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THERMAL TOLERANCE CAN BE MAINTAINED AND ENHANCED BY PASSIVE, POST-EXERCISE INTERMITTENT HEAT EXPOSURE FOLLOWING HEAT ACCLIMATION IN A MILITARY CONTEXT

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Abstract Military personnel are required to operate in hot environments upon short notice. To preserve performance an elevated thermal tolerance could be maintained prior to deployment using heat acclimation (HA) followed by intermittent heat exposure (IHE). In a randomised manner, 19 participants completed 5 d of passive, post-exercise HA in either sauna or hot-water immersion (HWI) followed by 19 d of decay, or IHE every 2–3 days. A heat-stress test involving walking for 1 h in 33°C, 75% humidity in military dress was conducted before HA, after HA, and following the decay or IHE period. Following HA, performance was unaffected, while mean rectal temperature (↓0.3°C), and mean heart rate reduced (↓8 bpm). Following the decay period, performance reduced in the decay group (↓2.6 min) while no change was seen with IHE. IHE saw mean rectal temperature continued to decrease (↓0.1°C) while sweat rate increased (↑0.1 L.h-1), changes not seen in the decay group. These findings showed HA to induce beneficial thermoregulatory adaptations that could be enhanced by IHE in a manner that can be practicably implemented within groups that need to deploy into hot environments at short notice.

Key words: thermoregulation, heat acclimation, military medicine, cardiovascular, intermittent heat exposure

Background

Military units are predisposed to heat illnesses due to restrictive clothing that limits heat loss (Havenith, 1999), carried loads that adds to heat production (Knapik, 1997), and mission objectives that prevent behavioural adaptations, which are exacerbated when work occurs within hot or humid environments. Furthermore, an inability to access or rely upon cooling methods means mitigation strategies that occur prior to deployment are desirable (Ashworth et al., 2020). Previously we adapted modern HA techniques to provide meaningful physiological changes relating to performance in only 5 days (Ashworth et al., 2022). These strategies utilised saunas and hot-water immersion as methods that do not require specialised facilities or interfere with other training objectives, and had previously shown beneficial physiological adaptations (Heathcote et al., 2018; Zurawlew et al., 2016).

However, military deployment notice can be as short as 12 h and therefore implementing a multiweek HA strategy is challenging, and more efficient strategies are required. One technique that could reduce the timeframe is intermittent heat exposure (IHE), whereby periodical exposure to heat could provide sufficient stimuli to prevent the decay of adaptations (Pryor et al., 2019; Taylor, 2000). When used following a HA programme, a single active exercising IHE session every 5 d can sustain beneficial adaptations in heart rate and core temperature (Pryor et al., 2019). If adaptations can be sustained by periodic exposure to heat, it may be possible to establish and maintain an elevated baseline thermal tolerance within an individual for a prolonged period. By raising the thermal tolerance of a military unit, it is conceivable that if rapid deployment was required military personnel could depart upon request with minimal effects on performance and safety. Furthermore, achieving this with passive heat exposures would minimise the impact on other training objectives, and be more feasible for military cohorts. To investigate this concept, the aim of the current study was to determine the effects of passive, post-exercise IHE as method to retain beneficial physiological adaptations and performance to the heat in a military context.

Methods

Experimental Design and Overview

Each participant completed an initial short-term HA programme using post-exercise, passive HA using either sauna (SAU) or hot-water immersion (HWI), as detailed below. Following HA, participants from each of these conditions were randomised into decay (DEC) or intermittent heat exposure (IHE) groups, with four subgroups: sauna decay (DEC_{SAU}), sauna IHE (IHE_{SAU}), HWI decay (DEC_{HWI}) and HWI IHE (IHE_{HWI}). Those in the IHE groups completed additional HA sessions every 2-3 d over an 18 d period involving exercise and passive, post-exercise heat exposure, while DEC groups completed the exercise component only. Heat-stress tests (HSTs) simulating a 1 h pack march, were conducted in hot-humid conditions (33°C, 75% relative humidity) to assess performance before (pre-HA HST) and after initial HA (post-HA HST), as well as following the 18 d decay and IHE period (post IHE HST).

Participants

Nineteen recreationally active participants took part in the experiment (age 31.7 ±9.8 years, body mass 82.7 ±14.4 kg, $\dot{V}O_2$peak 52.6 ±6.1 $mL.min^{-1}.kg^{-1}$), split into an IHE group of ten and a decay group of nine. Fifteen participants had previously completed a structured HA programme as part of another study (Ashworth et al., 2022) which had concluded at least 6 wk prior, allowing for adequate decay of beneficial adaptations (Ashley et al., 2015), while four were new participants. All participants provided informed consent prior to participation in line with the *Declaration of Helsinki* and institutional ethics approval (AUT Ethics Committee, 18/195).

