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ORIGINAL ARTICLE

Effectiveness of short-term heat acclimation for highly trained athletes

Andrew T. Garrett · Rob Creasy · Nancy J. Rehrer · Mark J. Patterson · James D. Cotter

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Abstract Effectiveness of short-term acclimation has generally been undertaken using untrained and moderately-trained participants. The purpose of this study was to determine the impact of short-term (5-day) heat acclimation on highly trained athletes. Eight males (mean ± SD age 21.8 ± 2.1 years, mass 75.2 ± 4.6 kg, $\dot{V}O_{2peak}$ 4.9 ± 0.2 L min^{-1} and power output 400 ± 27 W) were heat acclimated under controlled hyperthermia (rectal temperature 38.5°C), for 90-min on five consecutive days (T_a = 39.5°C, 60% relative humidity). Acclimation was undertaken with dehydration (no fluid-intake) during daily bouts. Participants completed a rowing-specific, heat stress test (HST) 1 day before and after acclimation (T_a = 35°C, 60% relative humidity). HST consisted 10-min rowing at 30% peak power output (PPO), 10 min at 60% PPO and 5-min rest before a 2-km performance test, without feedback cues. Participants received 250 mL fluid (4% carbohydrate; osmolality 240–270 mmol kg^{-1}) before the HST. Body mass loss during acclimation bouts was 1.6 ± 0.3 kg (2.1%) on day 1 and 2.3 ± 0.4 kg (3.0%) on day 5. In contrast, resting plasma volume increased by 4.5 ± 4.5% from day 1 to 5 (estimated from [Hb] & Hct). Plasma aldosterone increased at rest (52.6 pg mL^{-1}; $p = 0.03$) and end-exercise (162.4 pg mL^{-1}; $p = 0.00$) from day 1 to 5 acclimation. During the HST T_{re} and f_c were lowered 0.3°C ($p = 0.00$) and 14 b min^{-1} ($p = 0.00$) after 20-min exercise. The 2-km performance time (6.52.7 min) improved by 4 s ($p = 0.00$). Meaningful physiological and performance improvements occurred for highly trained athletes using a short-term (5-day) heat acclimation under hyperthermia control, with dehydration.

Keywords Elite · Performance · Dehydration · Fluid regulation · Plasma volume

Introduction

Endurance-trained athletes respond physiologically as if they were already heat acclimatised (Taylor 2000) and the higher the background adaptation, the lower the adaptation response (Taylor and Cotter 2006). Therefore, highly trained athletes have less adaptive potential compared with untrained or moderately trained participants. However, it is highly trained athletes that are in most need of heat acclimation and they have to rely on research from lesser trained (and adapted) people. Short-term heat acclimation may be the preferred regime for highly trained athletes, as it potentially provides less disruption of quality training near to competition and is less expensive than longer-term protocols. Therefore, the principal aim of this work was to examine the extent to which highly trained athletes adapt to short-term heat acclimation.

It is also plausible that (1) controlled hyperthermia is an effective strategy for heat acclimation because it ensures strain is maintained across adaptation (Taylor 2000), and (2) dehydration should be permitted during the acclimation bouts because this magnifies the stimulus for the cardiovascular and fluid regulatory adaptations that are important

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A. T. Garrett (✉) · R. Creasy · N. J. Rehrer · J. D. Cotter
School of Physical Education, University of Otago, Dunedin, New Zealand
e-mail: andrewgarrett45@yahoo.co.uk

M. J. Patterson
Defence Science Technology Organisation (DSTO), Melbourne, Australia

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features of the heat-adapted phenotype and seem unlikely to compromise regime in the adaptation (Fan et al. 2008; Ikegawa et al. 2011; Judelson et al. 2008; Osterberg et al. 2010). Furthermore, the effectiveness of short-term heat acclimation, using controlled hyperthermia, has only been examined in untrained (Turk and Worsley 1974; Weller and Harrison 2001) or moderately trained (Creasy 2002; Garrett et al. 2009; Regan et al. 1996; Taylor et al. 1995) participants. A recent study has demonstrated the effectiveness of a longer (10-day) heat acclimation protocol for highly trained cyclists (Lorenzo et al. 2010) in both cool temperate and hot conditions, although the experimental design of that study has limited the validity of the findings.

