cancer.

2.4 Lung cancer-specific death as a primary clinical outcome

Survival from lung cancer is studied using a clinical outcome of lung-elapsed time in days from the date of lung cancer diagnosis to the date of death for patients who died due to lung cancer or the earliest of the dates of last contact or 31 December 2019 for alive patients. Other causes of death not related to lung cancer were

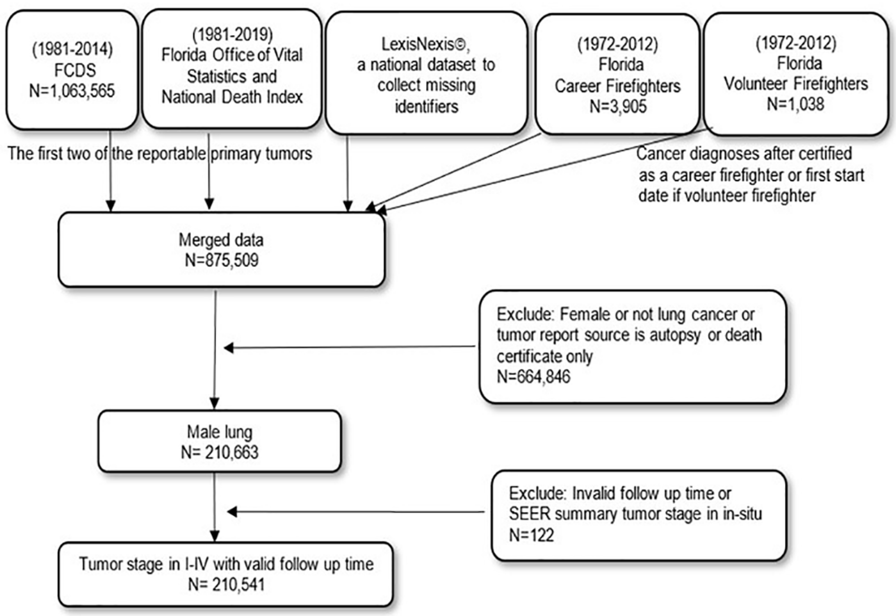

FIGURE 1
The data linkage flowchart from individual data sources to the final analytical dataset for male lung and bronchus cancer in Florida.

considered censored observations. Survival time in days was converted into months and years for easy interpretation. Calculation of survival time requires complete data on dates. Therefore, to be able to keep as many patients as possible in the analytical sample, missing days or months were imputed with day 15 (middle of a month) or the month of June (middle of a year) or July 1 if both day and month were missing.

2.5 Longest occupation held as a primary risk factor

Participants of the National Program of Cancer Registries (NPCR) collect information about the patients (29, 30). Text indicating usual occupation ("type of job patient engaged in for the greatest number of working years") and text indicating usual industry ("type of business or industry where patient worked in his or her usual occupation") were collected. *Via* medical record abstraction, occupation is the type of job the individual was engaged in for the longest time prior to a cancer diagnosis and might not necessarily be the highest-paid job or the most prestigious, but the one that accounted for the greatest number of working years. The central cancer registry then applies the U.S. Census occupation and industry coding system to translate reported text fields into coded variables. This allows for a systematic standard for analyzing occupation and industry data across time and geography.

In our study (Figure 1 and Table 1), the binary occupation variable (firefighter or non-firefighter) is considered the predictor variable in the regression models. Firefighters who were not identified *via* data linkage but with U.S. census-derived occupation codes in the cancer registry record as 3740, 3720, and 3750 were included as firefighters. For those who were only part of the linkage by both the Florida State FMO and LexisNexis©, they were further grouped based on whether they were career or volunteer firefighters. To be able to compare firefighters with several other occupations, non-firefighters were also regrouped as white collar (10–3540, 4700–5940), blue collar (6200–9000, 9030, 9040, 9050, 9120–9750), service (3540–3710, 3730, 3800–4650), and others/unknown (6010–6130, 9010, 9060, 9070, 9100, and unknown). Other occupations that were not grouped as broader occupational groups include but are not limited to farm workers, housewives, homemakers, students, retired, and disabled.

2.6 Covariables used for adjustment

Several variables used as additional covariables included the year of cancer diagnosis, age at cancer diagnosis (years), race, ethnicity, health insurance, neighborhood-level socioeconomic status (SES), cigarette use, SEER tumor stage, histology, treatment received for surgery, radiation therapy, and chemotherapy.

2.7 Statistical data analysis methods

The sources and codes for determining occupational groups were detailed (Table 1). The demographic and clinical characteristics of male lung cancer patients were summarized by frequencies and percentages for the entire sample and by occupation (firefighters, non-firefighters, and sub-occupational groups of non-firefighters) (Tables 2–5), and occupational group differences were compared using the chi-square test for independence. The Kaplan–Meier method for survival analysis was performed to calculate median survival time as well as the proportion of survival at 1, 3, 5, and 10 years (Figure 2 and Table 6). Log-rank tests were calculated to determine any differences among occupational groups and reported with Kaplan–Meier survival curves. Univariable and multivariable Cox proportional hazard regression models were fit for lung-cancer-specific death where occupation was the main effect in the models (Table 7, Supplementary Table 1). Multivariable models included additional

TABLE 1 The sources of firefighting occupation information for male lung and bronchus cancer patients (1981–2014).

Occupation		All patients	Source		Cancer registry census-derived occupation code[a]
			Linkage	FCDS	
	All patients	210,541	606	209,935	
Firefighters *n* = 761	Career	604	449	155	3740, 3720, 3750
	Volunteer	157	157	–	
Non-firefighters *n* = 209,780	White collar	8,818	–	8,818	10–3540, 4700–5940
	Blue collar	10,899	–	10,899	6200–9000, 9030, 9040, 9050, 9120–9750
	Service	1,880	–	1,880	3540–3710, 3730, 3800–4650
	Others/unknown[b]	188,183	–	188,183	6010–6130, 9010, 9060, 9070, 9100, and unknown

Source: Linkage includes Florida State Fire Marshal's Office (FMO) firefighters' employment and certification data (1972–2012) and LexisNexis©, a national dataset of legal, government, business, and high-tech information sources used to collect missing identifiers such as firefighter date of birth and social security number. FCDS is the Florida Cancer Data System incidence cancer records (1981–2014).

