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The Impact of Occupational Tasks on Firefighter Hydration During a Live Structural Fire

Adam Walker [1], Rodney Pope [2,3], Ben Schram [1,2], Richard Gorey [2] and Robin Orr [1,2,*]

1 Faculty of Health Sciences and Medicine, Bond University, Gold Coast 4226, Australia; awalker@student.bond.edu.au (A.W.); bschram@bond.edu.au (B.S.)
2 Tactical Research Unit, Bond University, Gold Coast 4226, Australia; rpope@csu.edu.au (R.P.); richard.gorey@student.bond.edu.au (R.G.)
3 School of Community Health, Charles Sturt University, Albury 2640, Australia
* Correspondence: rorr@bond.edu.au; Tel.: +0468-646-027

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Abstract: Structural firefighting is a highly stressful occupation with firefighters performing intense bouts of physical activity in environmental extremes while wearing impermeable, heavy and restrictive personal protective equipment. The aim of this study was to investigate the impact of performing occupational tasks during an active structural fire on firefighters' hydration status. Nine fully qualified firefighters (mean ± SD age = 39.22 ± 7.89 years) completed a 15 min 'live' fire scenario while performing occupational tasks. Urine Specific Gravity (USG), body weight and tympanic membrane temperature were measured pre-scenario and at 0 and 20 min post-scenario. There was a significant decrease in body weight (0 min and 20 min $p < 0.0005$) and increase in tympanic membrane temperature (0 min and 20 min $p < 0.0005$) following the fire scenario. There was no significant change in USG post-scenario. Short duration firefighting operations can cause significant fluid loss, as measured by change in body weight but not necessarily USG.

Keywords: firefighters; structural fires; occupational health; hydration; fire suppression

1. Introduction

Firefighting is a highly stressful occupation with firefighters exposed to a multitude of physical and environmental stresses during their normal duties [1]. Structural fires require firefighters to perform intense bouts of physical activity in environmental extremes, such as high heat and dense smoke, while wearing impermeable, heavy and restrictive personal protective equipment (PPE) [2–5]. The physically demanding nature of firefighting combined with the substantially reduced water permeability, evaporative heat capacity and increased energy demands of wearing PPE can result in a reduced cooling capacity and likely dehydration due to high sweat rates [6–9].

Without adequate fluid intake firefighters may experience the adverse effects of dehydration [2,10]. Effects include decreased core body temperature control [5], decreased heat tolerance time [11], decreased cardiac output with higher heart rates [12], and reductions in aerobic power [13] and muscle endurance [2]. Psychological effects include increased subjective perception of exertion and reduced attention, vigilance and short-term memory [2]. These may lead to detrimental effects on firefighter health, safety and performance.

Evidence investigating firefighter hydration during structural fire suppression is both limited and conflicting. Angerer et al. [14], Holsworth et al. [3], Carlton et al. [15] and Smith et al. [5] all investigated firefighter hydration following structural fire suppression without fluid intake and found significant reductions in body weight ($p < 0.001$) [14] and haematocrit ($p < 0.001$) [3,5], indicating dehydration. Horn et al. (2012), on the other hand, allowed fluid intake during a fire suppression task and found mixed results, with body weight ($p < 0.001$) and salivary osmolality ($p < 0.001$) indicating dehydration, while urine specific gravity (USG), urine osmolality and urine colour ($p > 0.05$) indicated that hydration was maintained. Eglin et al. (2004) also allowed fluid intake but still observed a significant reduction in body weight, indicating mild hypo-hydration, while USG ($p > 0.05$) indicated hydration was maintained. Based on the current evidence it is unclear whether ad libitum drinking is sufficient to maintain hydration. However, it does appear that dehydration can occur rapidly due to the intensity of tasks and lack of time or ready access to fluids.

The objective of this study was to investigate the impact of performing occupational tasks during an active structural fire on firefighter's hydration status. In doing so the present study will provide evidence for the development and refinement of firefighter hydration protocols and health and safety guidelines to minimise adverse health effects and improve work performance.