Improvements in aerobic fitness and related physiological adaptation that occur, such as increased heat loss capacity and decreased rectal temperature (T_{re}), have been associated with increased tolerance to exercise in the heat (Armstrong and Pandolf 1988). Untrained (<50 mL kg^{-1} min^{-1}; $n = 8$) and trained (>55 mL kg^{-1} min^{-1}; $n = 7$) participants have been stress tested before and after heat acclimation (Cheung and McLellan 1998). Acclimation involved 1-h treadmill exercise at 40°C 30% RH, for 2 weeks of daily heat acclimation wearing nuclear, biological and chemical protective clothing. Acclimation increased sweat rate and decreased T_{re} and $\bar{T}_{sk}$ in trained participants but had no effect on exercise tolerance time. Untrained participants increased sweat rate but did not alter cardiac frequency (f_c) and T_{re} or exercise tolerance time. The modulating effects of hypohydration (2.5%) were also examined in that study and were found to increase f_c and T_{re} with a reduction in exercise tolerance time irrespective of training or acclimation status. The rate of rise in $\bar{T}_{sk}$ was less whereas the change in T_{re} and exercise tolerance time were greater in trained than in untrained participants. Therefore, it can be concluded from the work of Cheung and McLellan (1998) that long-term aerobic fitness resulted in a significant improvement in exercise-heat tolerance, regardless of hydration or acclimation status (Bourdon et al. 1987; Greenleaf Sargent 1965; Hubbard et al. 1984). More recently, Garrett et al. (2009) used short-term (5-day) heat acclimation, with moderately trained participants ($n = 10$), undertaken using controlled hyperthermia, in 90-min daily bouts. In this work a decrease in resting f_c (7%), T_{re} (0.7%), and an increase in PV (4.2%) and work capacity (14%) were observed. Therefore, in view of the overwhelming focus on individuals who are less well trained than the athletes who frequently use short-term heat acclimation, and the lesser adaptive potential of these athletes. The aim of this study was to determine the extent to which highly trained athletes would benefit physiologically from a short-term (5-day) heat acclimation protocol, using controlled hyperthermia, with dehydration.

Methods

Experimental design and overview

This study was conducted within the bounds of approval granted by the University of Otago Human Ethics Committee (Approval number 02/035). In the final preparations for an international rowing regatta, eight highly trained participants undertook one, 5-day heat acclimation regime with minimal fluid replenishment (DEHydrated; ~100 mL) during each daily acclimation session. The environmental chamber, housed in the School of Physical Education, University of Otago, was used to control ambient temperature and relative humidity. Participants' fluid-regulatory status was measured at rest and end-acclimation bout on day 1 and day 5. Thermoregulatory, cardiovascular function and performance were measured during a rowing-specific, exercising HST, administered on the day before and on the day after acclimation. Participants were asked to refrain from strenuous exercise 24 h prior to the HSTs as it has been demonstrated that lower resting core temperature contributes to reduced physiological strain during acclimation (Kampmann et al. 2008). This heat acclimation regime formed an integral part of the final pre-competition training camp (based in Dunedin, New Zealand; ~12°C, 40–50% RH) for the highly trained participants. They were competing in the lightweight category of the invitational I-Lan international collegiate rowing regatta in Taiwan (~35°C, 60–80% RH). The major focus of the pre-competition training camp was on team, tactical and tapering for performance. This was important as the eight rowers and one cox had spent limited time training and competing together as a team. The participants were relatively rested, in the tapering phase of training, which was considered to be important whilst undergoing heat acclimation. A general overview of the pre-competition training camp and heat acclimation regime for highly trained athletes is shown in Fig. 1.