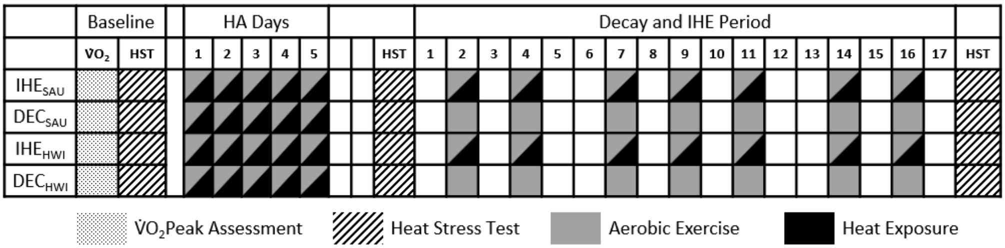

Figure 1. Schematical illustration of the experimental time scale. Each group completed baseline $\dot{V}O_2$ and heatstress tests (HSTs) participants. Within 2-7 d participants began a 5 d heat acclimation (HA) programme using passive, post exercise heating in either sauna (SAU) or hot-water immersion (HWI). A second HST was completed 3 d after completion of the HA programme, followed immediately by either a decay (DEC) or intermittent heat exposure (IHE) period. During this time the IHE group completed heat exposures as per the initial HA every 2-3 d, while the DEC group completed the exercise component only. After ~18 d all participants completed a final HST.

$\dot{V}O_2$Peak Assessment

Each participant completed a preliminary $\dot{V}O_2$peak aerobic assessment in temperate conditions on a motorised treadmill (Pulsar® 3p, h/p/cosmos, Germany), analysed with a calibrated metabolic system (Trueone 2400, Parvo Medicks, Utah, USA). Starting at 7 $km.h^{-1}$ intensity was increased by 1 $km.h^{-1}$ every 3 min, to a maximum of 15 $km.h^{-1}$ after which the gradient was increased in 1% increments. When the respiratory exchange ratio (RER) exceeded 1.00 stages were shortened to 1 min and continued until voluntary termination. All participants exceeded the minimum $\dot{V}O_2$peak of 40 $ml.kg^{-1}.min^{-1}$ required for entry into the study.

HeatStress Tests

Three HSTs were completed as per Figure 1. Each HST was completed at the same time of day by each participant, who avoided strenuous activity and limited alcohol and caffeine consumption for the 24 h preceding each HST. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), set to 33°C and 75% relative humidity (absolute humidity = 14 $g.m^{3}$). Following 10 min of seated rest in the chamber participants walked on a motorised treadmill at 5 $km.h^{1}$ at 1% incline for 1 h, while wearing standard militaryissue longsleeved shirt, trousers, helmet, body armour, a backpack, and their own shoes (full ensemble = 20.6 ±0.7 kg). After 1 h treadmill gradient increased 1% every minute (up to a maximum of 15%) until voluntary termination, 20 min elapsed, or upon reaching ethical limits of core temperature (> 39.5°C) or heart rate (> 95% age-predicted max for 10 s (Tanaka et al., 2001). Fluid consumption was permitted *ad libitum* up to a maximum of 2 L, as per military rations.

Temperature Measures

Core body temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) inserted 12 cm beyond the anal sphincter. Skin temperature was measured using thermistors placed on the chest, bicep, thigh and calf on the righthand side of the body and secured with surgical tape (3M Micropore Tape, 3M, New Zealand). Core and skin temperature were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK).

Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$T_{Sk} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf}$$

Averages over 10 min periods were used for analysis, while 1 min averages of sitting and at the end of steady-state walking were used for resting and end-exercise values, respectively.

Cardiovascular Measures

Cardiac frequency was measured using a 3lead electrocardiogram (Tango+, SunTech Medical, North Carolina), with values recorded at 15 min intervals after a baseline measure was taken while seated inside the chamber. Resting and end-exercise heart rate values were obtained after 5 min of seated rest and after 55 min of walking, respectively.

Sweat Rate

Wholebody sweat rate was estimated using pre and postexercise seminude body mass, corrected for fluid consumption (*(semi-nude weight change + fluid consumption) ÷ walking time*) (Buono et al., 2009). To calculate unevaporated sweat rate weight was measured immediately prior to and immediately following entry and exit from the heat chamber in full dress (*(semi-nude weight change – fully dressed weight change) ÷ walking time*) (Amos et al., 2000).

Hydration Measures

Prior to, and immediately following each trial, participants provided a urine sample that was analysed for urine specific gravity (USG) using a refractometer (Atago, Japan).

Initial Heat Acclimation Protocol

Participants completed post-exercise, passive HA sessions on five consecutive days. Each session comprised of 40 min continuous aerobic exercise, followed by up to 40 min of either sauna or HWI.

