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ARTICLE

The effects of cranial cooling during recovery on subsequent uncompensable heat stress tolerance

Phillip J. Wallace, Anaïs T. Masbou, Stewart R. Petersen, and Stephen S. Cheung

Abstract: This study compared cranial (CC) with passive (CON) cooling during recovery on tolerance to subsequent exercise while wearing firefighting protective ensemble and self-contained breathing apparatus in a hot-humid environment. Eleven males (mean ± SD; age, 30.9 ± 9.2 years; peak oxygen consumption, 49.5 ± 5.1 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) performed 2 × 20 min treadmill walks (5.6 $\text{km}\cdot\text{h}^{-1}$, 4% incline) in 35 °C and 60% relative humidity. During a 20-min recovery (rest), participants sat and removed gloves, helmets, and flash hoods but otherwise remained encapsulated. A close-fitting liquid-perfused hood pumped 13 °C water at ~500 $\text{mL}\cdot\text{min}^{-1}$ through the head and neck (CC) or no cooling hood was worn (CON). During rest, neck temperature was lower in CC compared with CON from 4 min (CC: 35.73 ± 3.28 °C, CON: 37.66 ± 1.35 °C, $p = 0.025$) until the end (CC: 33.06 ± 4.70 °C, CON: 36.85 ± 1.63 °C, $p = 0.014$). Rectal temperature rose in both CC (0.11 ± 0.19 °C) and CON (0.26 ± 0.15 °C) during rest, with nonsignificant interaction between conditions ($p = 0.076$). Perceived thermal stress was lower ($p = 0.006$) from 5 min of CC (median: 3 (quartile 1: 3, quartile 3: 4)) until the end of rest compared with CON (median: 4 (quartile 1: 4, quartile 3: 4)). However, there were no significant differences ($p = 0.906$) in tolerance times during the second exercise between CC (16.55 ± 1.14 min) and CON (16.60 ± 1.31 min), nor were there any difference in rectal temperature at the start (CC: 38.30 ± 0.40 °C, CON: 38.40 ± 0.16 °C, $p = 0.496$) or at the end (CC: 38.82 ± 0.23 °C, CON: 39.07 ± 0.22 °C, $p = 0.173$). With high ambient heat and encapsulation, cranial and neck cooling during recovery decreases physiological strain and perceived thermal stress, but is ineffective in improving subsequent uncompensable heat stress tolerance.

Key words: firefighting, cooling strategy, exertional heat illness, thermal perception, occupational physiology.

Résumé : Cette étude compare l’effet du refroidissement crânial (« CC ») par rapport au refroidissement passif (« CON ») durant la récupération sur la tolérance à un exercice subséquent avec le port d’un ensemble de lutte contre l’incendie et un appareil respiratoire autonome dans un environnement chaud et humide. Onze hommes (moyenne ± écart-type; âgé, 30,9 ± 9,2 ans; de la consommation d’oxygène de pointe, 49,5 ± 5,1 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) effectuent 2 × 20 min de marche sur un tapis roulant (5,6 $\text{km}\cdot\text{h}^{-1}$, pente de 4 %) dans une température de 35 °C et une humidité relative de 60 %. Au cours des 20 minutes de récupération (repos), les participants restent assis et ne portent pas de gants, de casque et de cagoule de feu, mais gardent leur tenue vestimentaire de protection. Les participants portent une cagoule de refroidissement ajustée dans laquelle circule de l’eau (~500 $\text{mL}\cdot\text{min}^{-1}$, 13 °C) pour refroidir la tête et le cou (« CC ») ou ne portent pas cette cagoule de refroidissement (CON). Au repos, la température du cou est inférieure dans la condition CC comparativement à CON de la 4^{e} minute (CC: 35,73 ± 3,28 °C, CON: 37,66 ± 1,35 °C, $p = 0{,}025$) jusqu’à la fin (CC: 33,06 ± 4,70 °C, CON: 36,85 ± 1,63 °C, $p = 0{,}014$). La température rectale s’élève dans les conditions CC (0,11 ± 0,19 °C) et CON (0,26 ± 0,15 °C) au repos et ne présente pas d’interaction significative d’une condition à l’autre ($p = 0{,}076$). Le stress thermique perçu est inférieur ($p = 0{,}006$) de la 5^{e} minute dans la condition CC (médiane 3; quartile 1: 3, quartile 3: 4) jusqu’à la fin du repos comparativement à CON (médiane 4; quartile 1: 4, quartile 3: 4). Toutefois, on n’observe aucune différence significative ($p = 0{,}906$) du temps de tolérance entre CC (16,55 ± 1,14 min) et CON (16,60 ± 1,31 min) lors du deuxième exercice; de même, on n’observe aucune différence de température rectale du début (CC: 38,30 ± 0,40 °C, CON: 38,40 ± 0,16 °C, $p = 0{,}496$) à la fin (CC: 38,82 ± 0,23 °C, CON: 39,07 ± 0,22 °C, $p = 0{,}173$). Dans un milieu à température élevée et avec une tenue de protection, le refroidissement du crâne et du cou durant la récupération suscite une diminution du stress physiologique et du stress thermique perçu, mais est inefficace pour pallier le stress thermique subséquent sans compensation. [Traduit par la Rédaction]

