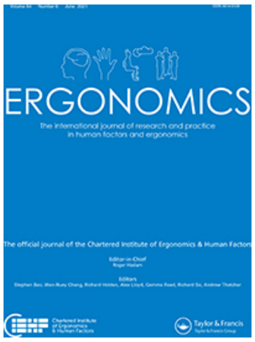

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Effects of firefighting hood design, laundering and doffing on smoke protection, heat stress and wearability

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ABSTRACT

Firefighter hoods must provide protection from elevated temperatures and products of combustion (e.g. particulate) while simultaneously being wearable (comfortable and not interfering with firefighting activities). The purpose of this study was to quantify the impact of (1) hood design (traditional knit hood vs particulate-blocking hood), (2) repeated laundering, and (3) hood removal method (traditional vs overhead doffing) on (a) protection from soot contamination on the neck, (b) heat stress and (c) wearability measures. Using a fireground exposure simulator, 24 firefighters performed firefighting activities in realistic smoke and heat conditions using a new knit hood, new particulate-blocking hood and laundered particulate-blocking hood. Overall, soot contamination levels measured from neck skin were lower when wearing the laundered particulate-blocking hoods compared to new knit hoods, and when using the overhead hood removal process. No significant differences in skin temperature, core temperature, heart rate or wearability measures were found between the hood conditions.

Practitioner Summary: The addition of a particulate-blocking layer to firefighters' traditional two-ply hood was found to reduce the PAH contamination reaching the neck but did not affect heat stress measurements or thermal perceptions. Modifying the process for hood removal resulted in a larger reduction in neck skin contamination than design modification.

Abbreviations: ANOVA: analysis of variance; B: new particulate-blocking hood and PPE (PPE configuration); FES: fireground exposure simulator; GI: gastrointestinal; K: new knit hood and PPE (PPE configuration); L: laundered particulate-blocking hood and PPE (PPE configuration); LOD: limit of detection; MLE: maximum likelihood estimation; NFPA: National fire protection association; PAH: polycyclic aromatic hydrocarbon; PPE: personal protective equipment; SCBA: self-contained breathing apparatus; THL: total heat loss; TPP: thermal protective performance

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Personal protective equipment; firefighting; chemical exposures; heat stress; wearability

1. Introduction

The firefighting personal protective equipment (PPE) ensemble is designed to protect firefighters from an array of hazards. A particularly challenging ergonomics problem exists in the area of the neck and head where thermal protection is required to protect the thin dermal layers and vasculature, while still allowing necessary and critical movement of the head. Furthermore, the skin on the head and neck are important regions of heat exchange. While additional layers in the hood may be useful for burn protection, these same layers may interfere with heat dissipation, thus exacerbating heat stress. Further, the skin in the neck region is relatively thin and provides an area where transdermal absorption of products of combustion may be important. Thus, the balance between protection (from fireground particulate and elevated environmental temperatures) and wearability (e.g. thermal perceptions, comfort, breathability, impact on the range of motion) must be understood before new hood designs/interventions are widely accepted by the fire service.

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The firefighting hood has often been considered the protective ensemble component offering the firefighter the lowest level of protection (Avsec 2019). The hood is traditionally comprised of one to three layers (though two is the most common) of knit material. Traditional designs attempt to strike a balance between thermal protection to mitigate skin burn risk and breathability to promote heat loss. The risks associated with heat strain due to firefighting activities is a constant concern for firefighters and has been investigated by several research groups (Barr, Gregson, and Reilly 2010; Burgess et al. 2012; Colburn et al. 2011; Horn et al. 2013; Hostler et al. 2016; McQuerry, Barker, and DenHartog 2018; Romet and Frim 1987; Sothmann et al. 1992; Walker et al. 2015). These studies demonstrate that firefighting activities can result in elevated body temperature, and in some cases rapid changes in core temperature. Increasing the layers used in the design of the hood to reduce burn risk may further increase the heat strain experienced during emergency operations. Recognising the need to balance protection and thermal burden, PPE standards such as NFPA 1971 include tests such as thermal protective performance (TPP) and total heat loss (THL) (National Fire Protection Association 2018). However, these standards include no requirement for human testing.

Concerns about further encapsulating firefighters and exacerbating heat stress influenced early design and adoption. Thus, TPP is not as robust as in other components of the firefighting PPE ensemble. As a consequence of the lower TPP, dermal protection from moisture and particulates is also lower for the hood than other components of PPE. Firefighters have become increasingly aware of the elevated cancer risk associated with firefighting (LeMasters et al. 2006; Pinkerton et al. 2020), and the firefighting hood has received particular attention due to the relatively lower protection provided. Structural fires that involve household furnishings produce a wide variety of contamination (Austin et al. 2001a, 2001b; Jankovic et al. 1991) that include polycyclic aromatic hydrocarbons (PAHs) and benzene. Dermal exposure is an important exposure pathway for firefighters (Fent et al. 2014; Keir et al. 2017; Stec et al. 2018), as studies have reported PAH contamination in the neck region after firefighting activities (Baxter et al. 2014; Fent et al. 2014, 2017; Fernando et al. 2016; Stec et al. 2018; Wingfors et al. 2018) and shown that PAHs can be readily absorbed through the skin (VanRooij, Bodelier-Bade, and Jongeneelen 1993, VanRooij et al. 1993, VanRooij et al. 1994; Brzeźnicki, Jakubowski, and Czerski 1997).

