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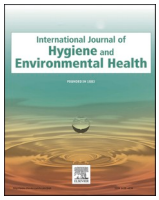

Acute cardiovascular responses of wildland firefighters to working at prescribed burn

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ABSTRACT

Wildland firefighters at prescribed burns are exposed to elevated levels of wildland fire smoke (WFS) while performing physically demanding tasks. WFS exposure has been linked to increases in hospital and emergency admissions for cardiovascular disorders in the general population. However, knowledge about the cardiovascular effect of occupational WFS exposure among wildland firefighters is limited. To provide a better understanding of the effect of this exposure scenario on acute hemodynamic responses, resting systolic/diastolic blood pressure (SBP/DBP) and heart rate (HR) of wildland firefighters were measured before (pre-shift), after (post-shift), and the morning (next morning) immediately following prescribed burn shifts (burn days) and regular work shifts (non-burn days). A total of 38 firefighters (34 males and 4 females) participated in this study and resting BP and HR were recorded on 9 burn days and 7 non-burn days. On burn days, HR significantly increased from pre-to post-shift (13.25 bpm, 95% CI: 7.47 to 19.02 bpm) while SBP significantly decreased in the morning following the prescribed burns compared to pre-shift (−6.25 mmHg, 95% CI: −12.30 to −0.20 mmHg). However, this was due to the decrease of SBP in the firefighters who were hypertensive (−8.46 mmHg, 95% CI: −16.08 to −0.84 mmHg). Significant cross-shift reductions (post-shift/next morning vs. pre-shift) were observed in SBP on burn days compared to non-burn days (−7.01 mmHg, 95% CI: −10.94 to −3.09 mmHg and −8.64 mmHg, 95% CI: −13.81 to −3.47 mmHg, respectively). A significant reduction on burn days was also observed from pre-shift to the following morning for HR compared to non-burn days (−7.28 bpm, 95% CI: −13.50 to −1.06 bpm) while HR significantly increased in pre-to post-shift on burn days compared to non-burn days (10.61 bpm, 95% CI: 5.05 to 16.17 bpm). The decreased BP observed in wildland firefighters might be due to a high level of carbon monoxide exposure and exercise-induced hypotension. The increase in HR immediately after prescribed burns might be attributable to WFS exposure and physical exertion in prescribed burn shifts. The results suggest that wildland firefighting exposure might cause a distinct hemodynamic response, including SBP reduction and HR increment, especially for those who have pre-existing hypertension.

1. Introduction

Millions of acres of forest lands are burned by tens of thousands of wildfires each year (NIFC, 2020), and release an enormous amount of wildland fire smoke (WFS) into the ambient air. In the United States, WFS has increasingly become an important source of air pollutants, especially particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and carbon monoxide (CO). The United State Environmental Protection Agency reported that the contributions of these two pollutants by wildfire events to the total national emissions have increased from ~16 to ~30% over the last decade (USEPA, 2019). Therefore, exposure to air pollutants from WFS emissions can cause substantial impact to public and occupational health.

Wildland firefighters, who are primarily responsible for wildfire suppression and prescribed burning, are more directly and frequently exposed to WFS compared to the general population. WFS contains numerous particulate and gaseous phase pollutants with the potential to cause health effects among exposed individuals (Adetona et al., 2016; Naeher et al., 2007). Positive associations between wildfire events and hospital or emergency room admissions for cardiorespiratory outcomes have been reported in previous population-based studies (Arbex et al., 2010; Johnston et al., 2007; Rappold et al., 2011). Acute respiratory

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symptoms and decline in lung function have also been observed in wildland firefighters following WFS exposures (Adetona et al., 2011b; Gaughan et al., 2008; Swiston et al., 2008; Wu et al., 2019). However, knowledge about potential cardiovascular responses as a result of WFS exposure in this occupational group is rather limited (Navarro et al., 2019). Positive associations between wildland firefighting career length and self-reported hypertension and heart arrhythmia were observed in a recent cross-sectional survey (Semmens et al., 2016).