Participants

Participants were eight male volunteers who were selected as New Zealand representatives for an international student rowing regatta. Participants ranged from 19 to 24 years and were highly trained (Table 1). Each participant was previously unacclimated to the heat. The acclimations occurred within the winter-spring, to minimise seasonal acclimatisation effects.

Heat stress tests (HST)

Participants (Table 1) were asked to rest for 60 min on arrival at the laboratory. Participants had 10 min rest

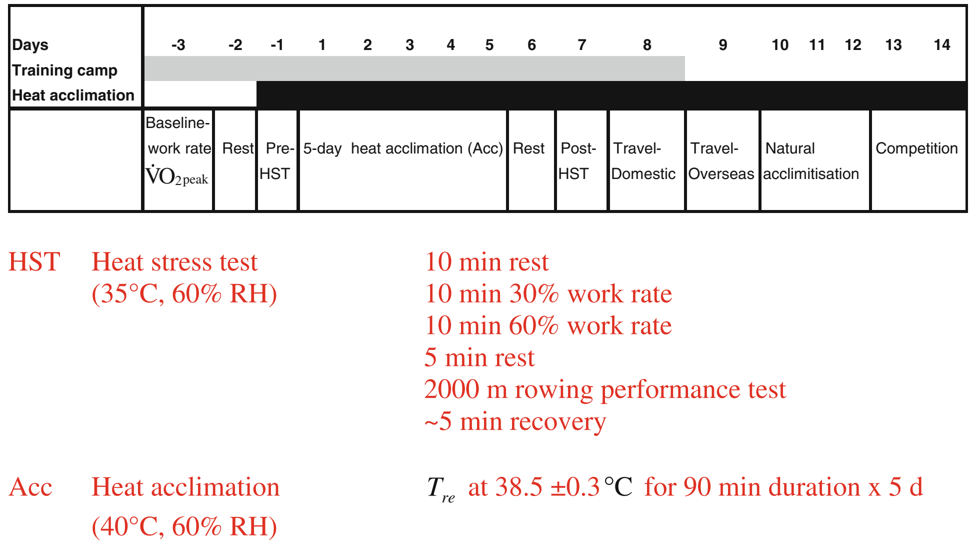

Fig. 1 Overview of the pre-competition training camp and short-term heat acclimation protocol for highly trained athletes

Table 1 Personal characteristics of highly trained participants

Participant	Age (years)	Body mass (kg)	$\dot{V}O_{2peak}$ (L min^{-1})	$\dot{V}O_{2peak}$ (mL kg^{-1} min^{-1})	PPO (W)
S11	19	73.1	5.10	69.7	400
S12	23	74.3	5.00	67.3	425
S13	23	69.8	4.80	68.8	350
S14	24	82.2	5.10	62.1	400
S15	20	69.4	4.86	70.0	425
S16	19	80.6	5.10	63.3	425
S17	23	76.2	4.89	64.2	400
S18	23	76.3	4.69	61.5	375
Mean	22	75.2	4.94	65.8	400
SD	2	4.6	0.19	3.5	27

$\dot{V}O_{2peak}$ peak oxygen uptake, *PPO* peak power output, using rowing ergometry, *SD* standard deviation

followed by 20 min of rowing (35°C, 60% RH, with a wind speed < 0.5 m s^{-1}) on a rowing ergometer (Concept, Concept II, Vermont, USA), at 30% of maximal work rate for 10 min and 60% maximal work rate for 10 min. Workloads were determined from the initial peak oxygen uptake ($\dot{V}O_{2peak}$) test on a rowing ergometer, using a sport-specific incremental test, designed for Rowing New Zealand (Smith 2003). The participants then rested for 5 min and were allowed to drink ad libitum before a 2,000-m rowing performance test. Participants were exposed to the heat stress conditions for ~45 min.