As the fire service has become more aware of the fireground risks, different control measures have been proposed to reduce contamination reaching the neck. PPE manufacturers have developed new designs for fire hoods aimed specifically to block particle penetration (particulate-blocking hoods). Fire departments have become more consistent in laundering their hoods after fireground and fire training exposures. Firefighters are being trained to take care of removing their hoods to avoid cross-contamination. However, the effectiveness of these measures in reducing exposure has not been well characterised. Tools for characterising weak points in the hood relative to contamination risk have been developed (Hill and Hanley 2015; Maness and Ormond 2017). The visual evidence from such demonstrations can be striking and has drawn the interest of fire departments and fire service organisations striving to reduce exposure to their members. However, these results have been largely qualitative to date. In a recent study using stationary mannequins in a high challenge exposure chamber, Mayer et al. (2020) found particulate-blocking hoods (designed to reduce particle penetration through hoods by 90%) reduced the amount of PAHs reaching the mannequins' necks by 34% compared to traditional knit hoods. However, particulate-blocking hoods did not eliminate the presence of PAHs in the neck region of mannequins. Additionally, contamination protection factors were reduced after 40 laundering cycles for both styles of hoods. The relative contribution of particle permeation through the hood fabrics versus penetration around interfaces between the hood and facepiece or hood and coat is unknown.

Importantly, even if a particulate-blocking hood could eliminate contamination from reaching the skin during the firefight, contaminants on the outside of hoods may also transfer to the skin during doffing (when hoods are removed). While qualitative evidence has been presented regarding the possibility of transfer of soot and particulate matter during PPE removal (Illinois Fire Service Institute 2018), no quantitative evidence of this phenomenon has been published. Thus, the contamination transfer may be a function not only of the ergonomics of the PPE design but of the removal process.

The purpose of this study was to quantify the impact of (1) hood design (traditional knit hood vs particulate-blocking hood), (2) repeated laundering (new hood vs exposed to smoke and laundered 40 times), and (3) hood removal method (traditional doffing vs overhead doffing) on (a) protection from contamination depositing on the neck, (b) physiological responses related to heat stress and c) firefighters' self-reported perceptions of wearability.

2. Methods

2.1. Participants

Currently active firefighters ($n = 24$) were recruited from fire departments in 14 states across the United States. The firefighters (23 male, 1 female) were (mean ± standard deviation) 39.29 ± 8.93 years old, weighed 90.95 ± 11.91 kg, and were 1.81 ± 0.11 m tall. To participate, firefighters must have completed a medical evaluation consistent with National Fire Protection Association (NFPA) 1582 in the past 12 months. Firefighters who had up to date training and were familiar with live-fire policies and procedures were recruited. Participants provided informed written consent indicating that they understood and voluntarily accepted the risks and benefits of participation. This study was approved by the University of Illinois Institutional Review Board.

2.2. Study design

Firefighters (n = 24) conducted identical simulated firefighting activities while wearing three different PPE conditions with the primary differences being hood type and laundering condition. The bunker gear was identical in material and design for all firefighters and was produced specifically for this study. Outer shell (Kevlar®/Nomex®), moisture barrier (ePTFE film) and thermal liner (Kevlar®/Lenzing FR® face cloth with Nomex® batting) were selected as among the most common options on the market at the time of production. Protective performance characteristics of this PPE ensemble have been reported previously (Horn, Kerber, Andrews, et al. 2020). Total heat loss (THL) of the new composite material was 254 W/m^2 and thermal protective performance (TPP) was 44.0 cal/cm^2, both of which exceed NFPA 1971 requirements (National Fire Protection Association 2018; 205 W/m^2 and 35.0 cal/cm^2, respectively). Hoods were commercially available NFPA 1971 (National Fire Protection Association 2018) compliant two-layer, knit Nomex® ('Knit') hoods and a three-layer hood with outer layers of knit Nomex® and a non-bonded polymer barrier as a third interstitial layer ('Blocking'). All participants wore hoods from the same manufacturer, make and model within each category After each trial, all hoods were laundered following NFPA 1851 guidelines (National Fire Protection Association 2020).

Firefighters participated in groups of three while wearing one of three different PPE configurations:

- **New Knit Hood and PPE (K)** – PPE and hoods were new for the first trial and laundered between each wear, with a maximum of 3 launderings prior to completion of the study
- **New Particulate-Blocking Hood and PPE (B)** – PPE and hoods were new for the first trial and laundered between each wear, with a maximum of 3 launderings prior to completion of the study
- **Laundered Particulate-Blocking Hood and PPE (L)** – Particulate-blocking hoods and bunker gear were exposed to smoke and laundered following NFPA 1851 guidelines (National Fire Protection Association 2020) 40 times (protocols reported elsewhere (Horn, Kerber, Andrews, et al. 2020)) prior to human subject trials. Laundered particle-blocking hoods were from the same manufacturer and were identical make and model as the new particle-blocking hoods.

Each firefighter participated in three different trials wearing each PPE configuration with the order of trials counterbalanced. Participants were enrolled only if they wore bunker gear within the defined range of sizes that were available for this study. Hoods are commercially available as 'one-size fits all' and were not specifically sized for individual fit.

Twelve firefighters (Group A) completed the testing protocol and then they removed their own PPE following commonly used methods ('Traditional'). In each case, firefighters pulled their hoods down around their necks after removing their helmets to allow access to their facepiece straps. The hood remained around their necks until it was pulled up and off over the head. The second group of twelve firefighters (Group B) received assistance from the research group in removing their fire hood immediately after the helmet was removed following each trial. For this group, the hood was pulled up over the head ('Overhead' method) instead of down around the neck, in a manner that was expected to reduce the possibility of the outer layer of the hood contacting the neck skin. There were no statistically significant differences in demographics between the participants in each doffing group.

All simulated firefighting activity was conducted in a fireground exposure simulator (FES) which was developed from a steel intermodal shipping container, divided into three compartments. The middle section served as a combustion chamber generated by burning a commercially available sofa, and fire effluent ducted into two exposure chambers with 3 firefighters in each end (Horn, Kerber, Lattz, et al. 2020). The timing of ignition, ventilation and suppression were patterned after a fireground study (Horn et al. 2018).

Three separate stations were set up within each chamber along the wall connected to the combustion chamber. Activities included stair climbing (three steps up and down outside of smoke exposure), crawling to simulate search as the chamber began to fill with smoke, hose advance (after which the couch fire was suppressed by research staff members) and overhaul as the chamber doors were opened to allow smoke to passively vent to the environment. All activities were conducted on two-minute work/rest cycles (e.g. two-minute stair climb, two-minute rest, two-minute search, etc.). Ignition of the sofa and ventilation of the chambers was timed to create conditions similar to what is experienced during residential firefighting operations.