2. Materials and Methods

This prospective observational cohort study involving repeated measures recruited nine firefighters (seven male and two female) from a state Fire and Emergency Service to participate in a 'live' structural firefighting scenario. Data was collected at a live fire training facility in Australia. All firefighters met the dedicated inclusion criteria; (1) fully qualified, (2) fit for normal duty, (3) cleared for participation by their supervisor, and (4) consented to participation. There were no exclusion criteria.

Firefighter characteristics of age, gender, experience and weight were recorded (Table 1). All personnel wore standard authorised PPE, Australian Defence Apparel Firefighter Garments Structural Uniforms (mean weight 21.39 ± 0.68 kg) and a Scott Advanced Carrying System Single Cylinder (6.8 L) Self Contained Breathing Apparatus (SCBA) (Scott Safety, Sydney, Australia), weighing 9.6 kg full and 8.6 kg empty, for the duration of the scenario.

Table 1. Descriptive characteristics of firefighter participants (n = 7).

	Mean ± SD	Range
Age (years)	39.22 ± 7.89	29–48
Experience (years)	7.89 ± 5.18	1–16
Unloaded weight (kg)	90.41 ± 21.35	62.40–126.6
Loaded body weight (kg)	111.80 ± 21.89	82.7–149.0

2.1. Scenario

Firefighters were randomly grouped into two teams of four and five firefighters respectively. Each firefighter was allocated a task (detailed below) and participated in pre-scenario USG, body weight, then tympanic membrane temperature testing (detailed below), before continuing to the scenario.

Two identical scenarios were set up on site, each with a team of participants and safety staff assigned to it. The scenario consisted of a burn 'load' within a designated structure, equivalent to a standard two seater couch fire, with two tasks typical of firefighting duties set up inside. These were: a low posture victim drag with an 80 kg dummy (7.5 min) and a hose drag (7.5 min), along a designated five metre area within the structure. The participants moved down and back in a crouched position at a slow, deliberate, pace.

Team one completed the scenario first. The scenario lasted for 15 min (limited by oxygen cylinder capacity), with firefighters swapping tasks on the command of a training instructor after 7.5 min. Following completion of the final task firefighters exited the structure and proceeded directly to tympanic membrane temperature testing followed by body weighing and USG specimen collection (discussed in detail below). After 20 min each firefighter completed the same test battery in the aforementioned order. Following a 30-min break to refuel the fire, ensure the structure reached a commensurate thermal profile, and complete post-scenario measures for team one, team two commenced the scenario and testing procedures.

Throughout the scenario two firefighting training instructors were positioned appropriately to ensure the adequate performance of tasks and safety of firefighters and research staff. These safety instructors did not collect any data. Ethics approval for this research was provided by Bond University Human Resources Ethics Committee (Protocol number RO1761).

2.2. Testing Protocol

All outcome measurements were recorded pre-scenario (PRE), immediately post scenario (0 min) and at 20 min post scenario (20 min). Each researcher performed the same measures at all time points of data collection to avoid potential inter-rater bias.

Following PRE testing, during the scenario and during the recovery period participants were not permitted to consume fluid or food unless directed to do so (e.g., for medical reasons) or choosing to withdraw from the study. During the recovery period participants remained in their PPE. This ensured standardisation of the protocol and aimed to replicate real life scenarios where firefighters would remain in PPE if the fire was still ongoing (rotated out for recovery) or there was a high potential for flare ups (re-ignition).

USG was selected as a measure as it is sensitive to changes in acute hydration status and is a valid marker of dynamic dehydration assessment [16,17]. A urine sample (~20 mL) was provided in a medical collection cup prior to pre-scenario body weight measurement and following post-scenario body weight measurements at 0 and 20 min. USG was determined using refractometry with the Altago PAL-105 refractometer (Atago, Co.ltd., Osaka, Japan) with each measure conducted by one researcher and confirmed by a second researcher. Scores were compared against the National Athletic Trainers' Association [18] refractometer score index to determine hydration status.