[a]Occupation code is item #330 from the North American Association of Central Cancer Registries (NAACCR) that uses industry code from the US census (https://www.census.gov/topics/employment/industry-occupation/guidance.html).

[b]Others/unknown includes farm workers, housewives/homemakers, students, retired, disabled, and unknown.

covariables to further adjust the differences that might happen due to year of cancer diagnosis, age at cancer diagnosis (years), race, ethnicity, health insurance, neighborhood SES, cigarette use, SEER tumor stage, histology, treatment received for surgery, radiation therapy, and chemotherapy. Unadjusted (HR) and adjusted hazard ratio (aHR) with a 95% confidence interval were calculated. Type I error was set to 5%, where a p-value less than 0.05 was considered statistically significant.

Data management and statistical analyses were conducted using the SAS Enterprise Guide v5.1 and SAS v9.4 for Windows (SAS Institute Inc. Cary, NC, USA). This study was approved by the Institutional Review Boards of the Florida Department of Health and the University of Miami.

3 Results

3.1 Analytical final study data consort

The study flowchart leading to the final analytical dataset is depicted in Figure 1. For our study, data were drawn from the aforementioned linkage, which included Florida firefighters with a

TABLE 2 Demographic characteristics of male lung and bronchus cancer patients by occupation: Florida Cancer Data System (1981–2014).

Characteristics	All patients		Occupation							
			Non-firefighters		Firefighters		Firefighters			
							Career		Volunteer	
	N	Col%	*N*	Col%	*N*	Col%	*N*	Col%	*N*	Col%
All patients	210,541	100.0	209,780	100.0	761	100.0	604	100.0	157	100.0
Year of cancer DX										
1981–1991	61,773	29.3	61,690	29.4	83	10.9	72	11.9	11	7.0
1992–2002	71,318	33.9	71,090	33.9	228	30.0	175	29.0	53	33.8
2003–2014	77,450	36.8	77,000	36.7	450	59.1	357	59.1	93	59.2
Age at diagnosis										
18–44	4,340	2.1	4,305	2.1	35	4.6	26	4.3	<10	–
45–54	19,575	9.3	19,473	9.3	102	13.4	77	12.7	25	15.9
55–64	50,111	23.8	49,887	23.8	224	29.4	182	30.1	42	26.8
65–74	76,965	36.6	76,703	36.6	262	34.4	201	33.3	61	38.9
75+	59,550	28.3	59,412	28.3	138	18.1	118	19.5	20	12.7
Race										
White	190,034	90.3	189,301	90.2	733	96.3	579	95.9	154	98.1
Black	18,334	8.7	18,308	8.7	26	3.4	24	4.0	<10	–
Others/unknown	2,173	1.0	2,171	1.0	<10	–	<10	–	<10	–
Ethnicity										
Non-Hispanic	193,120	91.7	192,370	91.7	750	98.6	596	98.7	154	98.1
Hispanic	14,840	7.0	14,831	7.1	<10	–	<10	–	<10	–
Unknown	2,581	1.2	2,579	1.2	<10	–	<10	–	<10	–
Insurance										
Uninsured	5,868	2.8	5,855	2.8	13	1.7	<10	–	<10	–
Insured	118,533	56.3	117,925	56.2	608	79.9	479	79.3	129	82.2
Unknown	86,140	40.9	86,000	41.0	140	18.4	116	19.2	24	15.3
SES—% poverty level										
20%–100% poverty	20,772	9.9	20,678	9.9	94	12.4	65	10.8	29	18.5
10%–<20% poverty	43,189	20.5	42,936	20.5	253	33.2	195	32.3	58	36.9

(Continued)

TABLE 2 Continued

Characteristics	All patients		Occupation							
			Non-firefighters		Firefighters		Firefighters			
							Career		Volunteer	
	N	Col%	N	Col%	N	Col%	N	Col%	N	Col%
5%–<10% poverty	37,743	17.9	37,540	17.9	203	26.7	167	27.6	36	22.9
0%–<5% poverty	15,621	7.4	15,551	7.4	70	9.2	61	10.1	9	5.7
Unknown	93,216	44.3	93,075	44.4	141	18.5	116	19.2	25	15.9
Cigarette use										
Never	14,934	7.1	14,887	7.1	47	6.2	40	6.6	<10	–
History	76,586	36.4	76,289	36.4	297	39.0	232	38.4	65	41.4
Current	79,104	37.6	78,809	37.6	295	38.8	239	39.6	56	35.7
Unknown	39,917	19.0	39,795	19.0	122	16.0	93	15.4	29	18.5

All p-values for comparing firefighters vs. non-firefighters and also for comparing career firefighters vs. volunteer firefighters vs. non-firefighters are less than 0.05, i.e., statistically significant, except the following: SES % poverty level and cigarette use were not statistically significant by occupation: firefighters vs. non-firefighters ($p > 0.05$). Cigarette use was not statistically significant by occupation: career firefighters vs. volunteer firefighters vs. non-firefighters ($p > 0.05$).
DX, diagnosis; SES, socioeconomic status reported as the percent poverty level of the patients' neighborhood at the time of cancer diagnosis; –, sample size less than 10 not reported due to confidentiality rules.

TABLE 3 Clinical characteristics of male lung and bronchus cancer patients by occupation: Florida Cancer Data System (1981–2014).