Mots-clés : lutte contre l’incendie, stratégie de refroidissement, malaise thermique de l’effort, perception thermique, physiologie du travail.

Introduction

Firefighting is physically demanding and includes prolonged work involving intervals of heavy high-intensity exercise that leads to increased levels of cardiovascular, metabolic, and thermal strain (Cheung et al. 2010). Romet and Frim (1987) found that during 24 min of simulated fire suppression, heart rate (HR) was consistently higher than 150 $\text{beats}\cdot\text{min}^{-1}$ and that core temperature rose by 1.3 °C. Horn et al. (2013) studied 4 bouts of live-fire training that consisted of 15–30 min of work and 20–40 min of recovery, and reported HR > 95% of age-predicted maximum during each bout and 1.8 °C rise in core temperature. Part of the high physiological strain from firefighting is due to the firefighter protective ensemble (FPE) and self-contained breathing apparatus (SCBA), which may exceed 25 kg. The protective ensemble increases the metabolic cost of exercise while impeding heat dissipation, resulting in increased heat storage, greater risk for exertional heat

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illness, and decreased work capacity (McLellan et al. 2013). Another limit to effective work comes from the finite air supply within the SCBA, as air consumption can be exacerbated by hyperthermic hyperventilation (White 2006).

Active cooling strategies used during recovery periods such as SCBA cylinder changes can be effective countermeasures against heat storage. Forearm immersion and facial misting significantly decreases core temperature and increases total work tolerance time compared with passive recovery in a hot environment (Selkirk et al. 2004). However, a limitation of forearm cooling is the need for removal of the jacket, and facial misting may be less effective in highly humid environments because of the decreased water vapour pressure gradient (Selkirk et al. 2004). Head cooling may be another effective method for attenuating thermal and cardiovascular strain. The head is densely vascularized, has minimal adiposity that makes for high thermoconductivity, experiences minimal vasoconstriction when exposed to cold, and is accessible with minimal removal of clothing (Froese and Burton 1957; Shvartz 1970). Hyperthermia also leads to a large and sustained increase in blood flow to the face and scalp through the external carotid artery (Bain et al. 2013; Sato et al. 2011). A wide range of cooling studies have demonstrated that the head can effectively dissipate heat (Nunneley et al. 1982; Pretorius et al. 2010; Rasch et al. 1991), though other research has questioned the capacity for major core temperature decreases during exercise-heat stress (Nelson and Nunneley 1998; Nybo et al. 2002). Previous studies that used head cooling or neck cooling collars prior to or during exercise in the heat demonstrated an improved tolerance time along with participants terminating exercise at a higher final core temperature (Tyler and Sunderland 2011). Independent of physiological alterations, head cooling may also improve exercise-heat tolerance through altered perception of thermal strain because of the high thermosensitivity of the head, face, and neck (Cotter and Taylor 2005). Directly cooling the face with a fan, lowering forehead skin temperature to 28 °C, and cranial head cooling is shown to decrease ratings of perceived exertion (RPE) and lower levels of prolactin during aerobic exercise in hot environments (Ansley et al. 2008; Armada-da-Silva et al. 2004; Mündel et al. 2007; Simmons et al. 2008*a*). The dampening of the perceived thermal strain has been shown to increase time to exhaustion along with delaying the point of voluntary termination of exercise, despite no differences in core temperature while wearing a neck cooling collar or through the use of cooling fans (Ansley et al. 2008; Tyler and Sunderland 2011).

The purpose of this study was to investigate the effectiveness of head and neck cooling, applied during recovery, on physiological and perceptual strain during subsequent exercise in the heat. Participants simulated firefighting work with treadmill exercise (~2–2.5 L·min^{-1}) in a hot and humid (35 °C, 60% relative humidity (RH)) environment while wearing full FPE and SCBA. We hypothesized that head and neck cooling would decrease thermal, cardiovascular, and perceived strain during the recovery period, resulting in better tolerance during subsequent exercise and decreased ventilatory demands.