Acute changes in body weight have been shown to reflect changes in body water, providing a practical and reliable measure of hydration [17,18]. Participants were weighed using Tanita BF-682W electronic scales (Tanita, Chicago, IL, USA) following provision of the urine sample pre-scenario and prior to the urine sample at 0 and 20 min post. Participants were weighed in station wear (unloaded), long pants and shirt, and after donning PPE (i.e., loaded) pre-scenario. Unloaded body weight was reweighed post scenario at 0 and 20 min and loaded body weight at 0 min. All measurements were recorded to the nearest 100 g. This unloaded measure was selected as it best represents the minimal amount of dress that would be worn when attending a fire without PPE and as such will have a higher translation to practice.

Tympanic membrane temperature has been used in the field to monitor body temperature of firefighters during recovery from intense fire operations [19]. Prior to body weight measurements, tympanic temperature was taken from under the flash hood of the left auditory canal by the same researcher on each occasion using a Liberty ET-100A thermometer (Liberty Health Products, Scoresby, Australia). Temperature was measured in degrees Celsius to the nearest 10th of a degree.

Temperatures and humidity within the designated 'burn' structure were measured via HMP77 Thermocouples (Vaisala Oyj, Vantaa, Finland). Environmental temperature and relative humidity outside the burn structure were taken from Bureau of Meteorology Brisbane Airport station observations [20].

2.3. Statistics

Changes in hydration were determined for each time-point following baseline (pre-fire) measurements, using the dependent variables of USG and body weight. Descriptive statistics were generated and described as mean ± standard deviation (SD). To investigate changes in outcome measures and determine their statistical significance between the pre-and two post-measures and following confirmation the data met underlying assumptions of the analysis, a repeated measures analysis of variance (ANOVA) was performed. If the repeated measures ANOVA revealed significant differences existed, a post hoc Bonferroni analysis was conducted to determine the time points between which the significant differences lay. Data were analysed using the Statistical Package for the Social

Sciences Version 20 (IBM Corporation, New York, NY, USA), with alpha levels set a priori at 0.05. A priori assessment of statistical power clearly indicated it was limited by the available sample size and this limitation was considered when interpreting non-significant results.

3. Results

The participants were seven males (mean age = 42.00 ± 5.13 years, mean experience = 8.43 ± 5.09 years; mean weight = 98.59 ± 17.13 kg) and two females (mean age = 36.50 ± 2.12 years, mean experience = 10.00 ± 1.41 years; mean weight = 71.15 ± 12.37 kg) who were all current firefighters. Participant numbers were limited by the live structural burn conditions, and particularly the numbers of participants who could be fully monitored to ensure their safety in the burn chamber on the day of data collection. Participant characteristics including age, experience and unloaded and loaded body weight are presented in Table 1. From the initial nine participants, two participants (one female and one male) were excluded from the study as a safety measure. While these firefighters completed the scenario, they were feeling the effect of heat and in order to ensure they did not develop heat illness, it was decided based on a priori safety rules to allow these participants to cease the measures, hydrate and remove their PPE. No further ill effects were observed, with both members recovering and returning to the group post event for the group debriefing that occurred.

The average temperature in the 'burn' structure was 40.0 °C (maximum 50.9 °C) at 0.3 m above the floor, 130–155 °C at 1.1 m above the floor, and 458.3 °C (maximum 571.5 °C) at the ceiling level (approx. 2.6 m). The average relative humidity within the 'burn' structure during the scenarios was 53.1% (maximum 58.6%). The ambient environmental temperature at the time of the burn scenarios was 24.8 °C with a relative humidity of 87%.

3.1. Hydration Outcomes

Table 2 shows the results for USG, unloaded body weight and tympanic membrane temperature at each time point, indicating statistical significance of observed differences, when present.

Table 2. Mean data ± SD and ranges for the pre-scenario and post-scenario measures.