Exercise

Upon arrival at the laboratory (19.2 ±0.5 °C, 62.8 ±2.2% RH) participants were weighed and had their auditory canal temperature measured. Exercise was conducted either on a graded treadmill or a stationary cycling ergometer, according to participant preference. Exercise was performed for 40 min at an individually prescribed intensity equivalent to their first ventilation threshold (V-slope method, (Shimizu et al., 1991)), calculated from the initial $\dot{V}O_2$peak assessment. Upon cessation of exercise, weight and auditory canal temperature were measured before participants were transferred to the sauna or HWI facility.

PostExercise Heating

Postexercise, passive heating was conducted either by sitting in a custom-built sauna (~70°C, 20% RH) or mid-sternum immersion in hotwater (~40°C) in a hot tub (Hot Spring, New Zealand). Prior to HWI participants were required to rinse off in warm water (<5 s). Auditory canal temperature was taken immediately preceding heat exposure, while baseline pulse, taken at the wrist was assessed upon exposure to the heat. During each heat exposure participants could drink up to 1 L of water *ad libitum.* Participants could terminate the session at any time but were requested to remain in the sauna or HWI for as long as they felt comfortable, up to 40 min. Measures were repeated every 10 min during the postexercise heating. Auditory canal temperature was taken every 10 min in the HWI, but this was not possible in the sauna where it was taken immediately upon exiting. A final set of measures were also taken if participants terminated the session early, if meaningful time (>2 min) had passed since the last measurement. Participants and drink bottles were then weighed to indicate fluid consumption and for calculation of sweat rate.

Intermittent Heat Exposure

Participants in either IHE group continued to complete HA sessions as per the initial heat acclimation protocol every 2–3 d for 18 d (Figure 1). Sessions were conducted identically to those during the initial HA protocol.

Decay

Participants in either DEC group continued to complete the exercise component of each HA session every 2–3 d for 18 d but received no heat exposure.

Statistical Analysis

Data from both sauna and HWI were pooled together for both DEC and IHE groups to improve statistical power due to the premature termination data collection due to COVID-19. The treatment of these groups as providing similar effects is warranted, based on previous research in this area (Ashworth et al., 2022), whilst these differences are also briefly compared within this manuscript.

All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria) using the lme4 and emmeans packages. Analyses produced estimated means, standard deviations, confidence intervals and p-values, which were adjusted using the Holm correction for multiple comparisons where appropriate. Absolute data are reported as estimated mean ±standard deviation (SD), while changes are reported as estimated mean change with a 95% confidence interval (i.e., HWI: ↓2 min, [-3, -1], $p = 0.003$ indicates a 2-minute reduction in the hot-water immersion condition that is significant, with a 95% confidence interval between a 1- or 3-minute reduction). Statistical analysis was split into four phases: 1) The primary analysis evaluated differences between pre-HA or post-HA and post-IHE HSTs for each group (DEC and IHE), and between preHA and postHA for each condition (SAU and HWI). A mixed model ANVOA was run for each variable within the specified comparison with fixed effects of pre-post and group, along with the interaction between the two, and a random effect of participant. Estimated means were calculated and used to obtain post-HA to post-IHE differences in each group: DEC or IHE. A significant interaction between group and pre-post was used to determine a difference between the groups. 2) Analyses of the change in variables during heat exposure across the HA and IHE period were conducted. Each variable was entered into a mixed model ANOVA with session and time (if appropriate) entered as fixed effects and participant entered as the random effect. ANOVAs were run for each condition, as well as compared between conditions by entering condition as an additional fixed effect. 3) A secondary analysis evaluated differences between conditions within a group (i.e. SAU vs HWI within IHE), a mixed model ANOVA was run within that group, with fixed effects of condition and pre-post as well as their interaction. If the interaction was significant, it was deemed that a difference in the change between the conditions existed. Estimated means were calculated and used to obtain differences between conditions in each group (i.e. DEC_{SAU} vs DEC_{HWI}).

Results

Post-IHE HSTs were conducted an average of 19 ± 3 d following the post-HA HST, with all participants completing all sessions at 2-3 d intervals. Participants in both IHE groups averaged 7.0 IHE sessions, while those in DEC averaged 7.5 sessions.

Heat Acclimation Sessions

During the HA period heating exposure time was not statistically different between conditions (SAU: 27.8 ±7.6 min; HWI: 30.9 ±8.9 min; SAU vs HWI: p = 0.052), and was found to increase only in the HWI condition (SAU: ↑0.5 min, 95% CI [–0.5, 1.5], p = 0.360; HWI: ↑0.7 min, [0.0, 0.1], p = 0.032; HWI vs SAU: p = 0.684). Heart rate reduced significantly between sessions in the sauna condition, but tended to increase during HWI (SAU: ↓2 $b.min^{-1}$, [-3, -1], p<.001; HWI: ↑1 $b.min^{-1}$, [0, 3], p = 0.074; SAU vs HWI: p = 0.001). No changes in sweat rate were seen in either group (both p > 0.262), while fluid consumption increased in the HWI condition only (SAU: No change (NC), [0.00, 0.01], p = 0.782; HWI: ↑0.05 L, [0.00, 0.10], p = 0.013; SAU vs HWI: p = 0.074). Tympanic temperature across sessions was found to reduce in sauna, but not HWI (SAU: ↓0.2°C, [–0.3, –0.1], p = 0.001; HWI: NC, [–0.2, 0.2], p = 0.636; SAU vs HWI: p = 0.323).

