BRIEF REPORT

Work Patterns Dictate Energy Demands and Thermal Strain During Wildland Firefighting

John S. Cuddy, MS; Joseph A. Sol, BS; Walter S. Hailes, MS; Brent C. Ruby, PhD

From the Montana Center for Work Physiology and Exercise Metabolism, The University of Montana, Missoula, MT.

Objective.—The purpose of this investigation was to characterize the effects of self-selected work activity on energy expenditure, water turnover, and thermal strain during wildland fire suppression. A secondary aim was to contrast current data with data collected 15 years ago using similar methods to determine whether job demands have changed.

Methods.—Participants ($n = 15$, 26 ± 3 years, 179 ± 6 cm, 78.3 ± 8.6 kg) were monitored for 3 days for total energy expenditure, water turnover, core and chest skin temperature, physical activity, and heart rate. Participants arrived to the mobile laboratory each morning, submitted a nude weight, ingested a temperature transmitter, provided a urine sample, and were equipped with a physiological and activity monitor. Participants completed live wildland fire suppression during their work shifts.

Results.—Mean core temperature was $37.6^\circ \pm 0.2^\circ\text{C}$, mean chest skin temperature was $34.1^\circ \pm 1.0^\circ\text{C}$, mean heart rate was 112 ± 13 beats/min, and the mean physiological strain index score was 3.3 ± 1.0 . Wildland firefighters spent $49 \pm 8\%$, $39 \pm 6\%$, and $12 \pm 2\%$ in the sedentary, light, and moderate-vigorous intensity categories, respectively. The mean total energy expenditure was 19.1 ± 3.9 MJ/d, similar to 1997 (17.5 ± 6.9 MJ/d). The mean water turnover in 2012 was 9.5 ± 1.7 L/d, which was higher ($P < .05$) compared with 1997–98 (7.0 ± 1.7 L/d).

Conclusions.—Wildland firefighters do not induce consistently high cardiovascular and thermal strain while completing arduous work in a hot environment despite fairly high chest skin temperatures. The total energy expenditure in the current study suggests job demands are similar to those of 15 years ago, while the increased water turnover may reflect a change in drinking habits.

Key words: skin temperature, core temperature, occupational physiology, field study

Introduction

Wildland firefighters (WLFFs) are subjected to a multitude of environmental and physical demands on a day-to-day basis. High energy (17.5 ± 6.9 MJ/d) and fluid demands (6.7 ± 1.4 L/d) result from 12 to 16 hours of physical labor

(229 ± 56 kcal/h for 16 hours) in hot environments in an effort to control wildland fires.^{1,2} Thermoregulation for the WLFF is challenged by high ambient and radiant temperatures, as well as wearing required personal protective equipment. When combined with high metabolic demand, this can lead to heat-related injuries, and even fatalities, as a result of rigorous occupational tasks and exposure to the elements.^{3,4} Firefighters self-regulate body temperature in response to different ambient conditions by altering work and rest cycles and work intensity.⁵ Objective measures of work effort, along with measures of thermal strain, have not been directly observed alongside the measures of total energy expenditure (TEE) and water turnover ($r\text{H}_2\text{O}$) during wildfire suppression. The purpose of this investigation is to characterize the effects of self-selected work activity on TEE, $r\text{H}_2\text{O}$, and thermal strain during wildland fire suppression. A secondary aim was to contrast the current data with data collected 15 years ago to determine whether the job demands have changed.

Disclaimer: The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Office of Naval Research or the Department of Defense. The investigators have conducted the research in adherence with the provisions of 32 CFR Part 219. Citations of commercial organizations and trade names in this report do not constitute an official Office of Naval Research endorsement or approval of the products or services of these organizations. The current project was funded by the Office of Naval Research, Grant Award N000140910850. The authors report no conflicts of interest.

Corresponding author: Brent C. Ruby, PhD, Director, Montana Center for Work Physiology and Exercise Metabolism, Department of Health and Human Performance, The University of Montana, 32 Campus Drive, Missoula, MT 59812-1825 (e-mail: brent.ruby@mso.umt.edu).