Moreover, exposure to ambient air pollutants has been linked to increased risks of many cardiovascular diseases, and elevation in blood pressure (BP) is among the physiological responses that are triggered by the exposure and that have been proposed as underlying mechanisms (Paolo et al., 2016; Rajagopalan et al., 2018). Smoke emission from burning solid fuels (e.g., wood, charcoal, and crop residues) is reported to be associated with increased BP (Baumgartner et al., 2011, 2018; Norris et al., 2016; Quinn et al., 2017; Young et al., 2019). In stove intervention studies, research participants had a lower BP level after receiving a clean or improved cookstove intervention to reduce smoke exposure from cooking with biomass fuels (Alexander et al., 2015; Clark et al., 2013; Quinn et al., 2017). The acute effect of cookstove smoke exposure on BP was also demonstrated in a controlled human exposure experiment (Fedak et al., 2019), though other studies did not find similar effects (Hunter et al., 2014; Unosson et al., 2013).

In addition to BP elevation, increased resting heart rate (HR) has also been suggested as an indication of cardiovascular strain in response to exposure to air pollutants (Brook et al., 2014; Morishita et al., 2015). Significant increase in HR among people who were exposed to woodsmoke compared to those who inhaled filtered air was observed in a controlled human exposure study (Unosson et al., 2013). In a firefighting simulation study, the HR of firefighters increased significantly after exposure to artificial smoke while performing firefighting activities in a smoke-diving room (Hemmatjo et al., 2018). A causal association between cigarette smoking and higher resting HR has also been reported in a meta-analysis study (Linneberg et al., 2015).

Results of the abovementioned studies, along with the toxicological properties of woodsmoke (Naeher et al., 2007), raises concerns about the impact of WFS exposure on the cardiovascular health among wildland firefighters (Adetona et al., 2016; Navarro et al., 2019). During wildland fire events, their personal exposure concentrations of $PM_{2.5}$ in WFS is often at least an order of magnitude higher than the 24-hr US National Ambient Air Quality Standard (NAAQS) (35 μg/m^3) (Adetona et al., 2011a; Reinhardt and Ottmar, 2004). As wildland firefighters work prolonged shifts while performing physically demanding tasks and without appropriate respiratory protection, their cardiovascular health might be impaired by such exposures. Between 2007 and 2016, heart attack was the leading cause of on-the-job deaths among wildland firefighters in the United States accounting for 24% of the total number (NWCG, 2017). A recent risk assessment also concluded that wildland firefighters have an increased risk of cardiovascular mortality due to WFS exposure (Navarro et al., 2019).

Given the elevated levels of WFS exposure experienced by wildland firefighters and the scientific evidence suggesting its adverse cardiovascular effects, we hypothesize that WFS exposure induces an acute subclinical change in hemodynamic function among the firefighters. In this study, BP and HR of wildland firefighters were measured before, after, and the morning immediately following prescribed burn shifts and regular work shifts. Acute cardiovascular responses were then assessed by studying changes of the hemodynamic parameters across the prescribed burn shifts compared to corresponding changes across regular work shifts.

2. Material and methods

2.1. Study location and wildland firefighters

In this study, a total of 38 wildland firefighters were recruited from the United States Department of Agriculture–Wayne National Forest (WNF) and Ohio Department of Natural Resources–Division of Forestry (ODNR-DF). The demographic information about the wildland firefighters, unadjusted hemodynamic parameter values, and the characteristics of the prescribed burn shifts are provided in Table 1. Each firefighter was briefed on the purpose, design, and procedure of the study. All firefighters were given adequate information to allow them to make a voluntary decision about participation in the study. Informed consent was then obtained from each of them.

A baseline questionnaire was administered to each firefighter at the beginning of participation to obtain information about demography (e.g., age, sex, height, weight), firefighting career (e.g., career length, numbers of past prescribed burns and wildfires), relevant health history (e.g., pre-existing and family history of respiratory, cardiovascular, and metabolic diseases), etc. Two questionnaires were also provided to the firefighters immediately after (work task questionnaire) and the morning immediately following the work shift (morning-after questionnaire) to obtain information about factors (e.g., smoking, second-hand smoke exposure, medication, and wood burning for residential heating) that could confound the association between WFS exposures and cardiovascular effects. No firefighter reported using any blood pressure medication, while two firefighters reported being smokers. This study was reviewed and approved by The Ohio State University Institutional Review Board (2017H0075).