Materials and methods

Participants

The experimental protocol and procedures were approved by the Bioscience Research Ethics Boards at Brock University and the University of Alberta, and conformed to the latest revision of the Declaration of Helsinki. All subjects were screened using the Physical Activity Readiness Plus Questionnaire and a full explanation of procedures, discomforts, and risks was given prior to obtaining written informed consent.

Eleven male participants were recruited from the university and firefighter communities for this experiment. The mean ± SD age, height, body mass, body fat percentage, and peak oxygen consumption ($\dot{V}O_{2peak}$) was 30.9 ± 9.2 years, 172.4 ± 21.8 cm, 80.0 ± 5.5 kg, 13.6% ± 2.8%, and 49.5 ± 5.1 mL·kg^{-1}·min^{-1}, respectively. The study was conducted at Brock University from February to April in a winter climate, such that participants were in a non-heat acclimatized state. For each subject, experimental sessions took place at the same time of day to control for circadian changes in thermal status, and were separated by at least a week to ensure proper recovery time and to reduce the potential for heat acclimation.

Clothing ensemble

Participants wore fire rescue service uniforms, consisting of pants and a short sleeve shirt (55% fibrous fire retardant fibre, 45% cotton, Lion Apparel, Dayton, Ohio, USA). Participants each wore National Fire Protection Association standard 1500 compliant FPE, including pants, jacket, helmet, facemask, flash hood, gloves, and SCBA. The SCBA consisted of a positive pressure regulator (Scott E-Z FLO), connected to a Scott pressure-reducing regulator, attached to a Scott 4.5 Air-Pak cylinder (Scott Safety, Monroe, N.C., USA) worn as part of a shoulder and waist supported backpack. The mean mass of the FPE and SCBA was 22.5 ± 0.5 kg. Participants wore their own running shoes to maximize walking comfort and safety during treadmill exercise. While direct materials testing of the particular garments was not obtained, very similar ensembles (Selkirk and McLellan 2004) had thermal resistance of 0.240 m^2·°C^{-1}·W^{-1} (1.55 Clo) and Woodcock vapour permeability coefficient of 0.27.

Anthropometry and fitness testing

Participants' stature (cm), mass (kg), and skinfold thickness at 7 sites (triceps, subscapular, abdomen, supra-iliac crest, mid-axilla, quadriceps, and pectoralis major) were measured. Body density (Jackson and Pollock 1978) and percent fat (Siri 1993) were calculated.

$\dot{V}O_{2peak}$ was determined at a thermoneutral temperature (~22 °C, 30% RH) in FPE and SCBA on a motorized treadmill. The treadmill speed was set at 5.6 km·h^{-1} with an initial incline of 0%. Incline increased by a 1% grade each minute until the participant reached volitional fatigue. Expired gases were collected through the SCBA mask and regulator, which was fitted with a Plexiglas cone over the exhalation ports (Eves et al. 2002). Gas exchange data were averaged over 30-s periods and the highest 30-s oxygen consumption ($\dot{V}O_2$) value was accepted as $\dot{V}O_{2peak}$.

Experimental protocol

A familiarization trial, identical to the passive cooling condition, was performed to ensure that participants were fully familiarized with the experimental protocol. Upon arrival to the laboratory, participants provided a small urine sample, and urine specific gravity (USG) was tested to ensure euhydration (1.000–1.020). If this threshold was exceeded the session was rescheduled. Nude body mass was obtained prior to instrumentation and upon de-instrumentation at the end of the experiment. Participants were then instrumented and fitted with FPE and SCBA, and then full gear mass was measured prior to the start of testing.

Following instrumentation, participants entered an environmental chamber set at 35 °C and 60% RH. The experimental protocol consisted of 2 identical exercise bouts with 1 rest period in between. The exercise bouts (Exercise1 and Exercise2) consisted of a 3-min warm up at 5.6 km·h^{-1} with a 2% incline, 20 min of exercise at 5.6 km·h^{-1} with a 4% incline, and a 3-min cool down at 3.5 km·h^{-1} with a 0% incline. Exercise was terminated because of volitional fatigue or attainment of rectal temperature (T_{re}) of 40.0 °C.

Following Exercise1, participants remained seated in the chamber for a 20-min rest period to simulate a SCBA cylinder change and rehabilitation period. Body mass in the FPE was recorded at the start and the end of the rest period. During rest, all participants consumed 250 mL of room temperature (35 °C) water.

In random order, one of the trials utilized active cranial cooling (CC) through use of a cooling hood, while the other trial used passive cooling (CON) during the recovery period. Passive cooling (CON) consisted of having participants seated in a chair where the SCBA, gloves, mask, and flash hood were removed, while the FPE jacket remained on and buttoned up. CC consisted of participants removing the SCBA, gloves, mask, and flash hood, then being fitted with a close-fitting custom liquid-perfused hood (Life Enhancement Technologies, Santa Clara, Calif., USA) that pumped 13 °C water at a rate of $\sim$500 mL·min$^{-1.}$ The cooling hood was tightly fitted to each participant's head with a pneumatic pump to maximize contact of the cooling hood with the head, face, and neck.