2.3. Study protocol

Following recruitment, participants completed informed consent and all required paperwork. Firefighters ingested a core temperature capsule 6–12 h prior to data collection. Upon arrival on each day, the pre-firefighting physiological measurements and chemical exposure samples were collected prior to the initiation of the live-fire evaluation as reported below. Firefighters donned the assigned hood in a laboratory setting and filled out a questionnaire regarding wearability perception of the hood. All firefighters cleaned their neck skin with cleansing wipes prior to firefighting to remove any trace PAH contamination.

The firefighter participants were then deployed to don the provided firefighting PPE, which included a personal air sampling device mounted on the outside of the coat at chest height to determine the magnitude of PAH combustion byproducts in the atmosphere. OVS-XAD-7 tubes, operated at 1 L/min, were analysed separately for particulate and vapor-phase PAHs using NIOSH Method 5506 (National Institute for Occupational Safety and Health 2013).

Physiological measurements were recorded immediately prior to entering the FES prop. Firefighters donned SCBA and went on air 15 s prior to beginning the stair activity and remained on air until they were clear of any smoke. Immediately after coming off supplied air, physiological measurements were repeated. After returning to the laboratory, participants doffed their assigned PPE and sat comfortably in a chair where post-activity skin wipes were completed followed by a post-fire wearability survey. Fire hoods from select participants were collected and samples removed for subsequent extraction of embedded PAHs.

2.4. Measures

2.4.1. Assessment of firefighter neck PAH protection

The impact of hood design on protection from PAH deposition was assessed in two parts. Wipe samples were collected from firefighters' neck skin to assess differences in the deposition. Additionally, material samples were removed from a select group of particulate-blocking and knit hoods to assess PAH contamination that was embedded in the outer and inner layers.

2.4.1.1. Dermal wipe samples. Dermal wipe samples were collected from the necks of firefighters and analysed for polycyclic aromatic hydrocarbons (PAHs). Similar to our previous study (Fent et al. 2017), investigators used cloth wipes (TexWipes) and corn oil to collect neck wipe samples. Because PAHs are lipid-soluble, the corn oil facilitated their collection. Collected wipes were placed into opaque containers and stored in coolers for transport to the analytical lab. The wipe samples were analysed for PAHs using NIOSH Method 5506 (National Institute for Occupational Safety and Health 2013).

2.4.1.2. Hood sampling. PAH contamination embedded in hood material was evaluated by cutting three square pieces of fabric (100 cm^2) from both the inside and outside layer of three particulate-blocking hoods and one knit hood. The new particulate-blocking and knit hoods were worn by participants during a single trial, and hoods were not laundered prior to sample collection. Samples were not collected from laundered particulate-blocking hoods. Investigators changed nitrile gloves and cleaned the scissors with isopropyl alcohol after collecting each sample, as previously described in Mayer et al. (2019). Each sample was placed into a new sealed plastic bag and shipped in opaque containers to the analytical laboratory to be analysed for PAHs using NIOSH methods 5506, modified for bulk material analysis (National Institute for Occupational Safety and Health 2013).

2.4.2. Assessment of firefighter physiological responses

Heart rate was monitored using a physiological status monitoring system integrated into the firefighter's base layer (Globe Manufacturing; Pittsfield, NH). The shirt system integrates a BioHarness 3 (Zephyr Technologies; Annapolis, MD) heart rate strap and software system to report heart rate at one Hertz with a resolution of 1 bpm. Firefighters donned their shirts prior to firefighting data collection and wore them throughout the scenario until release from rehabilitation. Heart rate was monitored throughout the protocol and recovery, though data are only reported prior to beginning the stair climb, immediately after ending the simulated firefighting activity, and the peak value achieved during simulated firefighting activities.

Core body temperatures were continuously measured throughout all data collection sessions. Participants swallowed a small disposable gastrointestinal (GI) temperature sensor capsule (VitalSense Temperature Capsule, Phillips Respironics; Murrysville, PA) 6–12 h prior to activity. A monitor (MiniMitter Vital Sense, Phillips Respironics; Bend, OR) was clipped to the firefighters' belts before and after firefighting and carried in their bunker coat after donning their PPE. This unit communicated with and recorded data from the GI temperature capsule with a $\pm 0.1\,^{\circ}$C accuracy. Core temperature was recorded every 60 s throughout the trial protocol and recovery, though data are only reported as the average value prior to the stair climb, the value immediately after ending the simulated firefighting activity, and the peak value achieved, which typically occurred a within 5–10 min after completion of the simulated activity.

Skin temperature was assessed using a hand-held probe (Dermatemp 1001, Exergen Corp., Watertown, MA) placed posterior to the masseteric tuberosity of the jaw beneath the ear. Skin temperature was measured with a $0.1\,^{\circ}$C resolution from the neck skin at two discrete time points, just before entering the structure (where the hood is pulled up) and immediately after leaving (once the hood was doffed).

2.4.3. Wearability perception surveys

Before and immediately following completion of the firefighting activities, participants were asked to complete a survey of their perceptions from each hood related to Overall Comfort, Thermal Feeling, and Moistness of the hood (on a scale of 1–7; 1 = very negative, 7 = very positive) as well as the degree to which the wearer sensed the following hood qualities): Tight, Hearing Reduction, Heavy/Thick, Stiff, Hot, Nonbreathable, Damp, Noisy, Movement Restriction, Nonstretchy (scale 1–5; 1 = Totally, 5 = None. The survey was previously developed specifically to assess textile comfort (Hollies et al. 1979).