Measure	PRE	POST	20 MIN POST
Urine Specific Gravity	1.016 ± 0.010	1.018 ± 0.010	1.018 ± 0.009
Unloaded Body Weight (kg)	95.57 ± 21.52	94.84 ± 21.35 *	94.37 ± 21.35 *#
Tympanic Membrane Temperature (°C)	36.53 ± 0.35	38.94 ± 0.42 *	37.76 ± 0.45 *#

* Significant change ($p \leq 0.001$) from pre-scenario. # Significant change ($p \leq 0.001$) from post-scenario.

3.2. Urine Specific Gravity

The USG results indicated that prior to the scenario participants were typically in a state of minimal dehydration (USG mean ± SD = 1.016 ± 0.010 au). One participant was considered to be severely dehydrated (1.035 au), five participants were minimally dehydrated (range 1.010–1.020 au) and one participant was well hydrated at the commencement of the scenario (1.005 au).

Given the small sample size, minimal changes observed in raw USG levels across time points (Table 1), and associated limited statistical power for making meaningful USG comparisons across these time points, no statistical comparisons of USG levels across the time points were conducted.

3.3. Body Weight

There was a significant decrease in the mean unloaded body weight of the firefighters, when compared to pre-scenario body weights, at both 0 min post scenario (−0.73 kg; −0.76%; $p < 0.001$) and 20 min post scenario (−1.20 kg; −1.27%; $p < 0.001$). There was also a decrease in body weight observed from 0 to 20 min post scenario (−0.47 kg; 0.52%; $p = 0.001$). Compared against the National Athletic

Trainers' Association [18] scoring index, the observed average −1.27% change in body weight between pre-scenario and 20 min post-scenario time points indicates a minimal change in hydration.

3.4. Tympanic Membrane

There was a significant increase in average tympanic membrane temperature of the firefighters from pre scenario to post scenario (mean change = 2.41 °C, $p < 0.001$). The temperature then decreased significantly from 0 min post-scenario to 20 min post-scenario (mean change = −1.19 °C, $p = 0.001$), although the temperature at 20 min post-scenario remained significantly higher than the temperature at pre-scenario (mean change pre to 20 min post = +1.23 °C, $p < 0.001$).

4. Discussion

The aim of this study was to investigate the impact of performing occupational tasks during an active structural fire on firefighters' hydration status. The main findings of this study were: (1) firefighters lost a significant amount of body weight during, and following, the scenario; (2) there was a significant increase in firefighter tympanic membrane temperature; and (3) tympanic membrane temperature recovered significantly following 20 min of rest after firefighters exited the burn scenario but not to baseline levels. The mean changes in USG levels across time points indicated in Table 1 were minimal but this finding should be viewed with caution and will not be further discussed since the sample size and associated statistical power to detect a meaningful change if one would have occurred in these circumstances in the underlying firefighter population were clearly low. Limited comparative data investigating firefighting hydration during active structural fires using any type of measure is available in prior published reports, making it difficult to provide measures for comparison. Despite its limited sample size, this study therefore represents a valuable addition to the existing literature, particularly in its findings relating to body weight change as a measure of the effects of structural firefighting on hydration and also based on the fact it utilised a scenario that reflected real structural fire suppression operations.

This study found that body weight decreased significantly following the fire scenario and at 20 min post-scenario. These results are similar to those observed in other studies investigating body weight loss, indicating fluid loss, following structural firefighting tasks [2,14,21]. In a similar study to the present one, it was found that following a 30 min structural fire operation involving occupational tasks, 49 firefighters wearing PPE and SCBA had a significant decrease in body weight (−0.6 ± 0.2 kg, 0.47%, $p < 0.001$) in temperatures of 200 °C at 1.5 m above ground and 700 °C below the ceiling [14]. However, these results from Angerer et al. [14], together with the results of this current study for the immediate post-scenario time point, need to be interpreted carefully as, although reaching statistical significance, they did not meet the National Athletic Trainers' Association dehydration criteria [18], requiring a minimum 1% decrease in body weight from a hydrated state to signify a change in hydration status.