Intermittent Heat Exposure Sessions

During IHE sessions, exposure time was significantly longer in the HWI than the sauna (SAU: 29.9 ±7.3 min; HWI: 36.6 ±5.7 min; SAU vs HWI: p < 0.001), although exposure time in the sauna increased across the IHE period (SAU: ↑0.8 min, [0.1, 1.6], p = 0.029; HWI: NC, [–0.02, 0.03], p = 0.867). No changes were observed in either condition for sweat rate (both p > 0.223), heart rate (both p > 0.244) or auditory canal temperature (both p > 0.245), although fluid consumption increased significantly more in the sauna condition (SAU: ↑0.04 L, [0.01, 0.07], p = 0.028; HWI: ↑0.02 L, [–0.03, 0.07], p = 0.360; SAU vs HWI: p = 0.039).

Heat-Stress Tests

Performance

Three participants (1 DEC_{HWI}, 1 IHE_{HWI} and 1 DEC_{SAU}) reached the 20-min ethical limit in each HST they completed and therefore were excluded from analyses of performance.

There was a tendency for improved time to exhaustion in SAU though differences between conditions were not statistically significant across the initial HA period (SAU: ↑3.9 min, 95% CI [–0.1, 7.5], p = 0.071; HWI: ↑3.3 min, [–0.8, 7.4], p = 0.105; Table 1). Following the decay and IHE period a significant reduction was seen in DEC compared to the post-HA HST (DEC: ↓2.6 min, [–5.1, –0.1], p = 0.038; IHE: ↑0.1 min, [2.2, 2.5], p = 0.898; Figure 2). When compared to the pre-HA HST both DEC and IHE groups tended to increase, but this did not reach statistical significance (DEC: ↑2.2 min, [–0.4, 4.8], p = 0.056; IHE: ↑2.3 min, [–0.1, 4.6], p = 0.056).

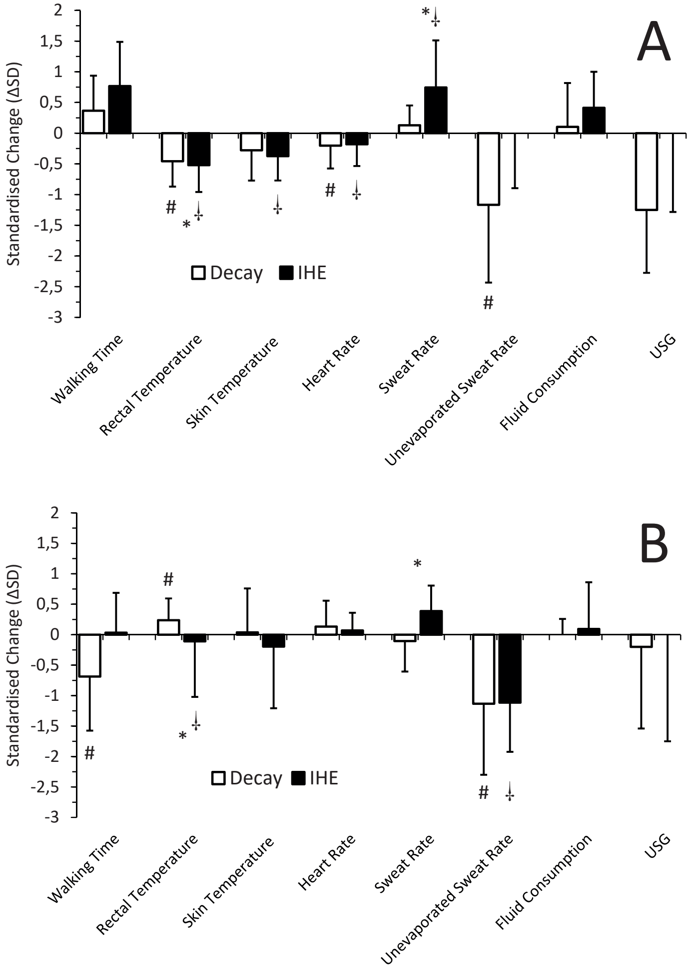

Figure 2. Changes in physiological variables following 19 d of decay or passive, post-exercise intermittent heat exposure (IHE) following an initial 5 d passive, post-exercise heat acclimation (HA) programme. Data are displayed as change from pre-HA values (A) and change from post-HA values (B). Variables are plotted as a function of the standard deviation (SD) of the baseline measures (i.e. (post-IHE – preHA) / $SD_{pre\text{-}HA}$). All data are displayed as mean ± SD. # $p < 0.05$ between baseline and decay value, ⸸ $p < 0.05$ between baseline and IHE value, * $p < 0.05$ between change in groups.