2.5. Statistical analysis

2.5.1. Assessment of firefighter neck PAH protection

Descriptive statistics are presented as median, mean, and range for the total PAH concentration ($\mu g/m^2$) measured from neck skin, stratifying by hood type (New-Knit; New-Blocking; Laundered-Blocking) and doffing method (traditional, overhead). Total PAHs were calculated by summing the 15 quantified PAHs. Non-detection rates were also provided. In carrying out the analytic statistics, a maximum likelihood estimation (MLE) method (Helsel 2006) for a large proportion of left-censored data (measurements below the LOD (<LOD)) was performed via the SAS procedure LIFEREG. Due to the known variation between trials conducted with the FES (Horn, Kerber, Lattz, et al. 2020), measurements of ambient air concentrations of total PAHs ($\mu g/m^3$) were included as a potential confounder in all models. Finally, in order to estimate the relative contributions of each of these parameters (hood design, doffing method, ambient air concentration) on the variability of neck skin concentrations of total PAHs, a multiple regression model incorporating a substitution method (Hornung and Reed 1990) was carried out, in which the non-detects were replaced with the minimal LOD of the 15 PAHs divided by two.

For material samples taken from hoods, descriptive statistics were presented as median, mean, range and non-detection rates, stratified by type of hood (New-Knit; New-Blocking) and location of sample (Inner, Outer). Total PAHs were calculated by summing the 15 quantified PAHs. Zero was used for non-detectable levels in the summation for hood results. A Wilcoxon signed-rank test was used to determine whether the change in outer and inner layer concentrations was significantly different from zero in each type of hood. A Wilcoxon rank-sum test was utilised to determine differences between inner layer particulate-blocking hoods and inner layer knit hoods.

These analyses were two-sided at the 0.05 significance level and conducted in SAS version 9.4 (SAS Institute, Cary, NC).

2.5.2. Assessment of firefighter physiological responses

Descriptive statistics are presented as mean and standard deviation for firefighters' heart rate, neck skin and core temperatures, stratified by hood type and timepoint. An analysis of variance (ANOVA) framework was employed to study changes in physiological variables over time (pre, post-activity) and between three hood conditions (New-Knit; New-Blocking; Laundered-Blocking). Peak heart rate and core temperatures were

Table 1. Total PAH levels (μg/m^2) and non-detectable samples (%) collected from neck skin under different hood designs stratified by doffing method.

Hood design	Doffing method	*n*	Non-detects[A] (%)	Median	Mean	Range	Hood design *p*-value[B]
New-Knit (K)	Traditional	12	8.3	123.0	224.0	<LOD–621	0.020
	Overhead	12	25.0	30.5	38.9	<LOD–157	
New-Blocking (B)	Traditional	12	25.0	101.0	196.0	<LOD–740	
	Overhead	12	58.3	<LOD	21.0	<LOD–71.2	
Laundered-Blocking (L)	Traditional	12	16.7	64.6	64.4	<LOD–179	
	Overhead	12	50.0	6.3	23.4	<LOD–104	

[A]LOD ranges for each PAH included in this analysis: acenaphthene = 0.5–3.0 μg, anthracene = 0.5 μg, benzo(a)anthracene = 0.5 μg, benzo(a)pyrene = 0.5 μg, benzo(b)fluoranthene = 0.5 μg, benzo(g,h,i)perylene = 0.5 μg, benzo(k)fluoranthene = 0.5 μg, chrysene = 0.5-0.8 μg, dibenzo(a,h)anthracene = 1.0–2.0 μg, fluoranthene = 0.5–0.6 μg, fluorene = 0.5 μg, indeno(1,2,3-cd)pyrene = 1.0 μg, naphthalene = 0.7–1.0 μg, phenanthrene = 0.5 μg, pyrene = 1.0 μg.
[B]Adjusting for doffing method and total air concentrations of PAHs.
Comparison result:.
New-Knit (greater log values) versus New-Blocking: *p*-value = 0.971.
New-Knit (greater log values) versus Laundered-Blocking: *p*-value = 0.009 (significantly different).
New-Blocking (greater log values) versus Laundered-Blocking: *p*-value = 0.016 (significantly different).

analysed using one-way ANOVA to study the impact of three hood conditions (New-Knit; New-Blocking; Laundered-Blocking). Variables were checked for normal distribution using Shapiro-Wilk tests. A relatively small number of distributions were found not to be Gaussian, but differences between means and median values were typically less than 5%. Therefore, means and standard deviations are reported for results. Confirmatory analyses were conducted on log-transformed data for the few non-normal data sets, which in all cases resulted in the same determination of statistical significance.

Unfortunately, due to some 'lost' core temperature capsules, invalid measurements (likely due to the sensor not having passed through the stomach prior to data collection), and interruptions of communications with sensors during data collection, there was some loss in the core temperature data set.

2.5.3. Wearability perception surveys

Descriptive statistics were presented as the mean and standard deviation for each of the survey elements, stratified by hood type and timepoint. Data were analysed using 3×2 ANOVA to study the impact of three hood conditions (New-Knit; New-Blocking; Laundered-Blocking) and time (pre, post-activity). Post hoc analysis was conducted using Tukey HSD Tests. All tests corresponding to ANOVA were two-sided at the 0.05 significance level and conducted in SPSS version 23 (IBM, Armonk, NY).

3. Results

3.1. Neck PAH protection

Table 1 presents comparisons of the neck skin total PAHs for three hood designs stratified by doffing method and controlling for air concentrations of total PAHs. A significant difference in neck skin total PAHs was found among the hood designs and laundering conditions studied ($p = 0.020$). Neck skin exposure levels from firefighters wearing laundered particulate-blocking hoods (overall median 32.6 μg/m^2; mean 43.9 μg/m^2; 33.3% non-detects) were significantly lower than firefighters wearing a new particulate-blocking hood ($p = 0.016$; overall median 108 μg/m^2, mean 43.8 μg/m^2; 41.7% non-detects) and new knit hoods ($p = 0.009$; overall median 132 μg/m^2, mean 62.3 μg/m^2; 16.7% non-detects) after controlling for doffing method and ambient air concentrations. Firefighters who utilized the overhead doffing method had lower magnitudes (and a higher number of non-detects) of neck skin total PAHs than those using the traditional doffing method (median of 15.7 μg/m^2 vs 93.7 μg/m^2, mean of 27.8 μg/m^2 vs 161.5 μg/m^2) irrespective of the hood design. Table 1 and Figure 1 illustrate the interrelationship between the hood designs and doffing methods on neck skin exposure PAH levels.