Methods

EXPERIMENTAL DESIGN

Twelve male and 3 female participants ($n = 15$, 26 ± 3 years, 179 ± 6 cm, 78.3 ± 8.6 kg, body mass index 24.3 ± 1.7 kg/m²) were recruited from two Type I Inter-agency Hot Shot fire crews and monitored for 3 days. Participants provided informed consent by signing a university-approved institutional review board consent form. The evening (approximately 10 PM) before beginning their work shift, participants were weighed in the nude using a calibrated digital scale (Ohaus CW-11, Ohaus Corp, Pinebrook, NJ), verbally provided their height, and were given an oral dose of tracer water, ²H₂¹⁸O (100 g; 1.82 g ¹⁸O per kg body mass, 0.13 g ²H₂ per kg body mass). Each day participants arrived to the mobile laboratory in the early morning, provided body mass, ingested a disposable temperature transmitter pill (Jonah capsule, Vitalsense, Mini Mitter, Bend, OR), provided a urine sample, and were equipped with the Hidalgo Equivital EQO2 LifeMonitor system (Hidalgo Limited, Cambridge, UK) which collected heart rate (HR) and received transmission from the core pill, and an ActiCal activity monitor (Mini Mitter). The isotopic enrichments of urines collected on each morning and evening were used to determine elimination rates, water turnover, and carbon dioxide production. For a more detailed report of these procedures, see Ruby et al.^{1,2} and Cuddy et al.⁶ Intensity of activity was determined by activity count cut points (≤ 99 , 100–1499, and ≥ 1500 for sedentary, light, and moderate/vigorous, respectively) as has been previously reported during similar work.⁷ After being equipped, participants went to work doing live wildfire suppression (High Park Fire, Fort Collins, CO, which burned 353.23 km², or 87,284 acres), which involved activities such as hiking, line digging, laying hose, chain sawing, clearing brush, lookout, and scouting. Work shifts (excluding drive time) averaged 11.4 ± 0.7 hours in duration. Participants reported to the mobile laboratory after the work shift, were weighed, provided a urine sample, and returned the monitors. Weather conditions were reported using the Fort Collins Weather Station Data Access (http://ccc.atmos.colostate.edu/~autowx/fclwx_access.php).

HIDALGO EQUIVITAL EQO2 LIFEMONITOR SYSTEM

Because of technical difficulties with the system (battery failure in the ingestible sensor owing to a manufacturing error in soldering), complete HR and core and chest skin temperature data for the entire work shift were collected on 29 of the 45 person-days. These variables are

expressed as descriptive data to characterize physiological strain patterns during these days of wildland fire suppression. Physiological Strain Index (PSI) score was computed based on Moran et al.⁸ A resting HR of 71 beats/min was used for all modeling.^{8,9}

RETROSPECTIVE RESEARCH DATA

To characterize the differences in TEE and rH₂O between the current data set and a study cohort from 15 years earlier, data were obtained from 2 studies by Ruby et al.^{1,2} The methods for tracer dose administration and analysis between the current and past studies are identical.

STATISTICS

All analysis was performed using SPSS for Windows Version 13 (Chicago, IL). Significance was set to probability values of less than .05. Data are reported as mean $\pm$ SD.

Results

BODY MASS

Differences in body mass were analyzed using a one-way analysis of variance. There was no change in morning body mass across the 3-day data collection period (77.3 ± 8.3 , 76.9 ± 8.3 , 77.5 ± 8.6 , and 77.0 ± 8.9 kg for mornings 1, 2, 3, and 4, respectively; $P = .12$).

HEART RATE AND CORE AND CHEST SKIN TEMPERATURE

See Table 1 for a complete profile of HR, core and chest skin temperature, and PSI over the course of 3 days of wildland fire suppression.

ACTIVITY

Activity was higher on day 1 compared with days 2 and 3, and day 2 was higher than day 3 ($P < .05$; Figure 1). Activity intensity profiles for the 3 days can be observed in Figure 2.