However, as firefighters in the present study typically arrived in a minimally dehydrated state, as indicated by their USG measures, the observed 0.76% change in body weight may be sufficient to signify a shift to a greater degree of dehydration. This was also seen in a similar study to the present one, which investigated firefighter hydration following a 30 min fire operation involving occupational tasks [15]. Firefighters lost 0.96% of body weight but arrived to commence their shift in a state of moderate dehydration. In both circumstances, due to firefighters arriving in a degree of dehydration, the firefighters may have reached a larger level of dehydration than the findings might initially indicate.

Following the 20 min rest period in the current study, body weight significantly reduced further, signifying firefighters becoming minimally dehydrated, with a 1.27% loss in body weight compared to pre-scenario. This highlights the fact that fluid loss can occur rapidly and that without fluid intake post occupational duties, fluid loss may continue to occur and increase dehydration risk even when the firefighter is removed from the 'fire'/burning structure. The extent of fluid loss observed in this study may have also been underestimated, as participants were weighed in their station wear, which is anticipated to have absorbed some of the fluid loss from sweating. Taking this into consideration, firefighters may have reached a dehydrated state earlier than first thought and to a greater extent than the results represent.

An equivalent situation was evident in an earlier study in which 14 firefighter instructors had a significant loss of body weight across several training exercises, causing mild hypohydration [21]. Results indicated a mean body weight reduction of 0.79% following 30 'hot fire exercises' totalling 33 min of firefighting, and a significant mean body weight change (1.59 ± 0.57 kg) following 6 'fire attack' and 8 'fire behaviour' exercises totalling 32 min in duration [21]. Furthermore, a recent study involving 35 firefighters found a significant body weight loss following a 3-h live fire training exercise [2]. The task involved 3–4 evolutions lasting 15–25 min, separated by 10–15 min with numerous occupational tasks. Both studies encouraged ad libitum drinking. These studies provide evidence that despite adequate fluid availability and sufficient breaks, fluid intake of structural firefighters can still be insufficient to counteract fluid loss from structural firefighting, as measured by body weight.

A major point of note is the fact that firefighters arrived on shift in a minimally dehydrated state. Only one firefighter arrived in a well hydrated state. Previous research has also found firefighters arrive in a seriously dehydrated state [2,10,15,21]. These findings continue to raise concerns of firefighters putting themselves at an increased risk of heat injuries and negative job outcomes by arriving for duty in a dehydrated state. Storing fluids on board the fire vehicles for pre-hydration and post-rehydration on the way to and from events is advocated to combat this. This may aid in pre-task hydration and the replacement of fluid loss known to occur from such an event. However, it should also be noted that in some circumstances, ad libitum drinking may not be sufficient to replenish fluid [2,21]. Furthermore, with adequate fluid replacement options available at fire stations, ensuring firefighters are aware of the risk of dehydration may help to encourage firefighters to follow such rehydration procedures [2].

This current study also found a significant increase in tympanic membrane temperatures at all time points. The measured mean increase of tympanic temperatures of 2.4 °C is substantially higher than those seen in the previous studies. To measure core temperature, Smith et al. (2001) utilised a gastro pill and found a mean increase of 0.9 °C and Angerer et al. (2008) and Carlton et al. [15] using tympanic membrane temperature found a mean increase of 0.7 °C and 1.29 °C respectively. A potential reason for the notable differences found in this current study may be due to the collection method of taking tympanic membrane temperature before removal of the flash hood. This was performed to get a representation of 'under-the-hood' environments as well as preventing cooling between the end of the scenario and the start of post event measures. Scenario factors such as length of exposure, 'burn' structure temperatures and tasks performed may also contribute to the observed differences between studies. Furthermore, a significant loss of body weight, as found in this study, has been suggested to increase core temperature and reduce tolerance to increases in core temperature [21,22]. This further reinforces the importance of hydration protocols to prevent against heat strain in firefighters.