2.2. BP and HR measurements and WFS exposure assessment

Systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured before (pre-shift, approximately at 8–10am), at least 20 min after (post-shift, roughly at 4–6pm), and the morning (next morning between 8 and 10am and about 16 h after the post-shift measurements) immediately following prescribed burn shifts (burn days) and regular work shifts (non-burn days). Resting BP and HR were measured simultaneously using the Welch Allyn Spot Vital Signs monitor (Welch Allyn, Skaneateles Falls, NY) either in the forest area or at the office. Before the measurements, firefighters were allowed to rest for at least 5 min and sit in a chair with their backs supported. Their legs were uncrossed, and their feet were held flat on the floor. The measurement was taken in accordance with the American Heart Association (AHA) guideline, and cuff size was determined based on AHA recommendation following the "small adult" (22–26 cm), "adult" (27–34 cm), "large adult" (35–44 cm)

Table 1
General characteristics of wildland firefighters, unadjusted hemodynamic parameters, and prescribed burn shifts.

Characteristics	Mean ± SD or[b]	
Wildland firefighters (N = 38)		
Age (yr)	35.63 ± 9.31	
Gender	Male: 34, Female: 4	
BMI (kg/m^2)	27.91 ± 5.04	
Career length (yr)	8.94 ± 7.88	
Current Smoker	Yes: 2, No: 36	
Hemodynamic parameters	*Burn days*	*Nonburn days*
SBP (mmHg)	133.56 ± 17.42	125.22 ± 12.60
DBP (mmHg)	80.82 ± 9.87	78.71 ± 7.89
HR (bpm)	73.87 ± 14.57	71.39 ± 13.35
Pollutant concentrations on burn days[a]		
$PM_{2.5}$ (mg/m^3)	1.43 ± 0.13	
CO (ppm)	7.02 ± 0.69	
BC (μg/m^3)	58.79 ± 5.46	
Prescribed burns[a]		
Work shift duration (hr)	5.09 ± 1.57	
Size of burned area (acre)	308.88 ± 193.13	
Averages of weather parameters at burns[a,b]		
Ambient temperature (°F)	84.17 ± 6.81	
Relative humidity (%)	26.16 ± 6.45	

[a] These measures were only recorded on burn days.
[b] These were measured by the real-time sensors on the aerosol monitors.

and "adult thigh" (45–52 cm) categories of the arm circumference (Pickering et al., 2005).

Wildland firefighters who participated in this study provided at least one measurement on burn or non-burn days. Some firefighters were represented on up to 6 and 4 burn and non-burn days, respectively. The number of firefighters who had at least one set of completed measurement is 26 on burn days (55 person-days) and 11 on non-burn days (11 person-days). Ten firefighters (31 person-days) had at least one complete set of samples on both burn and non-burn days. No significant differences were observed in age, BMI, and career length between firefighters who had at least one complete set and those who did not. In addition, the results of statistical models using data with and without firefighters with incomplete BP and HR measurement are similar.

Personal exposure to $PM_{2.5}$ during prescribed burns was measured in the breathing zone of the wildland firefighters using the lightweight MicroPEM aerosol sensor (RTI International, Research Triangle Park, NC). PAC7000 single gas detector (Draeger, PA) was also carried by the firefighters in the breathing zone to measure time-integrated CO concentrations in WFS emissions. Both monitors were calibrated in accordance with the manufacturer's instructions before and after each prescribed burn day. The concentration of black carbon (BC) in WFS particulates was determined using a SootScan™ Model OT21 Optical Transmissometer (Magee Scientific, Berkeley, CA). The concentrations of air pollutants in WFS are presented in Table 1.

2.3. Statistics

BP and HR at the time of measurement (pre-shift, post-shift, next morning) and according to the types of workday (burn days or non-burn days) were determined using linear mixed effect model (LMM) while controlling for firefighting career length, smoking status, and body mass index (BMI). These covariates could influence the hemodynamic responses and were associated with BP and HR among the study participants. To account for within-subject correlation in the repeated measurements collected per wildland firefighter, participant ID and the date of measurement were included as random effect variables in the model. The normality of the data was verified using the goodness of fit test (Shapiro-Wilk and Kolmogorov-Smirnov tests) and the appropriateness of the LMM was confirmed from the residual plot.

Cross-shift changes (post-shift or next morning vs. pre-shift) in BP and HR were assessed using LMM while controlling for previously mentioned covariates. Adjusted *p*-values based on the Tukey's HSD multiple comparison tests were used to determine if the cross-shift changes were significant. Confidence intervals were also constructed using Tukey's HSD tests. The differences in the cross-shift changes in BP and HR between burn and non-burn days were tested using the same model.