TOTAL ENERGY EXPENDITURE AND WATER TURNOVER

The mean TEE was 19.1 ± 3.9 MJ/d, and the mean rH₂O was 9.5 ± 1.7 L/d. Individual participant data, as well as means for all energy expenditure variables, can be seen in Table 2. A retrospective analysis of the current data set compared with the 2002 wildland fire paper by Ruby et al.¹ can be seen in Table 3.

Table 1. Physiological strain indices during 3 days of wildland fire suppression^a

Heart rate (beats/min)	% of shift	Core temp (°C)	% of shift	Skin temp (°C)	% of shift	PSI	% of shift
<100	37 ± 19%	<37.5	34 ± 24%	<30	2 ± 4%	Rest	9 ± 13%
100–120	25 ± 12%	37.5–38.0	48 ± 19%	30–32	13 ± 14%	1–2	33 ± 10%
120–140	20 ± 8%	38.0–38.5	17 ± 15%	32–34	27 ± 18%	3–4	38 ± 9%
140–160	12 ± 8%	38.5–39.0	1 ± 3%	34–36	44 ± 17%	5–6	17 ± 7%
160–180	4 ± 5%	39.0–39.5	n/a	36–38	14 ± 14%	7–8	2 ± 2%
≥ 180	1 ± 2%	≥ 39.5	n/a	≥ 38	n/a	9+	n/a

n/a, not applicable; PSI, Physiological Strain Index.

^a Data are expressed as percentage of work shift time (mean ± SD) that was spent within the designated range. n = 29 person-days.

AMBIENT CONDITIONS

Ambient high and low temperatures were 31.8°C and 19.1°C, respectively, for day 1, 34.0°C and 20.4°C for day 2, and 36.1°C and 20.4°C for day 3. Average hourly ambient temperature across the 3 days was 27.5° ± 3.2°C.

Discussion

This study comprehensively assesses the effect of work activity patterns on several physiological and thermo-regulatory parameters during wildland fire suppression in the western United States. The current data set suggests WLFFs expend 19.1 ± 3.9 MJ/d (4556 ± 943 kcal/d), have an rH₂O of 9.5 ± 1.7 L/d, and an overall physiological strain characterized as “little” to “low” (PSI, 0–4),⁸ which made up 81% ± 14% of the total work day. Further, these data suggest the TEE during wildland fire suppression has not changed in 15 years,

despite a higher rH₂O of 2.5 L/d in 2012 compared with 1997–98.

In the current study, WLFFs averaged 745 ± 191, 512 ± 89, and 385 ± 86 counts/min on days 1, 2, and 3, respectively, of fire suppression efforts. Because previous research during wildland fire suppression has demonstrated mean daily activity levels between 175 and 724 counts/min,^{7,10–12} the daily activity patterns in the current study are within the range of expected activity patterns during the job on days 2 and 3. Day 1, however, was the highest daily average collected to date (8 of 15 participants averaged >850 counts/min), resulting from a higher work intensity completing comparable tasks as days 2 and 3. The WLFFs in the current study spent 49% ± 8%, 39% ± 6%, and 12% ± 2% of time in the sedentary, light,

Figure 1. Activity patterns during 3 days of wildland fire suppression. Differences were analyzed using a one-way analysis of variance. Data are expressed as mean ± SD. * Higher compared with day 3, $P < .05$; † higher compared with day 2, $P < .05$.

Figure 2. Time spent at different intensities during wildland fire suppression over 3 days of work. Differences in time spent in different activity intensities were analyzed using 2-way repeated measures analysis of variance. Data are expressed as mean ± SD. * Different compared with days 2 and 3, interaction effect, $P < .05$; † different compared with day 3, interaction effect, $P < .05$; ^a different compared with light and moderate/vigorous within the day, interaction effect, $P < .05$; ^b different compared with moderate/vigorous within the day, interaction effect, $P < .05$.