Importantly, the multiple regression model conducted to estimate the impact of ambient air concentrations, hood design, and doffing method on the measured neck skin total PAHs found relative contributions of 1.96, 5.05 and 27.6%, respectively.

We compared PAH levels on the inner and outer layer hood material of new particulate-blocking and knit hoods worn by participants during a single trial (Table 2). Outer layer median PAH levels were similar in the knit hoods (median 1,800 ng/sample) and particulate-blocking hoods (median 1500 ng/sample). However, PAH levels on the inner layer of particulate-blocking hood samples were all below the LOD, while the levels on the inner layer of knit hoods were all above the LOD (median 230 ng/sample). Overall, the PAH level difference between the inner and outer layers for all hood samples was significant ($p = 0.001$). When stratified by hood type, the inner layer particulate-blocking hood levels were notably different from the outer layer levels

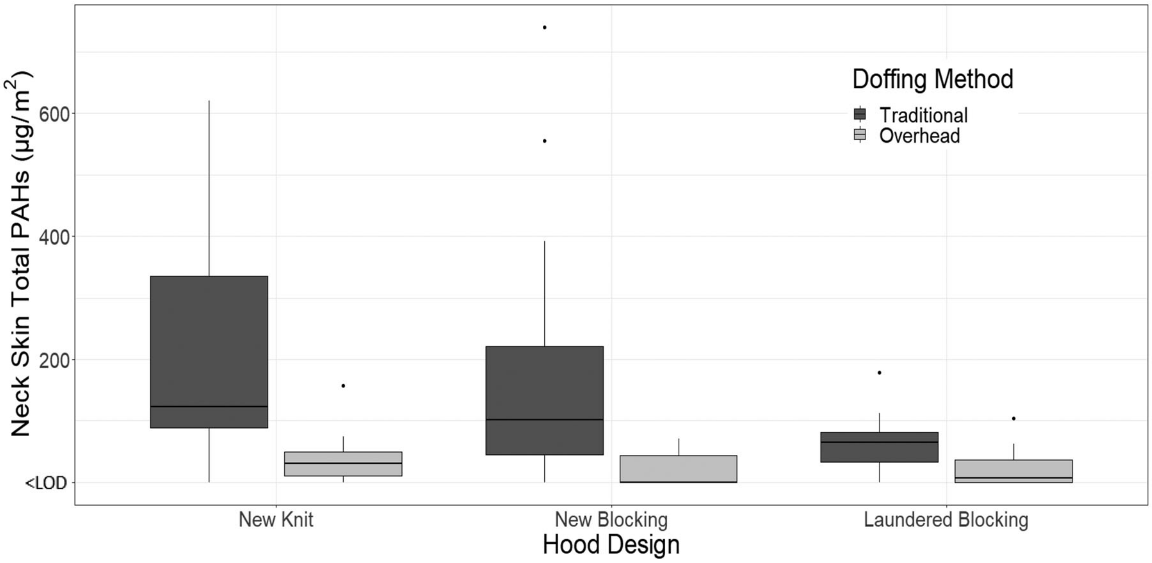

Figure 1. Boxplots of Total PAH levels (μg/m^2) collected from neck skin under different hood designs stratified by doffing method. The box represents the interquartile range (IQR), the horizontal line in each box represents the median, the upper whisker represents the upper fence 1.5 IQR above the 75th percentile, the lower whisker represents the lower fence 1.5 IQR below the 25th percentile, and the dots represent potential outliers.

Table 2. Comparison of inner/outer shell PAH levels (ng/100 cm^2 sample) in samples collected from one new knit hood and three new particulate-blocking worn for the same fire trial.

Hood design	Location	*n*	Non-detects[A](%)	Median	Mean	Range	Location *p*-value
New-Knit (K)	Inner	3	0	230	490	100–1140	0.2500
	Outer	3	0	1800	1440	560–1970	
New-Blocking (B)	Inner	9	100	<LOD[A]	<LOD	<LOD	0.0039
	Outer	9	0	1500	2600	570–7710	

[A]LOD ranges for each PAH included in this analysis: acenaphthene = 100–400 ng, anthracene = 100–400 ng, benzo(a)anthracene = 100–400 ng, benzo(a)pyrene = 100–400 ng, benzo(b)fluoranthene = 100–400 ng, benzo(g,h,i)perylene = 200–600 ng, benzo(k)fluoranthene = 100–400 ng, chrysene = 100–500 ng, dibenzo(a,h)anthracene = 200–700 ng, fluoranthene = 100–400 ng, fluorene = 100–400 ng, indeno(1,2,3-cd)pyrene = 100–500 ng, naphthalene = 100–400 ng, phenanthrene = 100–400 ng, pyrene = 300–900 ng.

($p = 0.0039$), whereas the difference was not significant for the knit hood. When we compared the PAH levels from the inner layer of the particulate-blocking hoods to the inner layer from the knit hoods, the difference was statistically significant ($p = 0.040$).

3.2. Heart rate, neck skin temperature, core temperature

Heart rate, neck skin temperature and core temperature increased during the firefighting trial (Table 3). While a significant time effect was detected for pre- to post-activity measures ($p < 0.001$ for all measures), there were no significant differences among the hoods tested or interaction effects. In all three hood conditions, firefighters' heart rates peaked at 171–173 bpm, which is approximately 95% of age-predicted maximal heart rate ([220-age]) for these participants. Neck skin temperature increased approximately 1.6° C during the firefighting activity while core temperatures peak values were approximately 0.8° C higher than baseline.