To examine the effect of heat acclimation on body core temperature, T_{re} was measured using a rectal thermistor (Thermistor 400, Mallinckrodt Medical Inc., St Louis, USA) placed in the rectum 10 cm beyond the anal sphincter. Temperature data was logged on a portable data logger (1200 series, Squirrel Grant Instruments, Cambridge, England). f_c was measured from the R–R interval of ventricular depolarisation (Polar Sport tester Advantage, Kemplele, Finland) during 20-min exercise of the heat stress test. Perceived body temperature and thermal comfort were measured at rest (5 min after entering the climatic chamber) and 20-min exercise of the heat stress test.

This protocol was designed to mimic rowing race conditions as closely as possible (Ingham et al. 2002; Secher 1993; Steinmacker 1993). The current world record for indoor 2,000-m rowing performance test is 5.58.5 min (Concept2 2011) and the average 2,000-m time for the eight highly trained male participants was ~6.40 min. Therefore, because they were able to perform at ~90% of world record pace, it is considered that they constitute as highly trained athletes. Furthermore, the pre-competition period training schedule, undertaken before the final training camp reflected the highly trained status of the participants. For example, in this training phase the training volume averaged 120 min per day. There was greater emphasis for on-water training, which contributed 80% and ergometer work made up 20% of total training time.

Approximately 30 min was spent each day for warm-up and cool-down. Therefore, total training time in the pre-competition training phase was greater than 14 h per week indicating a significant training load. The 2,000 m rowing ergometer performance test used in this study has previously demonstrated high reliability (CV: 0.6%) with well-trained athletes (Schabort et al. 1999) and a 0.7% CV has been reported using highly-trained rowers (Creasy 2002).

Acclimation protocol

Participants completed heat acclimation sessions consisting of 90-min exposure to hot and humid conditions (40°C, 60% RH, <0.5 m s^{-1} air speed) for five consecutive days. Modest hyperthermia (T_{re} of 38.5°C) was attained as rapidly as possible, maintained by regular adjustment of workload using a cycle ergometer (Monarch Ergomedic, Model 824E, Varberg, Sweden). Nominal fluid replacement (100 mL) was given during acclimation bouts not only to facilitate dehydration but also to minimise the perception of fluid deprivation. This high thermal loading was intended to emphasise heat acclimation more than the training stimulus and facilitate the tapering phase in the highly trained group prior to their overseas competition. This same acclimation protocol had previously been used with a lesser trained cohort and had elicited adaptation to heat stress conditions (Garrett et al. 2009). The mean ± SE of f_c, T_{re} and time to T_{re} 38.5°C were taken over the 90-min acclimation bout (Table 2). Urine and venous blood samples were obtained before and after acclimation bouts on day 1 and day 5 of acclimation.

Urinary measures

Using fresh urine samples, urine specific gravity (SG_u) and urine colour ($colour_u$) were measured using a calibrated refractometer (Uricon-N, Urine specific gravity refractometer, Atago Co., Tokyo, Japan) and urine colour chart (Armstrong et al. 1994, 1998), respectively. Urine volume was recorded and urine osmolality (osm_u) was analysed after the experiment using a vapour pressure osmometer (Model 5520 Vapro, Wescor, USA).

Blood measures

Plasma for the measurement of the fluid regulatory hormone aldosterone (200 μL) was stored using chilled K-EDTA tubes (1.6 mg mL^{-1}). Measurement of aldosterone used the Coat-A-Count aldosterone procedure (DPC's), which is based upon human serum calibrators, ^{125}Itracer and aldosterone anti-body coated tubes. The tube was decanted and counted in a gamma counter. The sample concentration was then determined from calibration standards (25–1200 pg mL^{-1}) and control samples, using a standard curve. The intra-assay coefficient of variation was 9.9% for duplicate measures and all samples for a given individual were analysed within the same assay. Plasma Na^+ was analysed using duplicate colorometric analysis (Cobas Mira Plus, New Jersey, USA). Plasma aldosterone and Na^+ were measured before and after day 1 and day 5 of the acclimation regime.