Characteristics	All patients		Occupation							
			Non-firefighters		Firefighters		Firefighters			
							Career		Volunteer	
	N	Col%	N	Col%	N	Col%	N	Col%	N	Col%
All patients	210,541	100.0	209,780	100.0	761	100.0	604	100.0	157	100.0
SEER stage										
Localized	34,078	16.2	33,959	16.2	119	15.6	99	16.4	20	12.7
Regional	49,236	23.4	49,011	23.4	225	29.6	182	30.1	43	27.4
Distant	98,403	46.7	98,045	46.7	358	47.0	274	45.4	84	53.5
Unknown	28,824	13.7	28,765	13.7	59	7.8	49	8.1	10	6.4
Surgery received										
No	163,357	77.6	162,803	77.6	554	72.8	430	71.2	124	79.0
Yes	45,996	21.8	45,793	21.8	203	26.7	171	28.3	32	20.4
Unknown	1,188	0.6	1,184	0.6	<10	–	<10	–	<10	–
Radiation received										
No	125,864	59.8	125,443	59.8	421	55.3	336	55.6	85	54.1
Yes	80,206	38.1	79,886	38.1	320	42.0	252	41.7	68	43.3
Unknown	4,471	2.1	4,451	2.1	20	2.6	16	2.6	<10	–
Chemotherapy received										
No	134,619	63.9	134,224	64.0	395	51.9	321	53.1	74	47.1

(Continued)

TABLE 3 Continued

Characteristics	All patients		Occupation							
			Non-firefighters		Firefighters		Firefighters			
							Career		Volunteer	
	N	Col%	*N*	Col%	*N*	Col%	*N*	Col%	*N*	Col%
Yes	70,387	33.4	70,051	33.4	336	44.2	263	43.5	73	46.5
Unknown	5,535	2.6	5,505	2.6	30	3.9	20	3.3	10	6.4
Histology										
NSCLC	148,986	70.8	148,413	70.7	573	75.3	455	75.3	118	75.2
SCLC	29,621	14.1	29,511	14.1	110	14.5	85	14.1	25	15.9
Unspecified/unknown	31,934	15.2	31,856	15.2	78	10.2	64	10.6	14	8.9
Vital status										
Alive/dead—other causes	42,209	20.0	42,013	20.0	196	25.8	157	26.0	39	24.8
Dead—primary diagnosis	168,332	80.0	167,767	80.0	565	74.2	447	74.0	118	75.2

All p-values for comparing firefighters vs. non-firefighters and also for comparing career firefighters vs. volunteer firefighters vs. non-firefighters are less than 0.05, i.e., statistically significant, except the following: Histology was not significant by occupation: firefighters vs. non-firefighters ($p > 0.05$); radiation and histology were not significant by occupation: career firefighters vs. volunteer firefighters vs. non-firefighters ($p > 0.05$). Vital status is based on incidence cases from 1981 to 2014 with passive follow-up up to 31 December 2019, where death was due to lung and bronchus cancer.
SEER, Surveillance, Epidemiology, and End Results (SEER) Program; NSCLC, non-small cell lung cancer; SCLC, small cell lung cancer; –, sample size less than 10 not reported due to confidentiality rules.

cancer diagnosis (*n* = 4,943; career: 3,905; volunteer: 1,038). The merged data yielded 875,509 patients with cancer. Patients were retained if lung cancer was the first two of the reportable primary tumors and excluded if the cancer was diagnosed after they were certified as a firefighter or after the start date as a volunteer. The patients were further excluded if they were female, if they had cancer in other cancer sites, or if their tumor report source was an autopsy or only a death certificate. This resulted in *n* = 210,663 male patients with lung cancer. Further exclusions were made on patients if they had invalid follow-up time or SEER summary tumor stage *in situ* (*n* = 122). The resulting final analytic dataset contained 210,541 male patients with lung cancer stages I–IV with valid follow-up time.

3.2 Patients' occupational groups

Occupation at the time of cancer diagnosis is considered a primary predictor variable that was grouped broadly first (firefighters and non-firefighters) and then with detailed occupational groups within firefighters (career, volunteer) and non-firefighters (white collar, blue collar, services, others/unknown) (Table 1). Out of the 210,541 male lung cancer patients, there were 99.6% non-firefighters and 0.4% (*n* = 761) firefighters [career: 604 (79.4%); volunteer: 157 (20.6%)]. Categorization of the longest-held job was not possible for nearly 90% of patients due to missing information or because they fell into the following categories: farm worker, housewife, homemaker, student, retired, and disabled.

3.3 Demographic and clinical characteristics of the patients by occupational groups

The demographic (Table 2) and clinical (Table 3) characteristics of the patients by firefighters and non-firefighters, along with broad occupational groups, were summarized by descriptive statistics.

Overall, the majority of the patients who were diagnosed during 2003–2014 (36.8%) were between 65 and 74 years old when diagnosed (36.6%); were white (90.3%) and non-Hispanic (91.7%); were insured (56.3%); were living in a neighborhood with a poverty level between 10% and 20% (20.5%); were ever smokers (74%; 37.6% current and 36.4% past smoker); had distant SEER stage (46.7%); had not received surgery (77.6%), radiation (59.8%), or chemotherapy (63.9%); had non-small cell lung cancer (NSCLC, 70.8%); and died due to lung cancer (80.0%).

Compared with non-firefighters (non-FF), a higher proportion of firefighters (FF) who were diagnosed between 2003 and 2014 (FF: 59.1% *vs.* non-FF: 36.7%) were diagnosed before the age of 65 years (47.4% *vs.* 35.2%), were insured (79.9% *vs.* 56.2%), were living in a neighborhood with poverty level ≥20% (12.4% *vs.* 9.9%), and were ever smokers, i.e., current and history (77.8% *vs.* 74%; current: 38.8% *vs.* 37.6% and history: 39% *vs.* 36.4%). However, there were fewer black (3.4% *vs.* 8.7%) and Hispanic (1.2% vs. 7.1%) patients among firefighters than among non-firefighters.

Compared with non-firefighters, a higher proportion of firefighters were diagnosed with regional (FF: 29.6% *vs.* non-FF: 23.4%) and distant (47% *vs.* 46.7%) tumor stage; received surgery (26.7% *vs.* 21.8%), radiation therapy (42% *vs.* 38.1%), or chemotherapy (44.2% *vs.* 33.4%); and diagnosed with NSCLC (75.3% *vs.* 70.7%). However, there were fewer lung cancer-related deaths (74.2% *vs.* 80%) among firefighters than among non-firefighters during the study period.

To be able to compare firefighters with different occupational groups, non-firefighters were further grouped into white collar, blue collar, service, and others/unknown. The demographic (Table 4) and clinical (Table 5) characteristics of the patients belonging to the firefighters group and the different occupational sectors were summarized by descriptive statistics.

TABLE 4 Demographics characteristics of male lung and bronchus cancer patients by detailed occupation status: Florida Cancer Data System (1981–2014).