3.3. Wearability perception surveys

Following firefighting activity, there were multivariate main effects of time ($p < 0.001$, $F = 8.96$) and hood type ($p = 0.001$, $F = 2.42$) in firefighter's perception of the three hoods (Table 4). The participants reported significantly more negative perceptions of overall comfort, thermal feeling, and moistness after firefighting activity compared to pre-activity levels. Additionally, sensations of the hoods as heavy or thick, hot, damp, providing movement reduction, and being non-stretchy increased from pre- to post-activity. In general, the particulate-blocking hoods were perceived less favourably with respect to hearing reduction, and

Table 3. Physiological responses for simulated firefighting trial in different hood designs and PPE laundering conditions.

	Heart rate (bpm)			Neck skin temp. (°C)		Core temp. (°C)		
Hood design[A]	Pre-FF	Post-FF	Peak	Pre-FF	Post-FF	Pre-FF	Post-FF	Peak
New-Knit (K)	91 (21)	154 (21)	171 (18)	32.6 (1.5)	34.0 (2.2)	37.2 (0.3)	37.8 (0.3)	38.0 (0.4)
New-Blocking (B)	89 (17)	157 (22)	172 (15)	32.9 (1.1)	34.2 (1.7)	37.2 (0.3)	37.8 (0.4)	38.0 (0.4)
Laundered-Blocking (L)	88 (17)	159 (29)	173 (19)	32.8 (1.5)	34.6 (2.1)	37.1 (0.3)	37.7 (0.3)	37.9 (0.3)

Note. There were no statistically significant differences between the various hood conditions.
[A]$n = 24$ except Heart Rate [L ($n = 23$)] and Core Temperature [K ($n = 22$), B ($n = 23$), L ($n = 21$)].

being heavy/thick, stiff, noisy, and nonstretchy. Some of these parameters (comfort level, and being heavy/thick, stiff, and nonstretchy) were perceived even less favourably compared to the knit hoods when the particulate-blocking hood had been laundered. However, there were no detectable differences between new and laundered particulate-blocking hoods.

4. Discussion

4.1. Neck skin PAH protection

The key findings from this study are that the firefighters' hood doffing method had the most dramatic effect on total PAH neck contamination, as the overhead hood removal process resulted in dramatically lower levels of contamination compared to the traditional hood doffing technique. Additionally, total PAH levels measured from neck skin were significantly lower when wearing the laundered particulate-blocking hood compared to wearing the new knit and new particulate-blocking hoods after adjusting for the doffing method and ambient air concentrations.

4.1.1. Impact of hood doffing technique

This study design provides the first opportunity to quantify the impact of an administrative control intervention designed to reduce cross-contamination from the outside of the firefighting PPE to the skin. For each of the hood designs studied, the mean contamination level measured from neck skin dropped when using the overhead doffing method compared to the traditional doffing method by 83% (224–38.9 μg/m^2) for New-Knit hoods, 89% (196–21.0 μg/m^2) for New-Blocking hoods, and 64% (64.4–23.4 μg/m^2) for Laundered-Blocking hoods. The number of firefighters who had no detectable contamination on their necks rose from 19% (7 of 36) when using the traditional method to 44% when using the overhead method (17 of 36). When comparing only the particulate-blocking layer hoods (including both new and laundered), the percentage without detectable contamination increased from 25% to 54% (6 of 24 to 13 of 24), suggesting an important additive effect of the two control measures. It is important to note, that teaching new hood doffing techniques can be implemented with any type of hood and resulted in as much as a 90% reduction in neck skin contamination in this study.

4.1.2. Impact of hood design

Total PAH level on firefighters' neck skin was impacted by hood design, but in a manner that showed important interactions with the hood doffing technique. Overall, we found no statistically significant difference in neck skin contamination after wearing the New-Knit and New-Blocking hood, while both were significantly higher than the Laundered-Blocking hood. This result was surprising given the differences in inner layer contamination from the hoods (230 ng/100 cm^2 sample for New-Knit hoods vs non-detect for New-Blocking hoods). The lack of contamination embedded in the inner layer of the New-Blocking hood suggests that neck skin contamination may be due to other pathways, such as leakage through the interface between hood and facepiece or hood and coat or cross-contamination during doffing.

The particulate-blocking hood utilised in this study was designed to reduce the penetration of contaminants to below 90% (National Fire Protection Association 2018). The post-use analysis did not detect any contaminants embedded in the inner layer of nine different samples from particulate-blocking hoods, indicating that the membranes in the hoods were successful in blocking contamination from permeating through the hoods during the simulated firefight. However, in the 48 measurements collected after firefighters wore a particulate-blocking hood (New-Blocking and Laundered-Blocking combined), 30 (63%) had detectable levels of contamination on the neck. In the group of 24 firefighters that implemented the overhead doffing with particulate-blocking hoods, 11 (46%) had detectable levels of contamination on the neck. This finding suggests that an alternate exposure pathway exists, likely between the hood to facepiece or hood to coat interface. Participants in this study were checked to ensure a proper overlap at both interface locations during the donning process,

Table 4. Firefighters reported perceptions of hoods before firefighting (Pre) and after activity (Post).