Physiological Variables

Across the intervention, rectal temperature was significantly lowered following both sauna and HWI HA (SAU: ↓0.3°C, [–0.4, –0.2], p < 0.001; HWI: ↓0.2°C, [–0.3, 0.1], p < 0.001; Figure 3). During the decay and IHE period a significant difference was observed between groups (p < 0.001) as the DEC group increased rectal temperature, while the IHE group which continued to reduce (DEC: ↑0.1°C, [0.1, 0.2], p < 0.001; IHE: ↓0.1°C, [–0.1, 0.0], p = 0.001; Table 1). However, when compared to the pre-HA HST, both groups had significantly lower rectal temperature (DEC: ↓0.1°C, [–0.2, –0.1], p < 0.001; IHE: ↓0.2°C, [–0.3, –0.2], p < 0.001), which was reduced significantly more in the

IHE group (DEC vs HWI: p = 0.048; Table 1). Although no difference was found between conditions within the IHE group (IHE_{SAU} vs IHE_{HWI}: p = 0.587), there was a significant difference between conditions within the DEC group, with DEC_{HWI} providing a larger reduction in rectal temperature (DEC_{SAU}: ↓0.1°C, [–0.2, 0.0], p < 0.001; DEC_{HWI}: ↓0.3 °C, [–0.5, –0.2], p < 0.001; DEC_{SAU} vs DEC_{HWI}: p = 0.005). No differences were observed in the rate of rise in rectal temperature after HA (both p > 0.327), or between either the pre- or post-HA and the post-IHE HSTs for DEC and IHE groups (all p > 0.127; Table 1).

Skin temperature was reduced following HA in the sauna condition only (SAU: ↓0.3°C, [–0.5, 0.2], p < 0.001; HWI: no change (NC), [–0.2, 0.3], p = 0.667; Table 1). No significant differences were detected between the post-HA and post-IHE HSTs in either DEC or IHE groups (DEC: NC, [–0.1, 0.2], p = 0.841; IHE: ↓0.1°C, [–0.3, 0.0], p = 0.079; Table 1). Compared to the pre-HA HST, both DEC and IHE groups tended towards a reduction in skin temperature although this was significant only in the IHE group, with no difference between groups (DEC: ↓0.1°C, [–0.3, 0.0], p = 0.072; IHE: ↓0.3°C, [–0.4, –0.1], p < 0.001; DEC vs IHE: p = 0.182). While the pre-HA to post-IHE HST comparison showed no difference between conditions in the DEC group (p = 0.536), within the IHE group there was a significant reduction in skin temperature in the IHE_{SAU} group, although this did not differ from the IHE_{HWI} group (IHE_{SAU}: ↓0.4 °C, [–0.6, –0.1], p < 0.001; IHE_{HWI}: ↓0.2°C, [–0.4, 0.1], p = 0.112; IHE_{SAU} vs IHE_{HWI}: p = 0.211).

Heart rate significantly reduced in both conditions following the initial HA period, with a greater decline following sauna HA (SAU: ↓11 $b.min^{-1}$, [–15, –7], p < 0.001; HWI: ↓5 $b.min^{-1}$, [–10, –1], p = 0.008; SAU vs HWI: p = 0.033; Table 1). Over the decay and IHE period no changes were observed in either group (both p > 0.172), with both groups remaining significantly lower than the pre-HA HST (DEC: ↓6 $b.min^{-1}$, [11, –2], p=.005; IHE: ↓5 $b.min^{-1}$, [-9, -1], p = 0.010; DEC vs IHE: p = 0.653; Table 1).

Table 1. Changes in physiological variables during heat-stress tests at baseline (pre-HA), following a 5 d HA programme (post-HA) and following either decay (DEC) or intermittent heat exposure (IHE) following the HA period. Pre- and post-HA values are displayed as mean ± SD, while the pre-post differences are displayed as mean change, with 95% confidence intervals.