Instrumentation

Rectal temperature was continuously measured using a flexible core temperature thermistor (Mon-A-Therm Core, Mallinckrodt Medical, St. Louis, Mo., USA), inserted 15 cm past the anal sphincter. Neck temperature (T_{neck}) was measured using a skin temperature thermistor located on the dorsal side of the neck between the C2 and C3 vertebrae. Temperature measurements were collected through a data logger (Smart Reader Plus, ACR Systems Inc., Surrey, B.C., Canada) and converted to 1-min averages.

Expired gases were collected during both exercise bouts to measure $\dot{V}O_2$ and carbon dioxide exhalation ($\dot{V}CO_2$) through the SCBA mask and regulator, which was fitted with a purpose-built Plexiglas cone over the exhalation ports (Eves et al. 2002). The distal end of the Plexiglas cone was connected to a metabolic cart (ML206 Gas Analyzer, ADInstruments Inc., Colorado Springs, Colo., USA) with a hose. Expired minute ventilation from the breathing apparatus was continuously measured and summed to calculate total air consumption for each exercise bout.

Perceptual measures of exercise, thermal and breathing stress were recorded every 4 min during each exercise bout and every 5 min during rest. RPE were recorded using the 15-point Borg Scale (Borg 1982). Perceived thermal stress of the body (TS) was given on a 9-point scale where 1 = "I am comfortable", 3 = "I am starting to get hot", 5 = "I am hot", 7 = "I am very hot", and 9 = "I am unbearably hot (Nelson et al. 2009). Perceived Breathing Stress (BrS) was presented on an 11-point scale as follows: 0 = "None at all", 3 = "Easy", 6 = "Somewhat hard", and 10 = "Maximal".

Statistical analyses

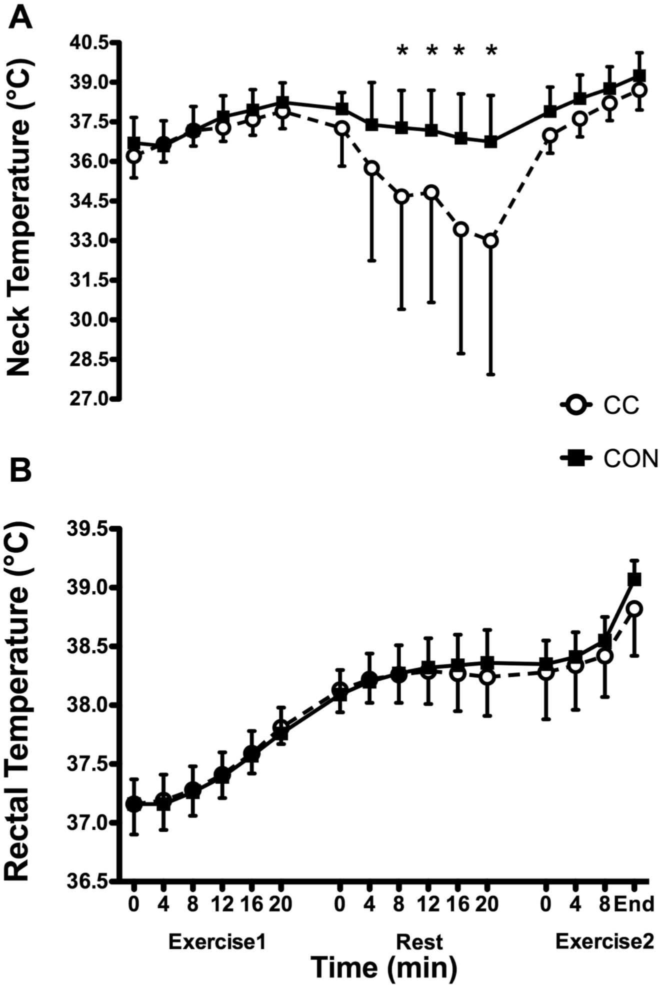
Data are presented as the mean ± SD. Normal distribution was assessed, and if the assumption of sphericity could not be met, the Greenhouse–Geissser correction was used. All continuous variables were analyzed with a 2-way (trial × time) repeated measures ANOVA, with a Bonferroni test used for all post hoc comparisons. Paired sample t tests were performed to test significant main effects at specific time points. A Wilcoxon signed-rank test was used to compare all ordinal data (RPE, TS, BrS) at each time point. These results are presented as the median (quartiles 1 and 3). Statistical significance was set at $p < 0.05$. All analyses were performed using IBM SPSS Statistics for Windows (version 20.0; IBM Corp., Armonk, N.Y., USA).