Table 2. Individual descriptive, energy expenditure, and water turnover values during wildland fire suppression efforts calculated from days 1–3 elimination rates

Sex	Age (y)	Ht (cm)	Exp (y)	TEE (MJ/d) [kcal/d]	EEA (MJ/d) [kcal/d]	TEE × BMR	rH ₂ O (L/d)	Mass (kg) ^a	
								Pre	Post
M	25	180	6	18.3 [4383]	9.1 [2168]	2.5	9.29	77.4	77.0
M	25	180	7	18.7 [4461]	10.2 [2428]	2.8	9.83	69.8	69.0
M	28	183	7	19.8 [4728] ^b	9.9 [2369] ^b	2.5 ^b	11.75	84.0	83.1
F	25	175	8	15.9 [3812]	8.4 [1998]	2.7	8.55	62.9	61.5
F	26	170	7	13.4 [3197]	5.8 [1378]	2.1	7.11	65.8	64.9
M	26	178	5	21.5 [5130]	11.7 [2808]	2.8	9.51	76.4	76.2
M	26	175	4	12.3 [2946]	3.8 [896]	1.7	11.74	76.1	75.7
M	23	188	4	23.5 [5624]	13.2 [3156]	3.0	11.53	90.5	94.4
M	25	178	5	20.0 [4774]	10.8 [2584]	2.8	8.14	73.1	72.7
M	22	180	4	21.5 [5131]	11.7 [2792]	2.8	7.87	79.5	78.4
M	23	178	5	19.3 [4605]	9.9 [2373]	2.6	11.35	86.4	86.5
M	21	183	4	18.3 [4369]	8.9 [2139]	2.4	9.45	80.0	79.5
M	26	178	7	24.3 [5811]	15.0 [3589]	3.5	10.39	75.3	75.3
M	29	193	9	25.5 [6083]	14.5 [3475]	3.0	9.74	91.1	89.8
F	33	170	11	13.8 [3290]	6.5 [1562]	2.4	6.05	71.5	70.8
Mean	26 ± 3	179 ± 6	6 ± 2	19.1 ± 3.9 [4556 ± 943]	10.0 ± 3.1 [2381 ± 746]	2.6 ± 0.4	9.49 ± 1.73	77.3 ± 8.3	77.0 ± 8.9

BMR, basal metabolic rate; EEA, energy expenditure of activity; Exp, experience; Ht, height; rH₂O, water turnover; TEE, total energy expenditure.

^a Pre body mass measurement taken on the first morning before the first work shift; post body mass measurement was taken on the morning of the fourth day.

^b Data are representative of 2 days of wildland fire suppression.

Table 3. Energy expenditure, water turnover, and body weight comparison between wildland fire suppression efforts in 1997–98 (N = 17) versus 2012 (N = 15). Differences for TEE and rH₂O between data from 1997–98 vs 2012 were analyzed using an independent t-test. Body mass differences between data from 1997–98 vs 2012 were analyzed using a 2 x 2 mixed design ANOVA with repeated measures.

	TEE (MJ/d)	TEE (MJ · d ⁻¹ · kg ⁻¹)	TEE × BMR	rH ₂ O (L/d)	rH ₂ O (mL · d ⁻¹ · kg ⁻¹)	Mass (kg) ^a	
						Pre	Post
WLFF 1997–98	17.5 ± 4.1	0.25 ± 0.06	2.6 ± 0.5	7.0 ± 1.7 ^b	100 ± 20 ^b	69.6 ± 8.6	69.4 ± 8.5
WLFF 2012	19.1 ± 3.9	0.24 ± 0.04	2.6 ± 0.4	9.5 ± 1.7	121 ± 18	77.3 ± 8.3 ^c	77.0 ± 8.9
t test P value	0.27	0.60	0.95	<0.001	0.004		

BMR, basal metabolic rate; rH₂O, water turnover; TEE, total energy expenditure; WLFF, wildland firefighter.

^a Pre body mass measurement taken in the morning before the first work shift; post body mass measurement was taken in the morning on the fourth day (2012) or sixth day (1997–98).

^b Indicates difference compared with 2012 (*P* < .05).

^c Indicates main effect for group (*P* < .05).

and moderate-vigorous intensity categories averaged over the 3 days of fire suppression efforts, a shift from the typical percentages seen in recent papers (sedentary, 61% to 66%⁷ and 74%¹¹ of time; moderate-vigorous, 0% to 7%⁷ and 5%¹¹).