Changes in the concentration of haemoglobin [Hb] and haematocrit [Hct] were used to determine the relative change in plasma volume described by Dill and Costill (1974). Venous blood samples (5 mL) were taken from an antecubital vein (Vacutainer Precision Glide 21-gauge needle, Becton–Dickinson Vacutainer Systems) by phlebotomy without stasis and immediately analysed—in sexplicate—for [Hb] (Willoughby et al. 2002), (Model OSM3, Radiometer, Copenhagen, Denmark) and [Hct] [using a Hawksley Microhaematocrit centrifuge (Sussex, UK) and a Micro-capillary reader (Damon/IEC Division, MA, USA)].

Table 2 Thermal strain, body mass change (%), haemoglobin and haematocrit on the first and last day of heat acclimation for highly trained rowers

	Day 1	Day 5	p Value
Mean f_c (b min^{-1})	121 ± 4	120 ± 3	0.67
Mean T_{re} (°C)	38.3 ± 0.1	38.2 ± 0.1	0.87
Time to 38.5°C (min)	28.0 ± 1.5	31.0 ± 1.8	**0.01**
Body mass change (%)	1.6 ± 0.1	−2.3 ± 0.1	0.35
Haemoglobin (g dL^{-1})	15.3 ± 2.0	15.1 ± 1.9	**0.05**
Haematocrit (%)	43.5 ± 0.7	42.5 ± 0.8	**0.05**

Cardiac frequency (f_c), rectal temperature (T_{re}), time to T_{re} 38.5°C, body mass change, haemoglobin and haematocrit on day 1 and day 5 of acclimation, undertaken without fluid rehydration

Data mean ± SE are for eight highly trained males for whom data were available across all sessions

Statistically significant differences by paired t test analysis are shown in bold

The percentage change in plasma volume was analysed from day 1 to day 5 of the acclimation regime and calculated using the mathematical equation developed by Dill and Costill (1974).

Data analysis

The stress response of dependent measures at rest and end-exercise were analysed using paired *t* test analysis and reported as mean with 95% confidence intervals (95% CI). The relationship (r) between variables was calculated using the Pearson Product Moment Correlation and expressed as r^2 and p value. Urinary measures on day 1 versus day 5 acclimation were analysed using one-way analysis of variance (ANOVA) with repeated measures and Tukey's post-hoc test ($\alpha = 0.05$).

Results

Thermal strain, haemoglobin and haematocrit

Thermal strain, haemoglobin and haematocrit from day 1 and day 5 acclimation are shown in Table 2. The thermal strain was consistent between days illustrated by mean cardiac frequency (f_c) and rectal temperature (T_{re}) responses. Time to 38.5°C was longer on day 5 than on day 1 (Table 2; $p = 0.01$). Therefore, less work was performed on day 1 than on day 5 (Fig. 2; $p = 0.05$).

Plasma volume

The percentage change in plasma volume derived from resting haemoglobin and haematocrit (Table 2) increased from day 1 to day 5 acclimation for highly trained participants (4.5 ± 1.6%; $n = 8$).

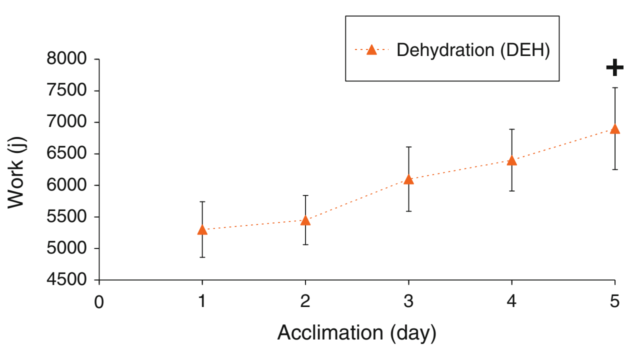

Fig. 2 Work output on the first day (1) to the last day (5) of dehydration acclimation after 90-min heat exposure. Data are mean ± SE for eight highly trained males. Significant difference $^{+}p < 0.05$; day 1 versus day 5 acclimation analysed using one-way analysis of variance (ANOVA) with repeated measures and Tukey's post-hoc test to isolate differences between days

Plasma volume and VO_{2peak}

There was a weak association (r^2 and p value) between ΔPV from day 1 to day 5 acclimation and $\dot{V}O_{2peak}$ (0.20, $p = 0.05$).