Results

Exercise1

All participants began each trial in a euhydrated state with no differences ($p = 0.200$) in USG between the CC (1.007 ± 0.005) and the CON (1.004 ± 0.001) conditions. There were also no differences ($p > 0.05$) in starting nude body mass between conditions (CC: 79.05 ± 4.57 kg, CON: 79.22 ± 4.65 kg). All participants successfully completed Exercise1. Rectal temperature, T_{neck}, HR, and minute ventilation ($\dot{V}_E$) significantly (all $p < 0.05$) increased during exercise in both conditions. There were no differences between conditions for T_{re} and T_{neck} (Fig. 1), HR (Fig. 2), or $\dot{V}_E$ (Fig. 3) at any time points. Total air consumption was not different ($p = 0.341$) between CC (1137.2 ± 80.7) and CON (1163.7 ± 103.3) or at any time point. $\dot{V}O_2$ significantly rose ($p < 0.05$) from the start (CC: 1.55 ± 0.20 L·min^{-1}, CON: 1.64 ± 0.28 L·min^{-1}), to the end of Exercise1 (CC: 2.32 ± 0.23 L·min^{-1}, CON: 2.47 ± 0.37 L·min^{-1}) with no significant differences ($p > 0.05$) between conditions. $\dot{V}CO_2$ significantly increased ($p < 0.05$) from the start (CC: 1.21 ± 0.08 L·min^{-1}, CON: 1.26 ± 0.16 L·min^{-1}), to the end of Exercise1 (CC: 2.07 ± 0.19 L·min^{-1}, CON: 2.12 ± 0.19 L·min^{-1}) with no significant differences ($p > 0.05$) between conditions. Perceptions of exercise, thermal, and breathing stress increased significantly (all $p < 0.05$) over time, but there were no differences ($p > 0.05$) between conditions at any time point during Exercise1 (Fig. 4).

Fig. 1. Neck and rectal temperatures during Exercise1, rest, and Exercise2. *, Significant difference between cranial (CC) and passive cooling (CON).



Rest

Cranial cooling was successful in creating 2 distinct cooling conditions, as there were significant within-subjects effects ($p < 0.05$) for T_{neck} between CC and CON during rest. Neck temperature was significantly lower in the CC condition compared with the CON condition from 4 min (CC: 35.73 ± 3.28 °C CON: 37.66 ± 1.35 °C, $p = 0.025$) of rest until the end of rest (CC: 33.06 ± 4.70 °C CON: 36.85 ± 1.63 °C, $p = 0.014$) (Fig. 1). Rectal temperature rose in both conditions from the start (CC: 38.15 ± 0.18 °C, CON: 38.10 ± 0.20 °C) until the end of rest (CC: 38.26 ± 0.34 °C, CON: 38.37 ± 0.27 °C) (Fig. 1). There were no significant main effect ($p = 0.735$) in T_{re} between CC and CON. Similarly, while ΔT_{re} was 0.26 ± 0.15 °C during CON and 0.11 ± 0.19 °C during CC, there remained no interaction effect ($p = 0.076$) between CON and CC during rest. HR decreased ($p < 0.05$) from the start of rest until the end in both CC (start: 123.0 ± 4.23 beats·min^{-1}; end: 105.27 ± 2.85 beats·min^{-1}) and

Fig. 2. Heart rate during Exercise1, rest, and Exercise2. b·min⁻¹, beats·min⁻¹. *, Significant difference between cranial (CC) and passive cooling (CON).