Similar to previous findings, the HR and core temperature of WLFFs in the current study did not reflect high levels of cardiovascular or thermal strain.¹³ Sixty-three percent of the time WLFFs exhibited HR values less than 120 beats/min (daily average, 112 ± 13 beats/min), whereas 82% of the time core temperature was below 38.0°C. Rodríguez-Marroyo et al⁵ found that for wildfires of more than 5 hours in duration, mean core temperature was 37.8° ± 0.3°C, similar to the current study, whereas mean core temperature was 37.6° ± 0.2°C during work shifts lasting 11.4 ± 0.7 hours. WLFFs have learned practical strategies to alleviate heat stress, particularly avoiding unnecessary heat by keeping a safe distance from the fire, self-pacing at an intensity appropriate to their fitness level (when not resting, WLFFs work at an intensity between 7 and 10 kcal/min, or an oxygen consumption of 1.4 to 2.0 L/min), evaporating sweat via appropriate clothing, and replacing sweat losses by drinking.¹³

Although HR, core temperature, and PSI appear low, the thermal demand from the environment coupled with wearing personal protective equipment creates a challenging microenvironment, as evidenced by chest skin temperatures. In this study, 42% of the time chest skin temperature was less than 34.0°C, whereas 58% of the time chest skin temperature was greater than 34.0°C, of which 14% ± 14% of time chest skin temperature was between 36.0° and 38.0°C. This narrowing of the core-to-skin gradient can have adverse impacts on performance.¹⁴ Buller et al⁹ demonstrates that above chest skin temperatures of 35.0°C, exercising humans are likely to

reach PSI values of 7.5 and greater if HR rises, particularly above approximately 160 beats/min. Perhaps the self-pacing practices of experienced WLFFs have a strong relationship to internal feedback mechanisms related to elevated skin temperatures. WLFFs will keep cardiovascular strain low (reduced work output via frequent rest breaks) to compensate for higher ambient conditions, thus maintaining an overall lower thermal strain.

In the 15 years since these data were collected (summers of 1997–98), firefighters anecdotally claim the job has changed substantially, with suppression efforts being much more conservative to minimize risk. Because accelerometer technology was not available for the 1997 TEE study, no direct comparison between studies can be made for activity patterns and their effect on TEE. In the current study, the mean TEE was 19.1 ± 3.9 MJ/d (4556 ± 943 kcal/d), whereas the previous study reported mean TEE as 17.5 ± 4.1 MJ/d (4177 ± 979 kcal/d). There was no difference between the TEE, although rH₂O was higher in 2012. In the current study, mean rH₂O was 9.5 ± 1.7 L/d, whereas in the previous paper it was 7.0 ± 1.7 L/d, a mean difference of 2.5 L/d. This comparison for TEE and rH₂O should be approached with caution, as each study represents a small sample size compared with the number of WLFFs in the workforce.

However, the higher rH₂O in 2012 compared with 1997–98 warrants evaluation. Water turnover, a composite metric consisting of water in and water out of the body, is influenced by self-selected behavioral cues that regulate ingestion (water in), as well as the metabolic work rate and sweat rate, which is affected by the ambient conditions (water out). Ambient conditions during the current study were slightly cooler in 2012 compared with the 1997–98 study, with an average high temperature of 34.0° ± 2.2°C compared with 35.3° ± 2.6°C, respectively. In spite of the temperature being

cooler by 1.3°C, the rH₂O was higher during the 2012 study. The TEE is not different between studies, and thus the metabolic work rates are comparable. Uniforms in the past 15 years have not changed, and thus different evaporative potential from clothing cannot contribute to the higher rH₂O resulting from a higher sweating rate. The difference between the two studies is likely an increased self-selected higher intake of fluid (although intake was not measured) throughout the work shift, because neither group lost body weight during the study period. During daily safety briefings at wildfires there is a strong emphasis on aggressive fluid intake to prevent dehydration. Perhaps this ideology has influenced the drinking patterns of WLFFs, as previous studies (all between 1997 and 2007) show mean rH₂O values 7.0 ± 1.7 L/d, 6.7 ± 1.4 L/d, and 6.6 ± 2.1 L/d across a total of 59 participants in 3 separate studies,^{1,2,12} respectively.