Characteristics	All patients		Occupation													
			Non-firefighters		Firefighters		Non-firefighters							
							White collar		Blue collar		Service		Others/ unknown	
	N	Col%	*N*	Col%	*N*	Col%	*N*	Col%	*N*	Col%	*N*	Col%	*N*	Col%
All patients	210,541	100.0	209,780	100.0	761	100.0	8,818	100.0	10,899	100.0	1,880	100.0	188,183	100.0
Year of cancer DX														
1981–1991	61,773	29.3	61,690	29.4	83	10.9	82	0.9	81	0.7	<10	–	61,518	32.7
1992–2002	71,318	33.9	71,090	33.9	228	30.0	2,020	22.9	2,440	22.4	329	17.5	66,301	35.2
2003–2014	77,450	36.8	77,000	36.7	450	59.1	6,716	76.2	8,378	76.9	1,542	82.0	60,364	32.1
Age at diagnosis														
18–44	4,340	2.1	4,305	2.1	35	4.6	191	2.2	286	2.6	68	3.6	3,760	2.0
45–54	19,575	9.3	19,473	9.3	102	13.4	762	8.6	1,556	14.3	279	14.8	16,876	9.0
55–64	50,111	23.8	49,887	23.8	224	29.4	2,295	26.0	3,144	28.8	566	30.1	43,882	23.3
65–74	76,965	36.6	76,703	36.6	262	34.4	2,964	33.6	3,614	33.2	603	32.1	69,522	36.9
75+	59,550	28.3	59,412	28.3	138	18.1	2,606	29.6	2,299	21.1	364	19.4	54,143	28.8
Race														
White	190,034	90.3	189,301	90.2	733	96.3	8,367	94.9	9,804	90.0	1,613	85.8	169,517	90.1
Black	18,334	8.7	18,308	8.7	26	3.4	335	3.8	979	9.0	232	12.3	16,762	8.9
Others/unknown	2,173	1.0	2,171	1.0	<10	–	116	1.3	116	1.1	35	1.9	1,904	1.0
Ethnicity														
Non-Hispanic	193,120	91.7	192,370	91.7	750	98.6	8,294	94.1	10,204	93.6	1,727	91.9	172,145	91.5
Hispanic	14,840	7.0	14,831	7.1	<10	–	486	5.5	660	6.1	147	7.8	13,538	7.2
Unknown	2,581	1.2	2,579	1.2	<10	–	38	0.4	35	0.3	<10	–	2,500	1.3
Insurance														
Uninsured	5,868	2.8	5,855	2.8	13	1.7	268	3.0	691	6.3	124	6.6	4,772	2.5
Insured	118,533	56.3	117,925	56.2	608	79.9	8,129	92.2	9,750	89.5	1,683	89.5	98,363	52.3
Unknown	86,140	40.9	86,000	41.0	140	18.4	421	4.8	458	4.2	73	3.9	85,048	45.2
SES—% poverty level														
20%–100% poverty	20,772	9.9	20,678	9.9	94	12.4	962	10.9	2,236	20.5	357	19.0	17,123	9.1
10%–<20% poverty	43,189	20.5	42,936	20.5	253	33.2	2,564	29.1	3,973	36.5	619	32.9	35,780	19.0
5%–<10% poverty	37,743	17.9	37,540	17.9	203	26.7	2,866	32.5	2,819	25.9	534	28.4	31,321	16.6

(Continued)

TABLE 4 Continued

Characteristics	All patients		Occupation											
			Non-firefighters		Firefighters		Non-firefighters							
							White collar		Blue collar		Service		Others/ unknown	
	N	Col%	N	Col%	N	Col%	N	Col%	N	Col%	N	Col%	N	Col%
0%–<5% poverty	15,621	7.4	15,551	7.4	70	9.2	1,567	17.8	987	9.1	176	9.4	12,821	6.8
Unknown	93,216	44.3	93,075	44.4	141	18.5	859	9.7	884	8.1	194	10.3	91,138	48.4
Cigarette use														
Never	14,934	7.1	14,887	7.1	47	6.2	681	7.7	495	4.5	103	5.5	13,608	7.2
History	76,586	36.4	76,289	36.4	297	39.0	2,578	29.2	4,496	41.3	753	40.1	68,462	36.4
Current	79,104	37.6	78,809	37.6	295	38.8	4,121	46.7	4,120	37.8	698	37.1	69,870	37.1
Unknown	39,917	19.0	39,795	19.0	122	16.0	1,438	16.3	1,788	16.4	326	17.3	36,243	19.3

All p-values for comparing across occupation groups are less than 0.05, i.e., statistically significant.
DX, diagnosis; SES: socioeconomic status reported as the poverty level (percent) of the patients' neighborhood at the time of cancer diagnosis; –, sample size less than 10 not reported due to confidentiality rules.

TABLE 5 Clinical characteristics of male lung and bronchus cancer patients by detailed occupation status: Florida Cancer Data System (1981–2014).

Characteristics	All patients		Occupation											
			Non-firefighters		Firefighters		Non-firefighters							
							White collar		Blue collar		Service		Others/ unknown	
	N	Col %	N	Col %	N	Col%	N	Col %	N	Col %	N	Col %	N	Col %
All patients	210,541	100.0	209,780	100.0	761	100.0	8,818	100.0	10,899	100.0	1,880	100.0	188,183	100.0
SEER stage														
Localized	34,078	16.2	33,959	16.2	119	15.6	1,531	17.4	1,567	14.4	284	15.1	30,577	16.2
Regional	49,236	23.4	49,011	23.4	225	29.6	2,277	25.8	2,841	26.1	493	26.2	43,400	23.1
Distant	98,403	46.7	98,045	46.7	358	47.0	4,506	51.1	5,864	53.8	1,012	53.8	86,663	46.1
Unknown	28,824	13.7	28,765	13.7	59	7.8	504	5.7	627	5.8	91	4.8	27,543	14.6
Surgery received														
No	163,357	77.6	162,803	77.6	554	72.8	6,395	72.5	8,557	78.5	1,451	77.2	146,400	77.8
Yes	45,996	21.8	45,793	21.8	203	26.7	2,372	26.9	2,276	20.9	416	22.1	40,729	21.6
Unknown	1,188	0.6	1,184	0.6	<10	–	51	0.6	66	0.6	13	0.7	1,054	0.6
Radiation received														
No	125,864	59.8	125,443	59.8	421	55.3	4,906	55.6	5,758	52.8	961	51.1	113,818	60.5
Yes	80,206	38.1	79,886	38.1	320	42.0	3,679	41.7	4,821	44.2	854	45.4	70,532	37.5
Unknown	4,471	2.1	4,451	2.1	20	2.6	233	2.6	320	2.9	65	3.5	3,833	2.0
Chemotherapy received														
No	134,619	63.9	134,224	64.0	395	51.9	3,965	45.0	4,871	44.7	763	40.6	124,625	66.2
Yes	70,387	33.4	70,051	33.4	336	44.2	4,539	51.5	5,606	51.4	1,045	55.6	58,861	31.3