According to the BP thresholds defined by AHA, firefighters were classified into the normotensive/elevated BP (SBP $<$ 130 mmHg and DBP 80 $<$ mmHg; N = 16 [N = 7 normotensive; N = 9 elevated BP]) or the hypertension (SBP $\geq$ 130 mmHg or DBP 80 $\geq$ mmHg; N = 22) group. The classification of the firefighter participants into BP categories is based on the averages of multiple pre-shift measurements as was done in prior studies (Burkard et al., 2018; O'Neal et al., 2015; Sharman et al., 2015). An alternative classification is based on the consistency of pre-shift measurements with placement of the firefighters in the category within which greater than 50% of their multiple pre-shift measurements fell. Results of analyses using the alternative criterion are similar to those that are from models using the classification based on average BP measurements with 92% of the firefighter participants remaining in the same categories. The cross-shift changes in both groups are analyzed using the LMMs previously described. All the analyses were conducted using SAS version 9.4 (SAS Institute, Cary, NC) and a *p*-value less than 0.05 was considered significant.

3. Results

BP and HR according to the measurement time and adjusted for career length, smoking status, and BMI are presented in Table 2. Cross-shift changes in BP and HR of wildland firefighters working on burn and non-burn days are shown in Fig. 1. Overall, SBP significantly decreased in the morning following the prescribed burn shift compared to pre-shift while HR significantly increased from pre-shift to post-shift on burn days. No significant cross-shift changes of BP or HR were observed on non-burn days. For normotensive and elevated BP firefighters, HR significantly increased from pre-to post-shift without any cross-shift changes in BP on prescribed burn days. Contrarily, SBP significantly decreased from pre-shift to the next morning in the hypertensive group while HR significantly increased from pre-to post-shift on burn days.

The differences in cross-shift changes in BP and HR between burn and non-burn days are presented in Fig. 2. With all participants included, SBP from pre-shift to either post-shift or the next morning was significantly reduced on burn days compared to non-burn days. A similar trend was observed for the change in HR from pre-shift to the next morning. However, pre-to post-shift change in HR was significantly higher on burn days than on non-burn days. When the wildland firefighters are categorized, a significant increase of HR from pre-to post-shift but no other difference in cross-shift changes was observed on burn days compared to non-burn days in normotensive and elevated BP firefighters. Among the hypertensive firefighters, SBP significantly declined across the work shift (pre-to post-shift or the next morning), and HR increased from pre-to post-shift but declined from pre-shift to next morning on burn days relative to non-burn days.

4. Discussion

In contrast to a relatively large number of studies investigating the effects of WFS exposure on acute pulmonary and respiratory responses in wildland firefighters, there is very limited information about the acute cardiovascular effects of such exposure in this population. As wildland firefighters are more directly exposed to WFS across extended periods during wildfire suppression and prescribed burn activities, they might have a distinct cardiovascular response to WFS exposure compared with the general population. Therefore, we initiated this pilot study to investigate acute hemodynamic responses to WFS exposure by measuring changes in BP and HR among the firefighters before and following work at prescribed burns.

The decreases in BP that were observed in this study (~1–2 mmHg immediately after and ~3–6 mmHg the morning following prescribed burn shifts) are similar to those reported in previous controlled human exposure studies. Small decreases in both SBP and DBP (~1–2 mmHg) were observed between 10 and 40 min after 1-h woodsmoke exposure (~1 mg/m^3 PM_1) with moderate exercise among 16 healthy firefighters; their BP further decreased non-significantly (~5 mmHg) at 24 h after the exposure (Hunter et al., 2014). In another controlled exposure study, SBP was ~2–5 mmHg lower at 10–60 min after 3-h woodsmoke exposure (mean PM_1 of 314 μg/m^3) with intermittent exercise and DBP was consistently ~1–3 mmHg lower until 50 min after the exposure was terminated compared to the pre-exposure measurements (Unosson et al., 2013). In a recent study, SBP was 0.2–2.3 mmHg lower when measured 30 min after a 2-h exposure to woodsmoke ($PM_{2.5}$ from 10 to 500 μg/m^3) but subsequently was 2–3 mmHg higher 24 h following the exposure (Fedak et al., 2019).