Measure		Timing	Hood			Statistics			
			New-Knit (K)	New-Blocking (B)	Laundered-Blocking (L)	Hood	Hood, Post Hoc	Time	Interaction
Scale (1–7)	Comfort	Pre	6.0 (1.0)	5.8 (1.0)	5.3 (1.0)	$p = 0.006$; $F = 5.47$	KvL $p = 0.005$	$p = 0.011$; $F = 6.89$	
		Post	6.0 (0.8)	5.5 (1.3)	4.7 (1.6)				
	Thermal	Pre	4.8 (1.2)	4.6 (1.2)	4.5 (1.4)			$p < 0.001$; $F = 29.6$	
		Post	3.9 (1.2)	3.7 (1.3)	3.6 (1.3)				
	Moistness	Pre	7.0 (0.2)	6.9 (0.3)	6.9 (0.3)			$p < 0.001$; $F = 100.7$	
		Post	5.4 (1.1)	5.5 (1.2)	5.3 (1.4)				
	Tight	Pre	3.2 (1.0)	4.0 (0.9)	3.8 (1.0)				$p = 0.014$; $F = 4.59$
		Post	3.7 (1.0)	3.6 (1.0)	3.5 (1.2)				
Scale (1–5)	Hearing reduction	Pre	4.4 (0.7)	4.0 (0.9)	3.8 (1.0)	$p = 0.007$; $F = 5.28$	KvL $p = 0.026$ KvB $p = 0.012$		
		Post	4.5 (0.7)	3.8 (0.8)	3.7 (1.0)				
	Heavy/thick	Pre	3.8 (0.9)	3.1 (0.8)	2.6 (0.8)	$p < 0.001$; $F = 11.8$	KvL $p < 0.001$ KvB $p = 0.042$	$p = 0.002$; $F = 10.4$	
		Post	4.0 (0.9)	3.4 (0.9)	2.9 (0.8)				
	Stiff	Pre	4.5 (0.7)	4.0 (0.9)	3.4 (1.0)	$p < 0.001$; $F = 9.80$	KvL $p < 0.001$		
		Post	4.5 (0.9)	4.0 (0.9)	3.6 (1.1)				
	Hot	Pre	4.2 (0.8)	4.0 (0.7)	4.0 (0.9)			$p < 0.001$; $F = 20.8$	
		Post	3.7 (0.7)	3.4 (0.8)	3.5 (0.9)				
	Non-breathable	Pre	3.9 (0.7)	3.7 (0.8)	3.3 (0.8)				
		Post	3.5 (0.9)	3.6 (0.8)	3.2 (1.0)				
	Damp	Pre	4.9 (0.4)	4.8 (0.9)	4.8 (0.5)			$p < 0.001$; $F = 55.2$	
		Post	3.8 (1.0)	3.8 (0.9)	4.0 (0.9)				
	Noisy	Pre	5.0 (0.0)	3.7 (1.0)	3.5 (1.1)	$p < 0.001$; $F = 13.8$	KvL $p < 0.001$ KvB $p < 0.001$		$p = 0.040$; $F = 3.38$
		Post	4.8 (0.7)	3.9 (1.2)	4.0 (1.2)				
	Movement reduction	Pre	4.7 (0.6)	4.5 (0.7)	4.5 (0.7)			$p = 0.002$; $F = 10.5$	
		Post	4.5 (0.8)	4.0 (1.0)	4.1 (1.1)				
	Nonstretchy	Pre	4.3 (0.8)	4.2 (0.7)	3.7 (1.2)	$p = 0.005$; $F = 5.82$	KvL $p = 0.004$	$p = 0.024$; $F = 5.32$	
		Post	4.3 (0.8)	3.8 (1.0)	3.3 (1.3)				

resulting in an overlap that is likely better than what might be experienced in a chaotic fireground situation. However, the seal between each element is not expected to provide an impermeable barrier.

4.1.3. Impact of laundering

Anecdotally, a concern had been raised in the fire service that repeated laundering of hoods could possibly increase the risk of contamination reaching the firefighter due to stretching out of the material that creates a seal with the facepiece or possible physical damage to the barrier layer that might allow penetration. Somewhat unexpectedly, this study found that wearing Laundered-Blocking hoods resulted in significantly lower neck skin contamination than the New-Blocking hoods. However, this result appeared to depend on the hood doffing method. Samples collected after doffing with the overhead method had similar non-detection rates (50%, 58%) and mean values (23.4 $\mu g/m^2$, 21.0 $\mu g/m^2$). However, non-detection rates were lower (17%, 25%) and mean values (64.4 $\mu g/m^2$, 196 $\mu g/m^2$) were more disparate for the samples collected after firefighters used the traditional doffing method. Indeed, the differences between Laundered-Blocking and New-Blocking hoods were significant when the traditional doffing method was used, while the differences were not significant when the overhead doffing method was employed. Repeated laundering may impact the surface coatings and increase the surface area of the fibres in the hoods, which allowed the PAH contamination to embed deeper within the material of the hoods that were laundered 40 times compared to the new hoods. Thus, when the new hoods were pulled down around the neck (with traditional doffing), more PAH contamination was likely transferred to the skin than with laundered hoods. The impact of laundering on the secondary transfer of contaminants requires additional research.

4.1.4. Relative impact of control measures

Using a multiple regression model, it was possible to compare the relative impact of a PPE design intervention and hood doffing technique. In constructing this model, it was important to acknowledge that there were differences in air concentration measured in the personal air space of the firefighters as they completed the trials. These differences were attributed to day-to-day variations in exposure chamber concentrations due to environmental effects (Horn, Kerber, Lattz, et al. 2020) and differences in individual techniques for search, hose advance, overhaul, and even resting posture that could result in certain individuals being located higher in the structure than others. Therefore, we controlled for personal air concentrations of total PAHs in the analysis. The multiple regression model found the relative contributions of air concentration to the total variation in neck contamination to be approximately 2%. The hood type explained an additional 5% of the neck skin PAH exposure variability. However, the doffing method explained almost 28% of the variability in PAH neck skin levels, 5 times more than that attributed by the hood design.

4.1.5. Comparing FES to existing literature

Neck skin contamination levels in this study were higher than those measured from a simulated fireground study where firefighters wore the same hoods as used in the New-Knit condition in this study (Fent et al. 2017). In that project, 50% or more of the post-fire PAH measurements from the neck for the attack and search firefighters were non-detectable (<24 μg/m^2) while in this study we reported 8.3% and 25% for traditional and overhead doffing methods, respectively. In the Fent et al. (2017) paper, when PAHs were detected on the neck, firefighters conducting fire suppression and search and rescue tasks had 75th percentile values of 152 μg/m^2. In the current study, seventy-fifth percentile values from firefighters wearing the same type of hood were 369 and 50.2 μg/m^2 for traditional and overhead doffing methods, respectively. The differences in levels measured here may be attributed to differences in doffing methods and differences in ambient concentrations measured in personal air zones in the FES compared to the firefighters performing suppression and search and rescue on the fireground (Horn, Kerber, Lattz, et al. 2020). Higher detection rates in the current study may be partially attributed to differences in collection techniques. In this study, wipes were collected from the entire neck compared to one side of the neck in Fent et al. (2017).