(Continued)

TABLE 5 Continued

Characteristics	All patients		Occupation											
			Non-firefighters		Firefighters		Non-firefighters							
							White collar		Blue collar		Service		Others/ unknown	
	N	Col %	*N*	Col %	*N*	Col%	*N*	Col %	*N*	Col %	*N*	Col %	*N*	Col %
Unknown	5,535	2.6	5,505	2.6	30	3.9	314	3.6	422	3.9	72	3.8	4,697	2.5
Histology														
NSCLC	148,986	70.8	148,413	70.7	573	75.3	7,072	80.2	8,385	76.9	1,475	78.5	131,481	69.9
SCLC	29,621	14.1	29,511	14.1	110	14.5	1,014	11.5	1,574	14.4	268	14.3	26,655	14.2
Unspecified/unknown	31,934	15.2	31,856	15.2	78	10.2	732	8.3	940	8.6	137	7.3	30,047	16.0
Vital status														
Alive/dead—other causes	42,209	20.0	42,013	20.0	196	25.8	2,017	22.9	2,214	20.3	401	21.3	37,381	19.9
Dead—primary diagnosis	168,332	80.0	167,767	80.0	565	74.2	6,801	77.1	8,685	79.7	1,479	78.7	150,802	80.1

All p-values for comparing across occupation groups are less than 0.05, i.e., statistically significant. Vital status is based on incidence cases from 1981 to 2014 with passive follow-up up to 31 December 2019, where death was due to lung and bronchus cancer.
SEER, Surveillance, Epidemiology, and End Results (SEER) Program; NSCLC, non-small cell lung cancer; SCLC, small cell lung cancer; –, sample size less than 10 not reported due to confidentiality rules.

3.4 Cause-specific overall survival estimates

Surviving proportions at 1, 3, 5, and 10 years and the median survival of cause-specific overall survival by detailed occupational groups are summarized in Table 6. For all patients, the 1-, 3-, 5-, and 10-year survival rates were 44.6%, 27.4%, 23.8%, and 20.9%, respectively. Firefighters have a higher proportion of survival than non-firefighters at 1, 3, 5, and 10 years (FF: 54.4%, 34.8%, 29.7%, 26.3% *vs*. 44.6%, 27.4%, 23.8%, 20.9%, respectively). Career firefighters have a higher proportion of survival than non-firefighters at 1, 3, 5, and 10 years (career: 55%, 35.8%, 30.3% *vs*. volunteer: 52.9%, 31.2%, 27.4%, respectively) but slightly lower at 10 years (26.2% *vs*. 26.6%).

The Kaplan–Meier survival curves are depicted in Figure 2 based on the different levels of occupational groups. There were statistically significant differences between firefighters and non-firefighters (log-rank *p*-value < 0.001; Figure 2A), among non-firefighters and career firefighters and volunteer firefighters (*p*-value < 0.001; Figure 2B), and among firefighters and the blue collar, white collar, service, and others/unknown occupational groups (*p*-value < 0.001; Figure 2C). However, there were no significant differences between career firefighters and volunteer firefighters (*p*-value = 0.6909; Figure 2D).

3.5 Cause-specific overall survival regression models

The univariable and multivariable Cox proportional hazard regression models for cause-specific overall survival for male lung cancer patients with occupational groups as the main effect are summarized in Table 7 and Supplementary Table 1.

In the univariable models, compared with non-firefighters, firefighters have significantly higher cause-specific survival (HR = 0.82; 95% CI: 0.75–0.89); $p < 0.001$). Both career firefighters (0.81; 0.74–0.89; $p < 0.001$) and volunteer firefighters (0.84; 0.70–1.01; $p = 0.063$) have higher cause-specific survival, but only career firefighters were significantly different from non-firefighters. There were no significant differences in cause-specific survival between career and volunteer firefighters (0.96; 0.79–1.18; p=0.718). Compared with firefighters, the blue collar (1.17; 1.08–1.28; $p < 0.001$), service (1.13; 1.02–1.24; $p = 0.016$), and others/unknown (1.23; 1.14-1.34; $p < 0.001$) occupational groups had significantly lower cause-specific survival, but the difference for white collar workers failed to reach statistical significance (1.06; 0.98–1.16; $p = 0.166$).

Two multivariable models (Table 7, Supplementary Table 1) with two different occupational groups as the main effect variable were fit to account for the differences that might occur due to year of cancer diagnosis, age at cancer diagnosis (years), race, ethnicity, health insurance, neighborhood SES, cigarette use, SEER tumor stage, histology, treatment received as surgery, radiation therapy, and chemotherapy.

In multivariable model 1 (Table 7, Supplementary Table 1), the main effect was the three-level occupational variable (non-firefighters, career firefighters, volunteer firefighters). Compared with non-firefighters, firefighters have significantly higher cause-specific survival (adjusted HR = 0.84; 95% CI: 0.77–0.91; $p < 0.001$). Both career firefighters (0.86; 0.79–0.95; $p = 0.002$) and volunteer firefighters (0.76; 0.63–0.91; $p = 0.003$) have significantly higher