The decreased BP observed in wildland firefighters might partially be attributable to the time of measurement. In previous studies of controlled exposure to diesel exhaust particulates or concentrated ambient particulates, both systolic and diastolic pressures increased consistently during a 2-h exposure period but decreased immediately after the cessation of exposure (Byrd et al., 2016; Cosselman et al., 2012). BP measurement was performed at ~20 min and ~16 h after completion of prescribed burns due to logistical considerations for

Table 2
Blood pressure and heart rate (estimate with 95% confidence interval) of wildland firefighters (N; N: # of unique firefighters; person-days) by the time of measurement (pre-shift, post-shift, or next morning), types of workdays (burn or non-burn days), and blood pressure categories (normal/elevated or hypertensive).

Overall	N; N (# of unique participants; # of person-days)	SBP (mmHg)	DBP (mmHg)	HR (bpm)
		Est. (95% CI)	Est. (95% CI)	Est. (95% CI)
Burn days				
Pre-shift	33; 71	133.47 (130.13–136.81)	80.67 (78.59–82.76)	73.27 (69.86–79.68)
Post-shift	33; 71	131.69 (128.35–135.03)	78.05 (75.96–80.14)	86.52 (83.10–89.93)
Next morning	27; 55	127.22 (123.44–131.01)	77.09 (74.73–79.46)	73.13 (69.26–76.99)
Non-burn days				
Pre-shift	24; 41	124.93 (121.94–127.93)	78.63 (76.08–81.19)	71.48 (67.64–75.31)
Post-shift	22; 33	129.45 (126.11–132.79)	74.53 (71.68–77.38)	74.41 (70.13–78.68)
Next morning	14; 14	128.50 (123.36–133.63)	77.04 (72.67–81.41)	78.36 (71.80–84.93)
Normal/Elevated	N; N (# of unique participants; # of person-days)	SBP (mmHg) Est. (95% CI)	DBP (mmHg) Est. (95% CI)	HR (bpm) Est. (95% CI)
Burn days				
Pre-shift	12; 29	120.12 (116.99–123.26)	74.85 (72.38–77.31)	69.34 (65.13–73.55)
Post-shift	12; 29	120.67 (117.54–123.81)	72.81 (70.35–75.27)	85.03 (77.82–86.24)
Next morning	10; 25	117.24 (113.85–120.62)	73.24 (70.58–75.90)	69.65 (65.11–74.20)
Non-burn days				
Pre-shift	12; 20	115.83 (111.75–119.91)	73.61 (70.37–76.85)	69.03 (64.60–73.46)
Post-shift	11; 15	119.74 (115.17–124.32)	69.08 (64.45–72.72)	69.08 (64.11–74.05)
Next morning	6; 6	118.59 (111.15–126.03)	72.41 (66.50–78.32)	76.02 (67.95–84.10)
Hypertensive	N; N (# of unique participants; # of person-days)	SBP (mmHg) Est. (95% CI)	DBP (mmHg) Est. (95% CI)	HR (bpm) Est. (95% CI)
Burn days				
Pre-shift	21; 42	143.45 (139.35–147.55)	85.10 (82.18–88.02)	76.40 (72.19–80.62)
Post-shift	21; 42	139.98 (135.88–144.08)	82.05 (79.13–84.97)	90.05 (85.84–94.27)
Next morning	17; 30	134.99 (130.16–139.83)	79.86 (76.42–83.30)	75.34 (70.37–80.31)
Non-burn days				
Pre-shift	12; 21	133.60 (129.58–137.63)	83.46 (79.57–87.36)	74.00 (68.42–79.57)
Post-shift	11; 18	138.55 (134.10–143.01)	79.48 (75.17–83.79)	78.50 (72.32–84.68)
Next morning	8; 8	135.99 (129.38–142.60)	80.76 (74.36–87.15)	81.56 (72.41–90.72)

*The three measures (DBP, SBP, and HR) were collected in each measurement instance.