			Change from Post-Test	
Variable	Pre-HA	Post-HA	DEC	IHE
Time to Exhaustion (min)	8.8 ±4.7	12.42 ±4.6	↓3.4 (–6.4, 0.4) ^{β}	↑0.1 (–2.5, 2.8) †
Rectal Temperature (°C)				
Average	37.6 ±0.3	37.3 ±0.3*	↑0.1 (0.1, 0.2) $^{α, β}$	↓0.1 (–0.1, 0.0) $^{α, β, †}$
Resting	37.1 ±0.4	36.9 ±0.4*	↑0.2 (0.0, 0.3) ^{α}	↓0.1 (–0.2, 0.0) $^{α, β, †}$
End-Exercise	38.1 ±0.4	37.8 ±0.4*	↑0.1 (–0.1, 0.3) ^{β}	↓0.1 (–0.2, 0.0) $^{β, †}$
Slope ($°C.h^{-1}$)	1.3 ±0.3	1.3 ±0.3	NC (–0.2, 0.2)	NC (–0.2, 0.2)
Skin Temperature (°C)				
Average	35.8 ±0.4	35.6 ±0.3*	NC (–0.1, 0.2)	↓0.1 (0.3, 0.0) ^{α}
Resting	34.4 ±0.6	34.3 ±0.6	↑0.2 (–0.2, 0.6)	↓0.1 (–0.4, 0.3)
End-Exercise	36.4 ±0.4	36.3 ±0.4*	↓0.1 (–0.3, 0.1)	↓0.2 (–0.4, 0.0) ^{α}
Heart Rate ($b.min^{-1}$)				
Average	107 ±13	99 ±13*	↑3 (–1, 7) ^{α}	↑3 (0, 7) ^{α}
Resting	71 ±9	65 ±9*	↑4 (–3, 10)	↑3 (–3, 9)
End-Exercise	132 ±17	120 ±17*	↑3 (–4, 9) ^{α}	↑3 (–4, 9) ^{α}
Sweat Rate ($L.h^{-1}$)	1.1 ±0.3	1.2 ±0.3	NC (–0.2, 0.1)	↑0.1 (0.0, 0.3) $^{α, †}$
Unevaporated Sweat Rate ($L.h^{-1}$)	0.6 ±0.4	0.8 ±0.4	↓0.3 (–0.6, –0.1) $^{α, β}$	↓0.3 (–0.5, -0.1) ^{β}
Fluid Consumption (L)	0.9 ±0.5	1.0 ±0.5	NC (–0.2, 0.2)	NC (–0.2, 0.2)
USG Pre	1.017 ±0.007	1.014 ±0.007	↑0.002 (–0.004, 0.009)	↑0.004 (–0.002, 0.010)
USG Post	1.019 ±0.007	1.015 ±0.007	↑0.002 (–0.005, 0.009)	↑0.004 (–0.003, 0.011)

*indicates p < 0.05 between pre- and post-HA HSTs, ^{α} indicates p < 0.05 between pre-HA and post-IHE HST, ^{β} indicates p < 0.05 between post-HA and post-IHE HST, † indicates p < 0.05 between the change in Decay and IHE.

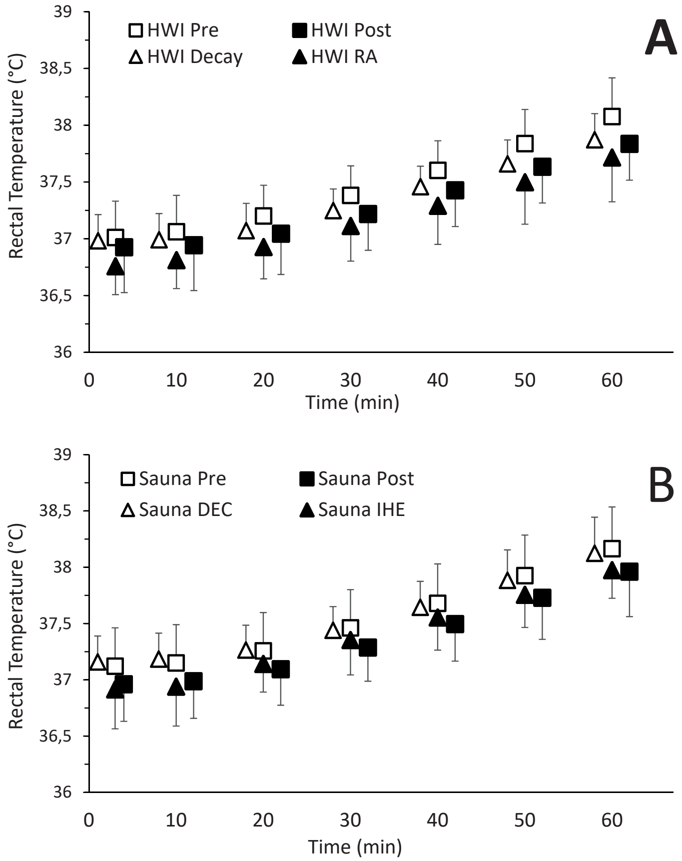

Figure 3. Changes in rectal temperature across a heat stress test (HST) conducted pre- and post-heat acclimation as well as following a period of decay or intermittent heat exposure in both hot-water immersion (HWI) (A), and sauna (B). Data are displayed as mean ±SD. Data are offset from 10-min time points for clarity.