Conclusions

Despite sustaining relatively high chest skin temperatures throughout the work shift, WLFFs modulate their work activity to effectively compensate for the environmental conditions and avoid heat-related injuries. The TEE in the current study suggests that the demands of the job are similar to those of 15 years ago, although the increased rH₂O may reflect a change in drinking habits by WLFFs. The physiological data suggests that Type 1 Hotshot WLFFs do an adequate job of managing their environmental and work demands so that they do not induce consistently high, and possibly dangerous, cardiovascular and thermal strain.

Acknowledgments

The authors would like to thank both fire crews for their volunteer efforts, and Dr Joseph Domitrovich for his technical assistance during data collection.

References

1. Ruby BC, Shriver TC, Zderic TW, Sharkey BJ, Burks C, Tysk S. Total energy expenditure during arduous wildfire suppression. *Med Sci Sports Exerc.* 2002;34:1048–1054.
2. Ruby BC, Schoeller DA, Sharkey BJ, Burks C, Tysk S. Water turnover and changes in body composition during arduous wildfire suppression. *Med Sci Sports Exerc.* 2003;35:1760–1765.
3. NIOSH. Wildland fire fighter dies from hyperthermia and exertional heatstroke while conducting mop-up operations—Texas. Fire Fighter Fatality Investigation and Prevention Program. NIOSH, Centers for Disease Control and Prevention; 2012. Available at: <http://www.cdc.gov/niosh/fire/reports/face201117.html>. Accessed January 7, 2015.
4. Cuddy JS, Ruby BC. High work output combined with high ambient temperatures caused heat exhaustion in a wildland firefighter despite high fluid intake. *Wilderness Environ Med.* 2011;22:122–125.
5. Rodríguez-Marroyo JA, López-Satue J, Pernía R, et al. Physiological work demands of Spanish wildland firefighters during wildfire suppression. *Int Arch Occup Environ Health.* 2012;85:221–228.
6. Cuddy JS, Reinert AR, Hansen KC, Ruby BC. Effects of modafinil and sleep loss on physiological parameters. *Mil Med.* 2008;173:1092–1097.
7. Cuddy JS, Gaskill SE, Sharkey BJ, Harger SG, Ruby BC. Supplemental feedings increase self-selected work output during wildfire suppression. *Med Sci Sports Exerc.* 2007;39:1004–1012.
8. Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. *Am J Physiol.* 1998;275(1 Pt 2):R129–R134.
9. Buller MJ, Latzka WA, Yokota M, Tharion WJ, Moran DS. A real-time heat strain risk classifier using heart rate and chest skin temperature. *Physiol Meas.* 2008;29:N79–N85.
10. Cuddy JS, Ham JA, Harger SG, Slivka DR, Ruby BC. Effects of an electrolyte additive on hydration and drinking behavior during wildfire suppression. *Wilderness Environ Med.* 2008;19:172–180.
11. Cuddy JS, Slivka DR, Tucker TJ, Hailes WS, Ruby BC. Glycogen levels in wildland firefighters during wildfire suppression. *Wilderness Environ Med.* 2011;22:23–27.
12. Montain SJ, Baker-Fulco CJ, Niro PJ, Reinert AR, Cuddy JS, Ruby BC. Efficacy of eat-on-move ration for sustaining physical activity, reaction time, and mood. *Med Sci Sports Exerc.* 2008;40:1970–1976.
13. Budd GM. How do Wildland firefighters cope? Physiological and behavioural temperature regulation in men suppressing Australian summer bushfires with hand tools. *J Therm Biol.* 2001;26:381–386.
14. Sawka MN, Cheuvront SN, Kenefick RW. High skin temperature and hypohydration impair aerobic performance. *Exp Physiol.* 2012;97:327–332.