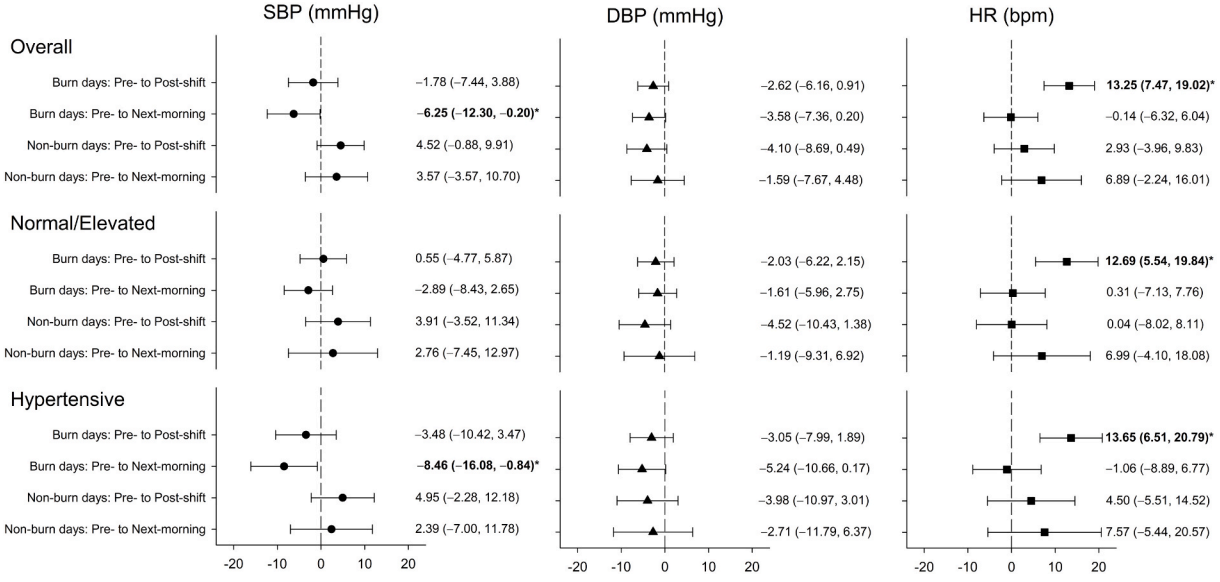

Fig. 1. Cross-shift changes (from pre-shift to post-shift or next morning) of blood pressure and heart rate on burn and non-burn days.

research personnel and less interruption to the work and routine of the firefighters. Therefore, the timing of increased BP increases due to wildland firefighting, if any, might be missed because of the choice of measurement time-points.

Additionally, it is possible that the dilatory and BP-lowering effects of other exposures at the fireline counteract the expected BP-raising effect of WFS-associated PM exposure (Cunha et al., 2020; Giorgini et al., 2015; Halliwill, 2001; Halonen et al., 2011; Wu et al., 2015). For example, post-exercise hypotension often occurs after dynamic exercise/training and the magnitude of BP reduction is associated with exercise intensity, exertion duration, and hypertension (Cornelissen and Smart, 2013; Eicher et al., 2010; Gomes Anunciação and Doederlein Polito, 2011; Halliwill, 2001; Rezk et al., 2006).

Wildland firefighters usually undertake rigorous fire tasks during prescribed burns. On a typical prescribed burn day, they are engaged in multiple physically demanding activities including burn preparation,

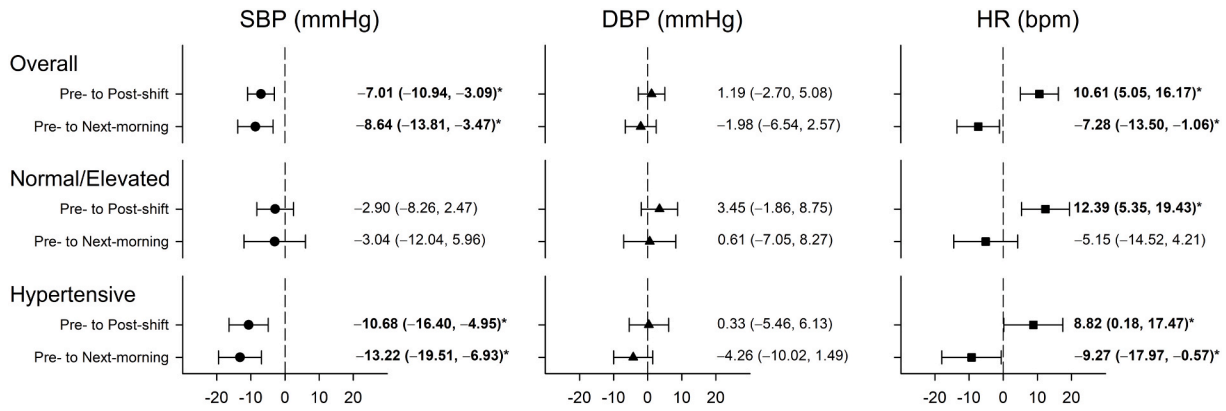

Fig. 2. Comparison of cross-shift changes (from pre-shift to post-shift or next morning) in blood pressure and heart rate between burn and non-burn days.