Sweat rate was unchanged following HA in either condition (both p > 0.206; Table 1, Figure 4). Furthermore, sweat rate was not significantly changed following the decay and IHE period despite a tendency to increase in the IHE group that was significantly different to the change in the DEC group (DEC: NC, [–0.2, 0.1], p = 0.507; IHE: ↑0.1 L.h^{-1}, [0.0, 0.3], p = 0.053; DEC vs IHE: p = 0.045; Table 1). When compared to the pre-test, the IHE group had a significantly elevated sweat rate (Figure 4) that had increased significantly more than in the DEC group (DEC: NC, [–0.2, 0.2], p = 0.620; IHE: ↑0.3 L.h^{-1}, [0.1, 0.5], p = 0.002; DEC vs IHE: p = 0.026).

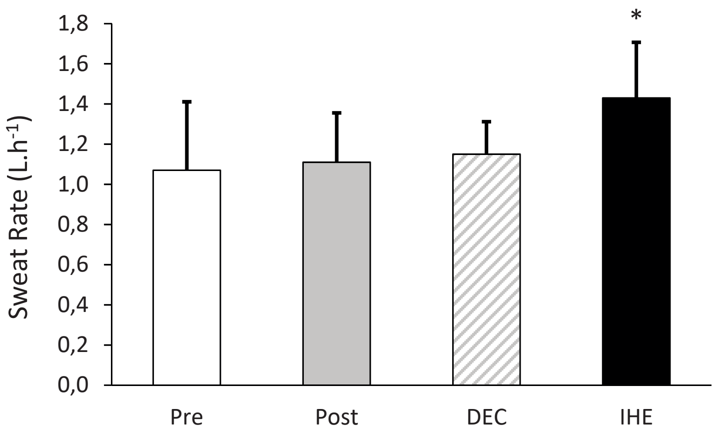

Figure 4. Changes in sweat rate over the course of HA and the subsequent decay (DEC) and intermittent heat exposure (IHE) period. Aggregated means of both groups (DEC and IHE) are used for pre and post, with the DEC and IHE results shown as projected changed based on the within group changes from post-HA to post-IHE HSTs. *p > 0.05 compared to pre-HA HST.

No changes in unevaporated sweat rate were seen over HA (both $p > 0.476$). Following the decay and IHE period, significant reductions in unevaporated sweat rate were seen in both groups, with no difference between groups (DEC: ↓0.3 $L.h^{-1}$, [–0.6, –0.1], $p = 0.005$; IHE: ↓0.3 $L.h^{-1}$, [–0.5, –0.1], $p = 0.006$; DEC vs IHE: $p = 0.675$; Table 1). When compared to the pre-HA HST, only the DEC group had a significant reduction, although this did not reach statistical significance compared to the IHE group (DEC: ↓0.4 $L.h^{-1}$, [–0.7, 0.0], $p = 0.040$; IHE: NC, [–0.3, 0.3], $p = 0.982$; DEC vs IHE: $p = 0.077$).

Fluid consumption did not change following HA (both $p > 0.469$) or following the decay and IHE period in either group compared to both the post-HA HST (both $p = 1.000$), and the pre-HA HST (both $p > 0.126$; Table 1). Similarly, no differences were seen in hydration as assessed by USG either before or after the HST over the course of HA (> 0.266), between post-HA and post-IHE HSTs (all $p > 0.205$) or between pre-HA and post-IHE HSTs (all $p > 0.152$; Table 1).

Discussion

The primary aim of this study was to determine the effectiveness of intermittent, passive, postexercise heat exposure (IHE) to maintain beneficial heat adaptations obtained from a prior shortterm HA programme. The present results indicate that IHE can maintain several important physiological parameters that aid physical performance and safety when operating in hot environments, and potentially enhance adaptations to resemble those seen in longer HA protocols.

Physical performance typically improves by 7% following short-term (<7 d) HA (Tyler et al., 2016), although time to exhaustion or capacity tests typically induce greater improvements (Scoon et al., 2007; Tyler et al., 2016). In the present study the initial 5 d HA saw no improvement in time to exhaustion although improvements have previously been seen in identical (Ashworth et al., 2022), and near identical protocols (Zurawlew et al., 2016). During the decay period following the initial HA, performance declined as expected, as underlying physiological adaptations diminish (Daanen et al., 2018). However, following IHE performance was maintained (Table 1; Figure 2), suggesting the continued heat stimulus retained thermoregulatory adaptations. Conversely, Gerrett et al. (2021) found performance reduced following a 5 d re-acclimation period (after 10 d controlled hyperthermia HA) compared to post-HA, despite maintaining other physiological adaptations. For military units with short deployment notice and concerns with heat-induced performance impairments, IHE provides a promising strategy that could maintain physical performance during operations in a hot climate.