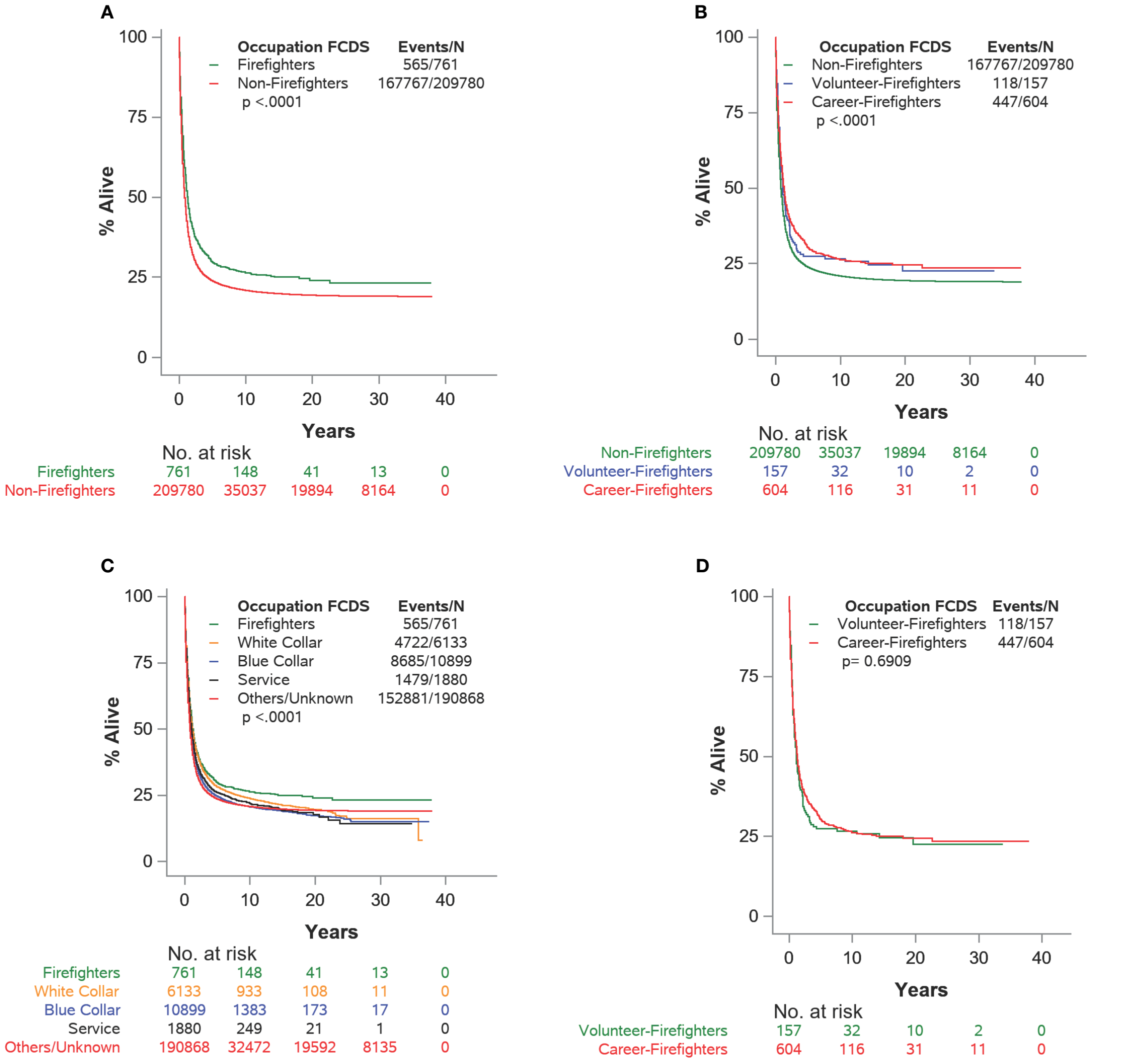

FIGURE 2
(A–D) Kaplan–Meier survival plots for cause-specific survival for male lung and bronchus cancer patients by detailed occupation status: Florida Cancer Data System (1981–2014).

TABLE 6 Survival proportions and median cause-specific survival time for male lung and bronchus cancer patients by detailed occupation status: Florida Cancer Data System (1981–2014).

Occupation	*N*	Survival proportions (%) with 95% confidence interval				Median survival (years)
		1 year	3 years	5 years	10 years	
All patients	210,541	44.6 (44.4–44.8)	27.4 (27.3–27.6)	23.8 (23.6–24.0)	20.9 (20.7–21.0)	0.1 (–)
All firefighters	761	54.5 (50.9–58.0)	34.8 (31.5–38.2)	29.7 (26.5–33.0)	26.3 (23.2–29.5)	0.1 (0.1–0.1)
Career	604	55.0 (50.9–58.8)	35.8 (32.0–39.6)	30.3 (26.7–34.0)	26.2 (22.7–29.8)	0.1 (0.1–0.1)
Volunteer	157	52.9 (44.8–60.3)	31.2 (24.1–38.5)	27.4 (20.7–34.5)	26.6 (20.0–33.7)	0.1 (0.1–0.1)
All non-firefighters	209,780	44.6 (44.4–44.8)	27.4 (27.2–27.6)	23.8 (23.6–24.0)	20.9 (20.7–21.0)	0.1 (0.1–0.1)
White collar	8,818	52.7 (51.6–53.7)	33.3 (32.3–34.3)	28.0 (27.1–28.9)	23.5 (22.6–24.4)	0.1 (0.1–0.1)
Blue collar	10,899	47.9 (47.0–48.8)	28.9 (28.1–29.8)	24.6 (23.8–25.4)	20.6 (19.9–21.4)	0.1 (0.1–0.1)
Service	1,880	50.1 (47.8–52.3)	30.8 (28.7–32.9)	26.0 (24.1–28.0)	21.9 (20.0–23.8)	0.1 (0.1–0.1)
Others/unknown	188,183	44.0 (43.7–44.2)	27.0 (26.8–27.2)	23.5 (23.3–23.7)	20.7 (20.5–20.9)	0.1 (NE–NE)

Survival estimates are based on incidence cases from 1981 to 2014 with passive follow-up up to 31 December 2019 for determining vital status.
NE, not estimable.

TABLE 7 Cox proportional hazard regression models for cause-specific survival for male lung and bronchus cancer patients by detailed occupation status: Florida Cancer Data System (1981–2014).