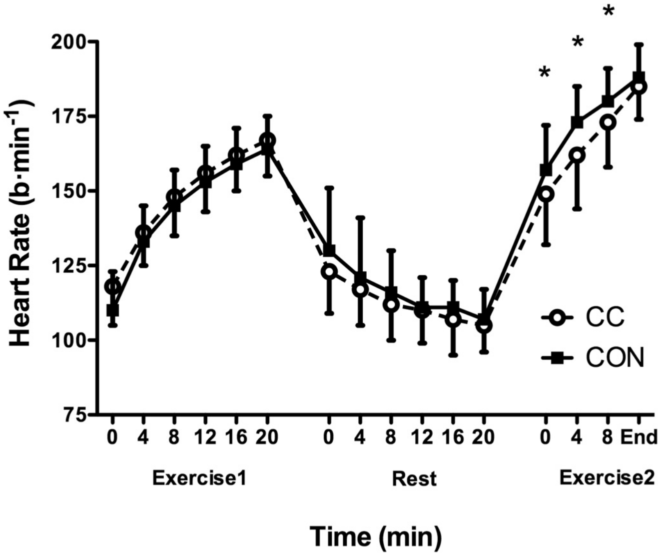
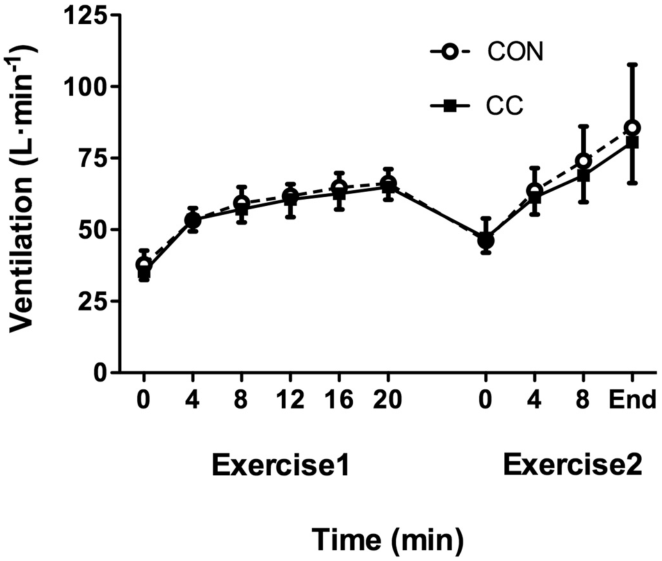


Fig. 3. Ventilation rates during Exercise1 and Exercise2. CC, cranial cooling; CON, passive cooling.



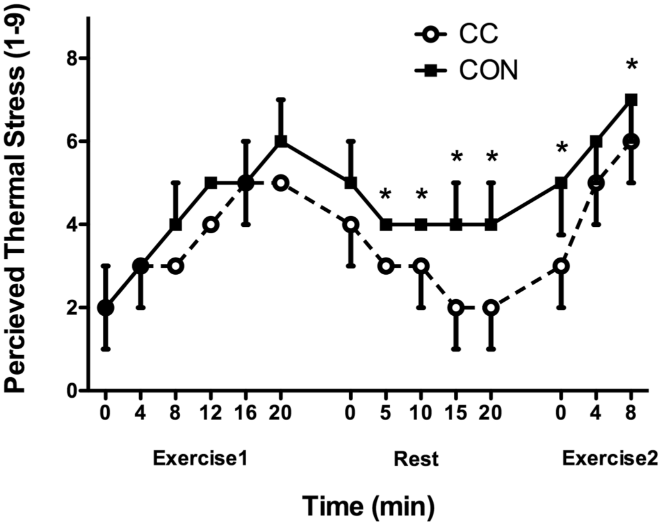
CON (start: 130.0 ± 6.36 beats·min⁻¹; end: 107.0 ± 3.14 beats·min⁻¹), with no significant ($p > 0.05$) differences in cardiovascular strain between conditions (Fig. 2).

There was a significant effect on the perception of thermal stress with CC during rest. Perceived thermal stress was not different at the start of rest (CC: 4 (3–5); CON: 5 (4–6); $p = 0.176$), but was significantly lower in CC compared with CON at 5 min (CC: 3 (3–4); CON: 4 (4–4); $p = 0.006$), 10 min (CC: 3 (2–4); CON: 4 (4–4); $p = 0.007$), 15 min (CC: 2 (1–4); CON: 3 (3–5); $p = 0.031$), and 20 min (CC: 2 (1–4); CON: 3 (3–5); $p = 0.005$) during rest.

Exercise2

One participant did not attempt Exercise2 because of heat-induced orthostatic intolerance experienced at the end of rest in both conditions. Therefore, analysis during Exercise2 was based on 10 participants. Three of the 10 participants completed Exercise2 in both the CC and CON conditions, while the remainder of participants stopped because of volitional exhaustion and none stopped because of reaching the T_{re} cut-off of 40.0 °C. There were no significant ($p = 0.906$) differences in tolerance time between CC (16.55 ± 1.14 min) and CON (16.60 ± 1.31 min). The maximum common tolerance time for $n = 10$ was 9 min, and therefore physiological and perceptual measurements were analyzed at t = 0, 4, and 8 min along with the final termination time point to compare all 10 participants.

Fig. 4. Perceived thermal stress during Exercise1, rest, and Exercise2. *, Significant difference between cranial (CC) and passive cooling (CON).