Reductions in core temperature are typically observed across HA (Faulkner, 2016; Heathcote et al., 2018; Tyler et al., 2016), consistent with the reduced rectal temperature at rest, at end-exercise, and on average following short-term HA in both conditions during the present study (Figure 3). The DEC group saw rectal temperature return to pre-HA values at a rate of ~1.7%.d^{-1} (Table 1; Figures 2 and 3), slower than typically reported (Daanen et al., 2018). Indeed, other protocols have found 2 wk of decay returned rectal temperature to pre-HA values (Garrett et al., 2009; Poirier et al., 2015), whereas after 18 d of decay in the current study, rectal temperature was still reduced relative to pre-HA (Figure 2A), potentially due to the continuation of aerobic exercise (Aoyagi et al., 1998; Cohen & Gisolfi, 1982).

With IHE, the initial reduction in rectal temperature was augmented, further increasing the capacity for heat gain to improve performance and safety (Aoyagi et al., 1994). Previous attempts to reobtain core temperature adaptations from a prior HA programme have returned differing results. Following 26 d of decay Weller et al. (2007) found a single day of re-acclimation (100 min walking at ~5.5 km.h^{-1} in 32°C, 18% RH) returned rectal temperature to post-HA values, while Ashley et al. (Ashley et al., 2015) suggested 4 d of re-acclimation after 2 wk of decay, and 5 d following 4 wk of decay, was required to restore rectal temperature. However, both these studies returned core temperature to the value seen post-HA, whereas in the current study (with IHE every 2–3 d) rectal temperature reduced beyond that of the initial HA programme (Figure 2B). Kirby et al. (2021) looked at IHE to sustain heat adaptations following post-exercise sauna HA, and found that three, 30-min sessions a week caused an additional 0.1°C reduction in rectal temperature, on top of the –0.2°C reduction seen during the initial HA, nearly identical to that seen in the current study. When mixed mode IHE (90-240 min in 40°C, 40% RH) was used every 5 d for 25 d following HA by Pryor et al. (2019) rectal temperature remained significantly lower than pre-HA, but no further decreases were observed. The greater volume of heat exposure used by Pryor et al. (2019) during HA may have induced stronger physiological adaptations that, may require smaller or less frequent stimuli to maintain (Moss et al., 2019). Indeed, the HAinduced change in end-exercise rectal temperature seen by Pryor et al. was ~3 times greater than that seen in the current study. While the minimal heat exposure (~2.5 h) used in the current study during the 5 d HA may have limited the upregulation of adaptive mechanisms (Moss et al., 2019), during the IHE period the additional exposure likely progressed these adaptations, causing changes typically associated with longer HA programmes. For groups planning to use IHE to maintain heat adaptations for a prolonged period, a shortterm HA programme may be sufficient.

One reason core temperature reduced with IHE might be the increase in sweat rate compared to preHA (Figure 4). IHE has previously been unable to maintain sweat rate adaptations, despite increasing over the initial HA period (Pryor et al., 2019). Sweat rate adaptations typically take over two weeks to occur (Poirier et al., 2015), so this finding is likely a result of the accumulated volume of heat exposure (Fox et al., 1964). The increased sweat rate following IHE helps regulate body temperature by facilitating evaporative heat loss (Amos et al., 2000). Achieving an increase in sweat rate using IHE following HA provides a much more efficient and practical means to obtaining heat adaptations in military personnel.

Central adaptations, such as heart rate, are among the fastest heat adaptations to occur (Faulkner et al., 2016), and were seen across HA. However, following the decay and IHE period both groups significantly increased heart rate, with no differences between the groups (Table 1, Figure 2B). While end-exercise heart rate decayed slower (1.3%.d^{-1}) than that seen in the literature (~2.3%.d^{-1}) (Daanen et al., 2018), this could be explained by the exercise component alone maintaining cardiovascular adaptations (Aoyagi et al., 1998). However, the similar rate of decay in the IHE group was unexpected. The lack of change observed here contrasts with that shown by Pryor et al. (Pryor et al., 2019) where post-exercise heart rate in the IHE group was ~14% lower than in the decay group. As most participants reached the time-limit placed on IHE sessions, the adaptive stimuli were likely lessened, preventing further adaptation (Gibson et al., 2019). A method that ensures constant progression of heat strain in passive heating protocols would be valuable both for the implementation of IHE, as well as longer passive, post-exercise heating programmes available in the current literature (Heathcote et al., 2018).

Conclusions

In summary, application of IHE to maintain adaptations from a previously conducted HA programme appears a beneficial approach, and in some cases may even enhance desirable physiological adaptations for performing in the heat. For military groups that may receive minimal notice before being deployed to a hot environment, a short passive, post-exercise HA programme, that is minimally disruptive to training and other commitments, may provide a basis for maintenance of elevated thermal tolerance, thereby improving operational performance and safety upon arrival in hot environments. Further research would better elucidate differences between passive heating modalities when used as IHE.

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Data availability statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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