Occupation	Univariate models		Multivariable models			
			Model 1		Model 2	
	HR (95% CI)	*p*-value	aHR (95% CI)	*p*-value	aHR (95% CI)	*p*-value
Non-firefighters	1.00 (reference)		1.00 (reference)		–	
Firefighters	0.82 (0.75, 0.89)	<0.001	0.84 (0.77, 0.91)	<0.001	–	
Non-firefighters	1.00 (reference)		1.00 (reference)		–	
Volunteer firefighters	0.84 (0.70, 1.01)	0.063	0.76 (0.63, 0.91)	0.003	–	
Career firefighters	0.81 (0.74, 0.89)	<0.001	0.86 (0.79, 0.95)	0.002	–	
Volunteer firefighters	1.00 (reference)		1.00 (reference)		–	
Career firefighters	0.96 (0.79, 1.18)	0.718	1.14 (0.93, 1.39)	0.213	–	
Firefighters	1.00 (reference)		1.00 (reference)		–	
Non-firefighters	1.22 (1.13, 1.33)	<0.001	1.20 (1.10, 1.30)	<0.001	–	
Firefighters	1.00 (reference)		–		1.00 (reference)	
White collar	1.06 (0.98, 1.16)	0.166	–		1.11 (1.02, 1.21)	0.016
Blue collar	1.17 (1.08, 1.28)	<0.001	–		1.15 (1.05, 1.25)	0.002
Service	1.13 (1.02, 1.24)	0.016	–		1.13 (1.03, 1.25)	0.012
Others/unknown	1.23 (1.14, 1.34)	<0.001	–		1.21 (1.12, 1.32)	<0.001

The multivariable models are additionally adjusted with variables such as year of cancer diagnosis, age at diagnosis, race, ethnicity, insurance, SES, cigarette use, SEER stage, histology, surgery as a treatment received, radiation therapy received, and chemotherapy received. Estimates for the variables used for adjustment were provided in Supplementary Table 1.
–, not applicable; HR, hazard ratio; aHR, adjusted hazard ratio; 95% CI, 95% confidence interval.

cause-specific survival than non-firefighters. Career firefighters have lower cause-specific survival than volunteer firefighters (1.14; 0.93–1.39; p = 0.213), but the result was not statistically significant.

In multivariable model 2 (Table 4, Supplementary Table 1), the main effect was the five-level occupational variable (firefighters, white collar, blue collar, service, others/unknown). Compared with firefighters, the white collar (adjusted HR = 1.11; 95% CI: 1.02–1.21; p = 0.016), blue collar (1.15; 1.05–1.25; p = 0.002), service (1.13; 1.03–1.25; p = 0.012), and others/unknown (1.21; 1.12–1.32; p < 0.001) occupational groups have significantly lower cause-specific survival.

4 Discussion

Our results suggest that Florida male firefighters had significantly higher cause-specific survival than non-firefighters. When compared with different non-firefighting sub-occupational groups, firefighters had significantly higher cause-specific survival. Among firefighters, although career firefighters had lower cause-specific survival than volunteer firefighters, this difference was not statistically significant.

Smoking is the leading cause of lung cancer and makes cancer treatments work less effectively (31). In the study, among patients with known smoking status, 74% were ever smokers (37.6% current and 36.4% past smokers). Although never and current smokers were slightly higher among firefighters, past smokers accounted for 39% of firefighters and 36.4% of non-firefighters. In Florida, a restrictive tobacco use hiring policy for firefighters took effect in 1989 and prohibited the hiring of firefighters that used tobacco products. Since 1989, all newly certified firefighters have been required to submit a sworn affidavit attesting that they have been a non-user of tobacco or tobacco products for at least the 12-month period immediately preceding the application (32, 33). The 1989 Florida law targeting firefighters is not an outright ban on the use of tobacco products once hired but rather focuses on tobacco use practices in the 12 months prior to the signing of the affidavit. There were no restrictions placed on currently serving firefighters, and once hired, firefighters that signed the affidavit were not bound to remain smoke-free. One possible explanation for the better survival among firefighters for a leading tobacco-associated cancer may be due to the implementation of a restrictive State of Florida tobacco use hiring policy in 1989, which led to a workplace climate that discouraged smoking.

Our analysis of data from 2013, 2015, 2016, and 2017 of the Florida Behavioral Risk Factor Surveillance System (BRFSS) includes the most recent years that featured the collection of industry and occupation data. The pooled BRFSS cigarette smoking rate for all Florida workers except firefighters is 16.7% (95% CI: 15.8–17.5). The estimated smoking rate in Florida firefighters is markedly lower (1.8%; 95% CI: 0.0–3.5) than all the other workers and for blue collar (25.4%; 23.1–27.8), service (19.6%; 17.7–21.6), and white collar (12.2%; 11.3–13.1). As reported in 2010–2011, the smoking prevalence rate had dropped to 9.8% in a non-random sample of 20 US fire departments (34). From 1992 to 2019, data from the Tobacco Use Supplement to the Current Population Survey (TUS-CPS) found that the smoking prevalence among firefighters declined (annual percentage change: −5.0%; 95% CI: −7.7% to −2.3%) (35). For broader US worker groups for the years 2014–2016, compared with nationally representative estimates of smoking rates, Florida firefighters had rates of smoking that were lower than for all worker occupational groups including workers employed in the life, physical, and social sciences (5.6%; 95% CI: 3.5–7.7) (36).

Improved survival for firefighters might be due to a healthy worker effect or possibly superior treatment compliance (37). Given that many firefighters are also cross-trained as EMTs/paramedics, they may have a level of medical knowledge that may favorably impact treatment engagement and better navigation to complex cancer care. In our study, we found that compared with non-firefighters, a higher proportion of firefighters received surgery (26.7% *vs*. 21.8%), radiation therapy (42% *vs*. 38.1%), and chemotherapy (44.2% *vs*. 33.4%).

4.1 Limitations and strengths

This is an observational retrospective cohort study from a statewide cancer registry that is enhanced with firefighter employee and certification data together with a national dataset of legal, government, business, and high-tech information sources and the state office of vital statistics and national death index.

This is the first population-based epidemiological study of cause-specific overall survival of those with a lung and bronchus cancer diagnosis comparing firefighters with non-firefighters and subgroups of non-firefighters in Florida. Our study is unique since we also included volunteer firefighters in our sample to be able to compare the differences between career and volunteer firefighters' lung cancer cause-specific survival.

This study is not without limitations. It is based on cancer records from a population-based cancer registry with passive follow-up for survival. Although the sample size was increased by including information from cancer registry occupation records, some of the other/unknown occupation categories might include retired firefighters who did not report their firefighting status. Information on occupation in cancer registries is also incomplete and inaccurate, which may have limited our ability to make comparisons with other broad worker groups (38).