lighting of fires, and the maintenance of fires within predetermined burn areas. Apart from hand tools, each firefighter also carries a backpack that weighs ~45-pound for most of the work shift (5.09 ± 1.57 h and 308.88 ± 193.13 acres of burned area, Table 1). On the contrary, wildland firefighters in this study usually worked in the office (e.g., attended meetings or annual fire refresher) during a regular 8-h non-burn day work shift.

As previous studies demonstrate about the association between BP reduction level and hypertension (Cornelissen and Smart, 2013; Halliwill, 2001), we hypothesize that the observed hypotension effect in this study was particularly apparent because of the predominant number of pre-hypertensive and hypertensive firefighters (58%) among the participants. This inference is supported by the result of cross-shift changes according to the different BP categories, showing that a significant decrease in BP was observed in hypertensive but not normotensive or elevated BP firefighters (Figs. 1 and 2).

Moreover, ambient temperature is inversely associated with BP (Giorgini et al., 2015; Halonen et al., 2011; Wu et al., 2015), and exercising in hot environments, such as would be experienced by wildland firefighters at prescribed burns (84.17 ± 6.81 °F in this study, Table 1), can exaggerate the acute hypotensive effect of exercise (Cunha et al., 2020; Halliwill, 2001). In a previous study investigating post-exercise hypotension among 7 men with elevated blood pressure (127.4/83.7 mmHg), SBP measured following two bouts of cycling exercise in hot environment (35 °C) was consistently lower (−0.3 to −4.7 mmHg) compared to measurements following the same exercise regime in normal environment (21 °C) across a 21-hr recovery period (Cunha et al., 2020). The authors of this study suggested that the post-exercise hypotension could be further aggravated by vasodilatory effect in response to heat load after the exercise (Cunha et al., 2020).

It should be noted that the observed acute lowering of BP may be harmful. Hypotension and BP below a nadir in treated hypertensives, especially with the presence of coronary artery disease, are associated with myocardial ischemic events (Divisón-Garrote et al., 2016; Divisón-Garrote et al., 2020; Messerli et al., 2006; Messerli and Panjrath, 2009; Owens and O'Brien, 1999). Furthermore, previous systemic reviews conclude that decrease in SBP during exercise stress testing is associated with increased risks of multiple cardiovascular events (Barlow et al., 2014; Schultz et al., 2017). Incidentally, myocardial infarction is the leading cause of non-accident on-the-job fatality among wildland firefighters, and exposure to PM, such as is contained in WFS, is associated with subclinical coronary artery disease (Butler et al., 2017; Jilani et al., 2020; NWCG, 2017).

Unlike $PM_{2.5}$ and BC that are commonly linked to BP increase, CO exposure seems to have a relaxation effect on blood vessels (Penney and Howley, 1991; Rezk-Hanna et al., 2019; Stec et al., 2008). Following exposure, CO interacts with soluble guanyl cyclase (sGC) and subsequently results in cyclic guanosine 3′-5′ monophosphate (cGMP) increase, leading to a vasodilatory effect (Stec et al., 2008). In previous controlled exposure studies, non-significant decreases in BP were observed following exposure to woodsmoke which contained 16 ppm of CO for 1 h or 25 ppm of CO for 3 h (Hunter et al., 2014; Unosson et al., 2013). BP was similarly reduced following 45-min in-vehicle exposures to CO (30.2–72.4 ppm) compared to when there was no CO exposure (0 ppm) (Lee et al., 2017). Personal CO exposure concentration across prescribed burns was 7.02 ± 0.69 ppm in this study (Table 1). However, actual exposure (inhaled amount) may be higher in the firefighters than for participants in the previous studies due to the increased breathing rates of firefighters while working at wildland fires that may rise up to 5–8 times above the resting rate (Navarro et al., 2019). While lower SBP was primarily observed among the hypertensive firefighters up to ~16 h following exposure to WFS, we were unable to determine from prior studies whether people with elevated BP or hypertension are more sensitive to this effect, and whether the vasodilatory and BP-lowering effects of CO exposure last beyond the first few hours of exposure.