Urinary measures

To determine hydration status measures of body mass, SG_u, $colour_u$ and osm_u on day 1 and day 5 of acclimation are shown in Fig. 3. Body mass significantly decreased ($p < 0.01$) from rest to end exercise on day 1 DEH, with increases in SG_u ($p < 0.05$) and $colour_u$ ($p < 0.01$). Similarly, on day 5 at rest to end exercise, body mass decreased ($p < 0.01$), with increases in $colour_u$ ($p < 0.01$).

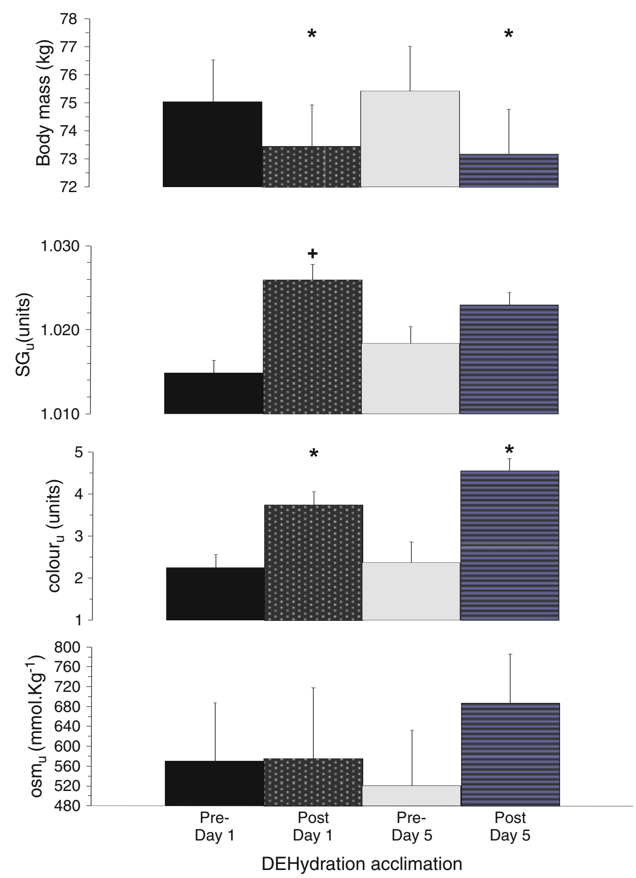

Fig. 3 Body mass, urine specific gravity (SG_u), urine colour ($colour_u$) and urine osmolality (osm_u) on days one and five of DEH acclimation regime. Data are mean ± SE for eight highly trained males. Significant difference $^{*}p < 0.01$; $^{+}p < 0.05$, pre versus post exercise on day 1 and day 5 acclimation by one-way analysis of variance (ANOVA) with repeated measures and Tukey's post-hoc test used to identify differences between days