This data adds to extensive evidence of the high thermal demands of firefighting and the real risk of the negative consequences of heat strain. As noted by Angerer et al. (2008), the ergonomic standard ISO 9886 sets the upper limit of core temperature increase per hour at 1.4 °C. In the current study employing a 15-min task, this limit was exceeded by all subjects. It is of further concern that the recommended safe upper limit of working core temperature of 38.5 °C [23], was also exceeded by all subjects. Temperatures ranged from 38.5 °C to 39.5 °C following the 'burn' scenario, highlighting how temperatures can rise substantially within just 15 min of commencing structural firefighting. Although tympanic membrane temperature is readily used in the field as a convenient measure of estimating core body temperature, caution is recommended when using these devices as a measure of heat strain as it has been shown to have poor agreement with direct measures such as ingestible capsules [24]. This suggests that caution should be applied in drawing firm conclusions from these results, and further research is warranted.

It was also of interest that with 20 min of rest, tympanic membrane temperatures were still a mean of 1.2 °C above baseline temperatures. These results parallel those by Eglin et al. (2004) who found core temperatures remained constant for 10–15 min post fire scenario. This fact may have been exacerbated by the firefighters resting in their PPE, thereby reducing opportunity for any potential cooling effect [6]. While this approach may be unlike typical procedures involving removal of PPE and commencement of cooling strategies, there may be occasions where firefighters are removed from the fire environment yet remain in their PPE (e.g., changing SCBA tanks before returning directly into the fire environment or working in an area where a flashover may still occur/reoccur). Extensive research into cooling strategies post-firefighting, such as hand and forearm cold water immersion [25–30], ice slurry ingestion [31] and cooling garments [32,33] has produced promising results. Firefighting agencies have adopted many of these strategies to aid in post activity cooling and rehydration, to ensure adverse events are minimised with the safety of firefighters paramount.

Limitations

The main limitations of this study were; limited control of real life variables, protocol factors and a small sample size. Our study was aimed at replicating an everyday event for a firefighter. As a result, no attempt was made to control their normal diet and caffeine intake. Acknowledging that these variables could affect the physiological response to the scenario, the aim of this study was to replicate the impact of firefighting on hydration in a situation as close to that faced by firefighters everyday as possible. Although this reduces standardisation of the protocol it provides a closer representation of the actual effects of structural firefighting in the field. Without taking this approach, some key findings would not have been discovered.

Having subjects weighed in station wear may have affected the results of the body weights measured in this study. As previously stated, weighing firefighters while wearing their 'station' clothing (which is typically worn underneath their PPE) may have led to an under estimation of their fluid loss, with sweat accumulating in the clothing impacting on the reliability of bodily fluid loss results.

The USG and body weight standards were compared against those developed by consensus for athletic populations. These may have limited application to firefighting personnel, who are exposed to extreme temperatures while wearing heavy impermeable PPE. However, there are no equivalent standards for personnel in firefighting organisations and thus the results of the current study provide a satisfactory benchmark by which to gauge hydration responses during structural firefighting.

A small sample size, common in studies with firefighting personnel, is another limitation of the present study. This limitation makes transferability of results to larger firefighter populations more difficult and the associated low level of statistical power prevented meaningful comparisons of USG levels across time points.

5. Conclusions

This study generated findings highly pertinent for firefighting personnel and organisations. Firstly, it is evident that even short duration firefighting operations can cause significant fluid loss with the potential to lead to dehydration. This may be exacerbated by firefighters arriving on shift in a dehydrated state. Secondly, the thermal effects of firefighting significantly affect firefighter tympanic membrane temperature. Without cooling strategies, the body temperature may remain elevated for at least 20 min, even outside of the fire event if the firefighters are required to remain in PPE. Due to the intense nature of structural firefighting and the potential for rapid dehydration, further research to determine fluid replacement requirements is warranted, with the aim of developing evidence-based guidelines to ensure the health and safety of firefighters.

Author Contributions: R.O. & R.G. designed the study. A.W. & R.O. gained ethics approval. R.G. gained departmental approvals. All authors collected the data. A.W., R.O. & R.P. analysed the results & drafted the manuscript. B.S. revised the manuscript for publication. All authors read and approved the final manuscript.

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