Rectal temperature and HR increased (all $p < 0.05$) over time throughout Exercise2. Rectal temperature was not different between groups at the start (CC: 38.30 ± 0.40 °C; CON: 38.40 ± 0.16 °C; $p = 0.496$) or at the end (CC: 38.82 ± 0.23 °C; CON: 39.07 ± 0.22 °C; $p = 0.173$) of Exercise2 (Fig. 1). There were significant ($p = 0.027$) within-subjects effects between CC and CON on HR response during Exercise2. HR was not statistically different at the start (CC: 149 ± 17.6 beats·min⁻¹; CON: 157 ± 15.6 beats·min⁻¹; $p = 0.072$) or at the end (CC: 185 ± 11.6 beats·min⁻¹; CON: 188.0 ± 11.3 beats·min⁻¹; $p = 0.121$) of Exercise2 (Fig. 2). However, HR was significantly lower in CC at 4 min (CC: 162.0 ± 18.7 beats·min⁻¹; CON: 174.0 ± 12.1 beats·min⁻¹; $p = 0.021$) and 8 min (CC: 173 ± 15.6 beats·min⁻¹; CON: 181.0 ± 11.0 beats·min⁻¹; $p = 0.028$) compared with CON.

There was a significant rise (all $p < 0.05$) in $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ over the course of Exercise2, with no significant within-subjects factors (all $p > 0.05$) between cooling condition. There were no differences in $\dot{V}_E$ at the start (CC: 47.13 ± 5.17 L·min⁻¹; CON: 46.17 ± 7.90 L·min⁻¹; $p = 0.644$) nor at the termination of exercise (CC: 80.52 ± 14.27 L·min⁻¹; CON: 85.65 ± 21.98 L·min⁻¹; $p = 0.331$) (Fig. 3). $\dot{V}O_2$ significantly rose ($p < 0.05$) from the start (CC: 1.78 ± 0.23 L·min⁻¹; CON: 1.78 ± 0.22 L·min⁻¹), to the end of Exercise2 (CC: 2.56 ± 0.25 L·min⁻¹; CON:2.54 ± 0.38 L·min⁻¹) with no significant differences ($p = 0.935$) between conditions. $\dot{V}CO_2$ significantly increased ($p < 0.05$) from the start (CC: 1.28 ± 0.17 L·min⁻¹; CON: 1.23 ± 0.20 L·min⁻¹), to the end of Exercise2 (CC: 2.20 ± 0.25 L·min⁻¹; CON: 2.17 ± 0.19 L·min⁻¹) with no significant differences ($p = 0.826$) between conditions. There were also no differences ($p = 0.788$) in total air consumption during Exercise2 between CC (1146.3 ± 332.0 L) and CON (1173.3 ± 307.0 L). Nude body mass significantly decreased ($p < 0.05$) from the beginning to the end of the trial (CC: 77.02 ± 5.11 kg; CON: 77.75 ± 4.56 kg) with no significant differences ($p = 0.275$) between conditions.

Perceptions of thermal, exercise, and breathing stress increased (all $p < 0.05$) during Exercise2. The attenuation of TS during rest with CC continued into Exercise2, as TS was lower in CC compared with CON at 0 min (CC: 3 (3–5); CON: 5 (4–6); $p = 0.024$) and 8 min (CC: 6 (5–7); CON: 7 (6–9); $p = 0.008$), though not at 4 min (CC:

5 (4–6); CON: 6 (5–7); $p = 0.167$) (Fig. 3). There were no differences for RPE at 0 min (CC: 11 (10–13); CON: 11 (10–12.0); $p = 0.461$) 4 min (CC: 13 (13–13); CON: 13 (13–14); $p = 0.730$) 8 min (CC: 15 (13–15); CON: 15 (14–16); $p = 0.141$). There were also no differences in BrS values at 0 min (CC: 2 (1–3); CON: 3 (2–4); $p = 0.096$), at 4 min (CC: 4 (3–4); CON: 4 (3–5); $p = 0.655$), and 8 min (CC: 5 (4–6); CON: 5 (4–6); $p = 1.000$).

Discussion

Compared with passive cooling, CC reduced T_{neck} by ~2–3 °C from the 4 min mark of recovery, and attenuated the rate of T_{re} rise during recovery. CC also improved thermal stress and HR during recovery and the initial minutes of Exercise2. While recognizing that T_{neck} does not equate to actual cranial cooling, some thermophysiological and perceptual benefit was obtained by using head cooling. However, CC did not lower T_{re} or improve exercise tolerance time during Exercise2. Hyperthermic hyperventilation was also not alleviated by CC, with no effect on ventilatory demands, total air usage, $\dot{V}O_2$, or $\dot{V}CO_2$ during Exercise2. These data suggest an overall mild but transient change that was due to cranial cooling, which largely did not benefit overall exercise–heat tolerance.