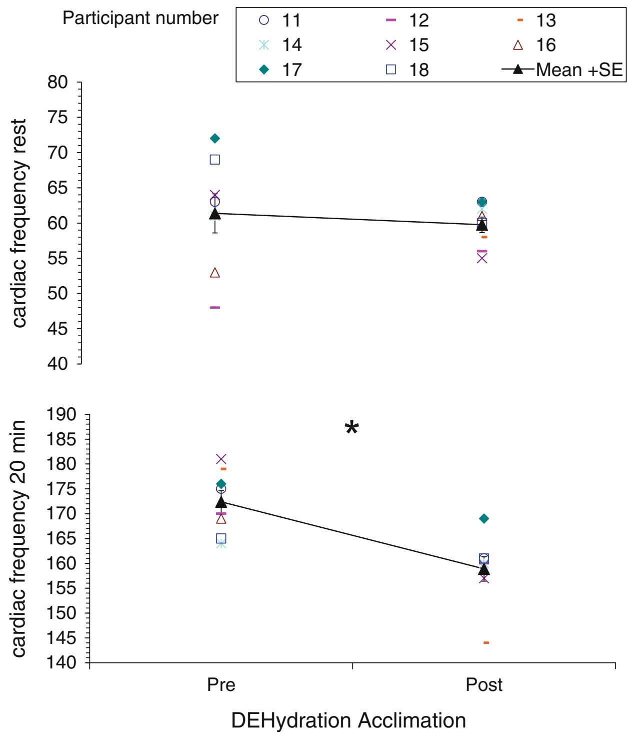

Fig. 4 Cardiac frequency at rest (*upper panel*) and after 10-min rowing at 30% maximal work rate and 10-min at 60% maximal work rate (*lower panel*) in the heat (35°C, 60% RH), before (pre) and after (post) acclimation, undertaken without rehydration during daily heat sessions. Statistically significant change; $*p < 0.01$ from pre acclimation. Data mean ± SE are denoted by a *black triangle* and *line* and expressed in b min^{-1} for eight highly trained males who undertook the acclimation regime

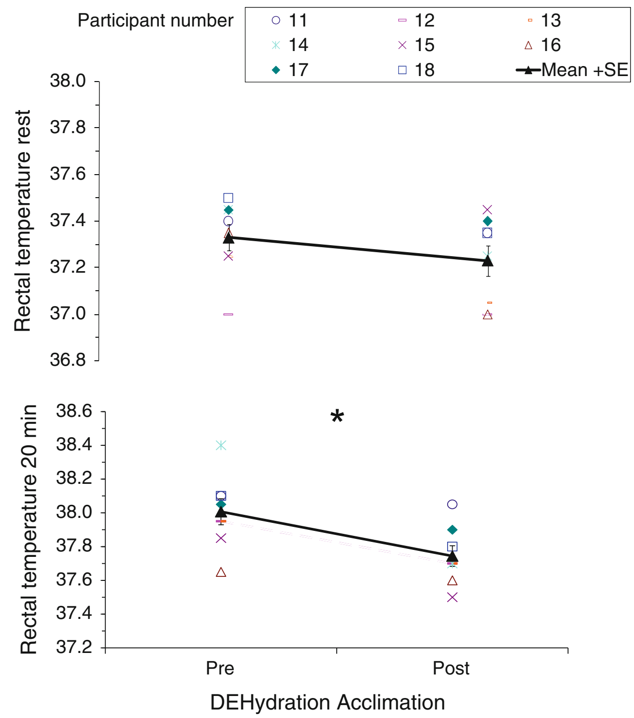

Fig. 5 Rectal temperature at rest (*upper panel*) and after 10-min rowing at 30% maximal work rate and 10 min at 60% maximal work rate (*lower panel*) in the heat (35°C, 60% RH), before (pre) and after (post) acclimation, undertaken without rehydration during daily heat sessions. Statistically significant change; $*p < 0.01$ from pre acclimation. Data mean ± SE are denoted by a *black triangle* and *line* and expressed in °C for eight highly trained males who undertook the acclimation regime

Cardiac frequency

f_c was measured at rest (Fig. 4, upper panel) and at completion of the 20-min fixed load exercise (Fig. 4, lower panel) of the heat stress test. Resting f_c had limited change across acclimation (Δ −4 b min^{-1}; 95%CI: −12 to 5 b min^{-1}; $p = 0.38$). However, exercising f_c was consistently reduced by 7.5% at 20-min exercise across acclimation (Δ −14: −23 to −5 b min^{-1}; $p = 0.01$). The time course of cardiac frequency in the heat stress test, pre and post-acclimation, is shown in Fig. 6.