Information on occupational carcinogenic exposure or the number of years in a firefighting career was not available when the analysis focused only on firefighters. The completeness of smoking status suffered from missing values. When the smoking status was known, the length of smoking quit time for past smokers was not known. Therefore, this limits our understanding of smoking cessation in lung cancer survival among firefighters compared with all the other occupational groups.

The results from this unique enhanced dataset should be interpreted cautiously due to limitations of individual exposure data both for firefighters and non-firefighters. Confounding factors such as time to any first cancer treatment and its duration and health behaviors that may influence cancer survival were not adjusted in all analyses, mostly due to limitation or non-existence of the related variables.

Female firefighters were not included in the analysis due to their small numbers. Therefore, further epidemiological research for lung cancer survival among female firefighters is warranted.

4.2 Conclusion

Firefighting is a hazardous occupation and firefighters face unique occupational exposures. Lung cancer survival was significantly higher among firefighters compared with non-firefighters. Compared with non-firefighters, firefighters had a statistically significant 16% (career 14%, volunteer 24%) lower risk of lung cancer cause-specific mortality. However, there were no significant survival differences between career and volunteer firefighters, even if career firefighters had a 14% higher risk of lung cancer cause-specific mortality than volunteer firefighters. Improved survival for firefighters might be due to a healthy worker effect to start with before cancer diagnosis or lower smoking rates among them and possibly superior treatment compliance and engagement with better navigation to complex cancer care. Given that many firefighters are also cross-trained as EMTs/paramedics, they may have a level of medical knowledge that may favorably impact treatment engagement and better navigation to complex cancer care. Additional epidemiological studies are needed to determine and link occupational and environmental exposure data to cancer cohort studies including female firefighters.

Data availability statement

The datasets presented in this article are not readily available because the datasets collected and analyzed for this study are not publicly available due to strict confidentiality agreements between the University of Miami and the Florida Department of Health, Florida Cancer Data System, Florida Fire Marshalls Office. This study was approved by the Institutional Review Boards of the Florida Department of Health and the University of Miami. A waiver of informed consent was granted given that cancer data is a reportable event for the purposes of cancer surveillance. Requests to access the datasets should be directed to the Florida Department of Health, health@flhealth.gov.

Ethics statement

This study was approved by the Institutional Review Boards of the Florida Department of Health and the University of Miami. A waiver of informed consent was granted given that cancer data is a reportable event for the purposes of cancer surveillance. Written informed consent for participation was not required for this study in accordance with national legislation and institutional requirements.

Author contributions

Study concept and design: TK-S, PP, and DL. Acquisition, analysis, and interpretation of data: TK-S, PP, WZ, and DH. Drafting of the manuscript: TK-S. Critical revision of the manuscript for important intellectual content: all authors. Statistical analysis: TK-S, WZ, DH, and PP. Obtained funding: EK. Administrative, technical, or material support: TK-S, DL, AC-M, and EK. Study supervision: TK-S, PP, and DL. All authors participated in the revision of the manuscript for important intellectual content and consented to the publication of this submitted manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Funding

This study received funding/support from the State of Florida Appropriation #2382A (Principal Investigator: EK) (https://umiamihealth.org/sylvester-comprehensive-cancer-center/research/firefighter-cancerinitiative). The research reported in this publication was also supported by the National Cancer Institute of the National Institutes of Health under Award Number P30CA240139. There was no funder/sponsor role in the design and conduct of the study; the collection, management, analysis, and interpretation of the data; the preparation, review, or approval of the manuscript; and the decision to submit the manuscript for publication. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The data used in this report were collected by The Florida State Fire Marshal's Office and the Florida Cancer Data System (FCDS), the statewide cancer registry funded by the Florida Department of Health (DOH), and the Centers for Disease Control and Prevention's National Program of Cancer Registries (CDC-NPCR). The views expressed herein are solely those of the author(s) and do not necessarily reflect those of the DOH or CDC-NPCR.

Acknowledgments

The authors wish to acknowledge the State of Florida and their firefighter colleagues for their continued support and ongoing contributions to the Firefighter Cancer Initiative at Sylvester Comprehensive Cancer Center. The authors also wish to acknowledge Dr. Feng Miao and Mrs. Laura A. McClure for their contributions to the earlier versions of study discussions and Dr. Kemi Ogunsina for providing insights on occupational grouping.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fonc.2023.1155650/full#supplementary-material

SUPPLEMENTARY TABLE 1
Cox Proportional Hazard Regression Models for Cause-Specific Survival for Male Lung and Bronchus Cancer Patients by Detailed Occupation Status: Florida Cancer Data System (1981-2014).

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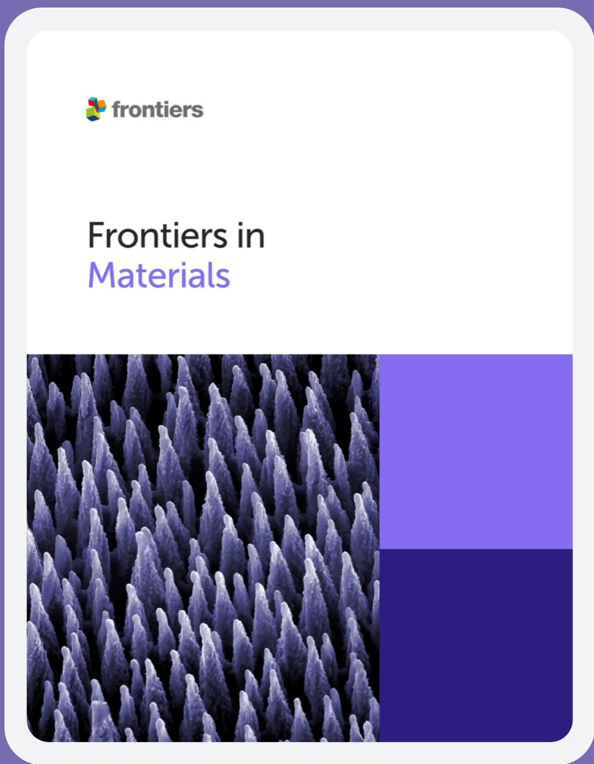

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