Despite the high external heat load, humidity, and near-total encapsulation during the recovery period, some physiological benefits were evident from cranial cooling. Specifically, T_{neck} directly under the cooling hood was lower, and cooling was sufficient to attenuate overall T_{re} increase during rest. There is potential that a longer cooling period would have shown significant differences between conditions, as head cooling blunted a rise in T_{re} compared with no cooling during 90 min of passive heating in a sauna (Simmons et al. 2008*b*). Debate exists regarding the efficacy of CC to sufficiently affect core temperature through direct skull cooling altering brain tissue or cranial circulation temperature. Direct measurement of aortic and jugular blood temperature demonstrated inadequate heat removal from the brain during exercise in the heat, resulting in average brain temperatures at least 0.2 °C higher than the rest of the body core during both normothermia and hyperthermia (Nybo et al. 2002). Modelling suggests that even in hot environments with minimal evaporative cooling and in a state of hyperthermia (40 °C brain temperature), surface cooling of the skull cooled only the most superficial layer (~1.5 mm) of the cerebrum, with deeper brain tissue reflecting systemic arterial temperature (Nelson and Nunneley 1998). However, during hyperthermia, there is a disproportionate and sustained rise in extracranial carotid artery blood flow to prioritize thermoregulation (Bain et al. 2013; Sato et al. 2011), suggesting the possibility for elevated heat extraction via the head and neck despite minimal impact on brain temperature. Using the identical cooling hood system and 10 °C inlet temperature in a normothermic environment, passive exposure resulted in a 0.37 °C decrease in rectal temperature, compared with no change (–0.04 °C) without the cooling hood (Reynolds et al. 2011). Such a large spatial separation between cooling and core measurement site, coupled with the statistically and practically significant decrease in rectal temperature, thus argues for the potential efficacy of both cranial cooling in general, and specifically the system employed in the present study.

Despite the mild thermal effects, CC positively improved thermal perception during the recovery period and as well as HR during initial stages of Exercise2, where TS was significantly lower from 5 min of rest through to the first 5 min of Exercise2, in parallel with a reduction in T_{neck} by ~2–3 °C (Fig. 1). These findings during rest are similar to Simmons et al. (2008*a*), which demonstrated with passive hyperthermia that thermal perception is improved along with a reduction in cardiovascular strain when core temperature is high and head and neck temperature is kept low. A lowered state of perceived thermal stress — even without attenuation of physiological strain — has been proposed to result in a maintenance or upregulation of voluntary exercise (Cheung 2010; Tyler and Sunderland 2011). However, this reduction of TS did not lead to an increase in tolerance time, nor a higher final T_{re} or HR at the end of exercise. Thus, cranial cooling transiently created a mismatch between what the brain perceived as the thermal state of the body as opposed to its true physiological state. While re-encapsulation and exercise rapidly eliminated this mismatch, caution must be used in occupational settings to ensure that individuals do not return to work based on perceived comfort, but only after rehabilitation objectives are met. Interestingly, the reduced perception in TS did not extend into differences in RPE. This differs from previous studies, where face cooling with a fan, reducing forehead temperature to 28 °C, or using intermittent head cooling reduced RPE during exercise in the heat (Armada-da-Silva et al. 2004; Mündel et al. 2007; Simmons et al. 2008*a*). The lack of change in RPE is surprising, as there was also a reduction in cardiovascular strain during the first few minutes of Exercise2. This could be due to the fact that the RPE scale lacks a true affective component because the scale uses descriptors of "light/easy" and "heavy/hard" that describe physical workload rather than hedonic terminology like "pleasant/unpleasant" or "comfortable/uncomfortable" (Cabanac 2006; Marcora 2009).

Effective and practical strategies to reduce thermal, cardiovascular, and metabolic strain experienced during firefighter activity are important to reduce the incidence of exertional heat illnesses. We designed a protocol using FPE and exercise at a metabolic rate occupationally relevant to fire suppression, whilst maximizing heat storage during both exercise and rest. This design approach may have also worked against seeing any benefit from CC, because of the high rate of heat storage potentially overwhelming any potential cooling benefit (McLellan et al. 2013). This experiment revealed that application of CC during 20-min recovery periods, where the individuals must remain within a hot environment and a high level of encapsulation, was only modestly and transiently effective in reducing physiological and perceptual thermal strain, with no benefit to improving tolerance time. This was coupled with no effect of CC on reducing hyperthermic hyperventilation, $\dot{V}O_2$, or total air consumption, such that no air supply savings would ensue. Thus, while head and neck cooling during recovery may attenuate thermal discomfort, it does not appear to provide significant ergogenic benefits to warrant use in occupational settings of intermittent work and recovery bouts with protective clothing in hot environments.

Conflict of interest statement

The authors declare that there are no financial or other conflicts of interest to disclose.

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