Contrary to the BP results, HR significantly increased by ~13 bpm in post-shift and subsequently returned to pre-shift levels in the mornings following prescribed burn days (Fig. 1). The pre-to post-shift change in HR on burn days was ~10 bpm higher compared to the changes on non-burn days (Fig. 2). Similar observations were also made in prior studies of controlled exposure to woodsmoke. Resting HR increased ~1–2 bpm within 30 min after a 1-h woodsmoke exposure (~1 mg/m^3 PM_1) with intermittent exercise (Hunter et al., 2014). A significant increase in HR from ~2 to 6 bpm at 1-h post-exposure following 3-h exposure to woodsmoke (~300 $\mu g/m^3$ PM_1) that did not occur following exposure to filtered air was observed in another study (Unosson et al., 2013).

Interestingly, the magnitude of the increase in HR observed in this study was much higher than what was observed in the other studies that are referenced. This could partly be due to the relatively prolonged exposure of the wildland firefighters to elevated level of WFS exposure at prescribed burn shifts ($PM_{2.5}$: 1.43 ± 0.13 mg/m^3 and BC: 58.79 ± 5.46 $\mu g/m^3$, Table 1). Detail of exposure assessment for wildland firefighters in this study has been reported elsewhere (Wu et al., 2021). Furthermore, the average duration of prescribed burn shifts was about 2–5 times longer than the duration in the controlled exposure studies (Hunter et al., 2014; Unosson et al., 2013).

Nonetheless, it should be noted that wildland firefighters were usually involved in more strenuous activities compared to the moderate exercise (on a bicycle ergometer with rest at 15-min intervals) performed in the controlled exposure studies (Hunter et al., 2014; Unosson et al., 2013). A recent firefighting simulation study also showed that structural firefighters' HR significantly increased from ~70 to ~160 bpm at the end of firefighting operation in a smoke-diving room (Hemmatjo et al., 2018). Since exercise intensity is also associated with HR increase (Eicher et al., 2010; Rezk et al., 2006), the elevated HR observed in wildland firefighters in this study might in part be due to

their physical exertion during prescribed burn shifts.

No association between air pollutants ($PM_{2.5}$, CO, and BC) in WFS emissions and cross-shift changes in BP or HR was observed in this study (data not shown). Nevertheless, a significant exposure-response was often observed in prior studies investigating the effect of biomass smoke exposure in an indoor environment (Baumgartner et al., 2011, 2018; Norris et al., 2016; Quinn et al., 2017; Young et al., 2019). The discrepancy between our results and those of others might be because the exposure-response associations in our study is obscured by a divergence between the external concentration and the dose of WFS exposure.

Several limitations should be noted when the result of this study is interpretated. First, there was no direct measurement of physical activity level. However, it was observed that firefighters were involved in more arduous tasks during prescribed burns whereas they typically worked in the office (e.g., attended meetings or annual firefighting refresher trainings) on a non-burn day. Secondly, schedule and preparation for a prescribed burn activity is often uncertain due to the dependence of its conduct on suitable weather conditions. Consequently, wildland firefighters were selected into this study by convenience sampling method rather than through randomization process.

In addition, the measurements in the morning following the work shifts were more difficult to obtain from the firefighters. Sixteen and 28 next morning measurements were missed on burn and non-burn days, respectively. To address concerns due to incomplete data, LMMs including only complete sets of measurements on burn and non-burn days were also used to evaluate acute cardiovascular responses. Therefore, any person-day with missing measurement points (before, after, and/or the next morning) were excluded in this alternate set of analyses. The results of analysis are similar to the findings presented in the table and figures (data not shown).

5. Conclusions

Reductions in SBP and increases in HR were observed in wildland firefighters immediately after and the morning following work at prescribed burns, presumably due to multiple fireline-related factors (e.g., WFS exposure, arduous tasks, and hot environment). Wildland firefighters might have a distinct cardiovascular response, especially in those who are hypertensive, following WFS exposure during prescribed burn shifts.

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Declaration of competing interest

The authors of this paper declare no conflict of interest.

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