4.2. Heart rate, neck skin temperature, core temperature

In the relatively brief scenario where firefighters performed multiple firefighting activities in an alternating work rest cycle, and consumed a single SCBA cylinder of air, there were no significant differences in selected physiological measurements among hood conditions. The bouts of activity employed in this protocol were relatively short, and in thermal environments representative of typical fireground operations (but not extreme conditions that may be encountered on occasion). Longer duration bouts or repeated bouts of activity (e.g. Horn et al. 2013; Hostler et al. 2016; Kesler et al. 2018; Walker et al. 2015), or higher environmental temperatures may have resulted in different physiological impacts among the hood conditions, particularly neck skin temperature. However, the lack of impact of different hood types is not unexpected, despite the increase in layers and insulation from the particulate-blocking hoods. Previous research has shown that changing insulation and design characteristics of bunker gear (Smith et al. 2011) or even changing from traditional long coat turnout gear to fully encapsulated bunker gear (Smith and Petruzzello 1998) had minimal impacts on heart rate and core temperature when firefighters were engaged in strenuous, self-paced work on the fireground.

The magnitude of firefighters' physiological changes from pre- to post-firefighting activities is consistent with previous research when firefighters conducted fire attack or training scenarios. As expected, conducting strenuous firefighting activities resulted in peak heart rates that were near the age-predicted maximal heart rate ([220-age]). Peak values reached in this FES trial (∼171 bpm) are comparable to those reported from firefighters completing firefighting activities of similar duration and during training drills (Barr, Gregson, and Reilly 2010). In the wide variety of studies reviewed by Horn et al. (2013), core temperature increases after firefighting activities ranged from 0.3 to 1.4 °C over many types of firefighting scenarios, many of similar duration to those studied here. Mean changes in firefighter's core temperature in this study (baseline to peak) of 0.8 °C are in the middle of this range. The physiological data reported here confirm that the heart rate and core temperature responses from firefighters conducting this FES protocol are similar to fireground and training ground activities, even though the firefighting activities were conducted in a more compact and controlled environment.

4.3. Wearability perception surveys

Perceptions of hood wearability are important to consider for the adoption and acceptance of new hood designs. The most significant differences in wearability perceptions between the hoods were related to hearing, noise, thickness, stiffness, and overall comfort as opposed to thermal impacts. The lack of perceived differences in 'Thermal', 'Hot', and 'Nonbreathable' is consistent with the differences in both core and neck skin temperatures between the hoods.

In each of the perceived measures where statistically significant differences were found between the three hoods, the firefighters always ranked the knit hood more positively and the laundered particulate-blocking hood least favourably. It should be noted, however, that while significant changes were noted, the differences were relatively minor, and may not have an important practical implication. For instance, firefighters rated the New-Knit hood as 'comfortable' and the Laundered-Blocking hood as significantly less so, but still between 'comfortable' and 'slightly comfortable'. The largest magnitude difference between the hoods was for sensations of 'Noisy' where the New-Knit hood was ranked as 5.0 before and 4.8 after firefighting (5 is 'none') while the New- and Laundered-Blocking hoods were ranked as 3.7 and 3.5 before and 3.9 and 4.0 after firefighting respectively (3 is 'mildly' and 4 is 'slightly'). The overall lowest ratings for all of the hoods were provided for Heavy/Thick, which was mostly negative for the Laundered-Blocking hoods (rated between 'mostly' and 'mildly').

In each of the perceived measures where statistically significant differences occurred between pre- and post-firefighting, the firefighters consistently ranked the hoods more positively before firefighting activity (other than perceptions of heavy/thickness, which were less negative after activity). The largest pre- to post-firefighting difference was noted for the related measures of 'Moistness' and 'Damp'. Not surprisingly, hoods were rated consistently near 'totally dry' prior to activity, but closer to 'breaking a sweat' after the strenuous firefighting activity.

Correlations were run between the perceptions and changes in physiological variables, heart rate, core temperature and neck skin temperature as well as peak heart rate and peak core temperature. No significant correlations were found.

4.4. Limitations

While this study has provided new information on the impact of PPE design, laundering and doffing methods on firefighter contamination, there are important limitations to consider. The FES protocol has important day-to-day variability as is typical in fireground responses, but a more controlled environment may provide additional insights into the relative contributions of each parameter to overall contamination. The two different doffing methods were utilised by separate groups, and this analysis could be strengthened with a repeated measures design. Studying, testing and implementing doffing methods from other occupations such as health care workers may further improve practices in the fire service (Phan et al. 2019). Finally, the comparison of contamination levels on the inner and outer layers of the knit and particulate-blocking hoods was based on a small number of comparisons, which should be followed up with a larger study that includes larger samples, additional technologies, and a wider range of contamination levels.

5. Conclusion

The impact of hood design, repeated laundering, and hood removal method on protection from contamination depositing on the neck, physiological responses, and firefighters' self-reported perceptions of wearability was assessed. Firefighters who used a controlled overhead doffing method to avoid cross-contamination had significantly lower neck skin PAH levels compared to those using a traditional method. In fact, in a multiple regression analysis to predict the neck skin total PAH contamination, the doffing technique explained over 25% of variability while hood design accounted for ~5%. Overall, PAH levels measured from neck skin were lower when wearing the particulate-blocking hoods compared to knit hoods, but contamination reaching the skin was not eliminated. No significant differences in neck skin temperature, core temperature, or heart rate were found between hood designs when firefighters conducted simulated firefighting activities using a single bottle of SCBA. Firefighters generally had more negative perceptions of their hoods after firefighting activities than before and tended to have more negative perceptions of particulate-blocking hood wearability compared to the knit hood. There was no perceptible difference related to thermal perceptions or feelings of dampness between the hood designs.

Overall, adding a particulate-blocking layer to the traditional two-ply hood was found to reduce the PAH contamination reaching the neck, but did not affect heat stress measurements or thermal perceptions. However, modifying the process of removing the hood resulted in a larger reduction in contamination than design modification.

Disclosure statement

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