Body temperature

T_{re} was measured at rest (Fig. 5, upper panel) and 20-min exercise (Fig. 5, lower panel) of the heat stress test. T_{re} at rest was not consistently lowered across acclimation (Δ −0.1: −0.3 to 0.2°C; $p = 0.64$). However, similar to the f_c response, T_{re} at 20-min exercise was attenuated across acclimation (Δ−0.3: −0.4 to −0.1°C; $p = 0.01$). After 20-min exercise T_{re} had decreased after (versus before)

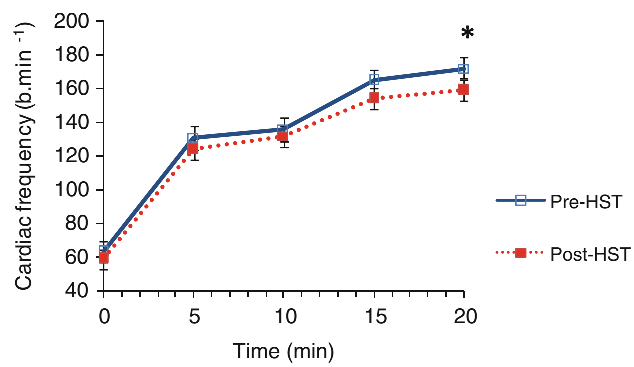

Fig. 6 Cardiac frequency timeline at rest, after 10-min rowing at 30% maximal work rate and 10 min at 60% maximal work rate in the heat (35°C, 60% RH), before (pre) and after (post) acclimation, undertaken without rehydration during daily heat sessions. Statistically significant change; $*p < 0.01$) from pre acclimation. Data mean ± SE and expressed in b min^{-1} for eight highly trained males who undertook the acclimation regime

acclimation in all participants (Fig. 6, lower panel). The time course of T_{re} in the heat stress test, pre and post-acclimation, is shown in Fig. 7.

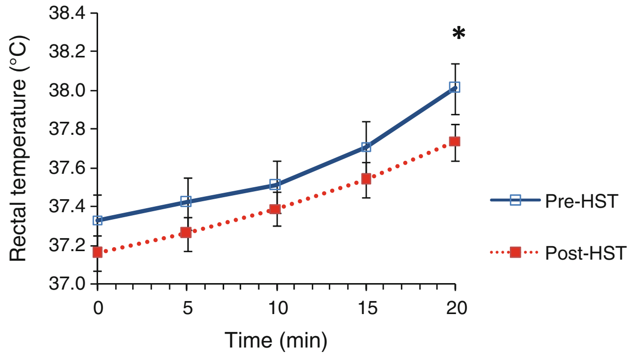

Fig. 7 Rectal temperature timeline at rest, after 10-min rowing at 30% maximal work rate and 10 min at 60% maximal work rate in the heat (35°C, 60% RH), before (pre) and after (post) acclimation, undertaken without rehydration during daily heat sessions. Statistically significant change; $^*p < 0.01$ from pre acclimation. Data mean ± SE and expressed in °C for eight highly trained males who undertook the acclimation regime

Psychophysical

Perceived body temperature and thermal comfort were measured at rest (5 min after entering the climatic chamber) and 20-min exercise of the heat stress test. Resting perceived body temperature was lower across acclimation (Δ −1: −2 to 0 units; $p = 0.04$) but there was no change at 20-min exercise (Δ 0: −0.5 to 0.5 units; $p = 0.98$). There was limited change in thermal comfort at rest (Δ −0.5: −0.5 to 0.5 units; $p = 0.37$) and 20-min exercise (Δ 0: −1.0 to 1.0 units; $p = 0.88$) across acclimation.

Plasma aldosterone

Plasma aldosterone was measured at rest (Fig. 8, upper panel) and 90-min acclimation (Fig. 8, lower panel) of day 1 and day 5 acclimation. Plasma aldosterone increased at rest (Δ 53: 7–98 pg·mL^{-1}; $p = 0.03$) and 90-min (Δ 162: 65–259 pg·mL^{-1}; $p = 0.01$) across the acclimation regime. Plasma aldosterone was greater in seven of the eight participants at rest and in all participants after 90-min acclimation on day 5 than on day 1. Importantly, the exercise and heat-induced increase within a session was considerably larger than the increase observed at rest across these acclimation days.

Sodium

Plasma Sodium concentration $[Na^+]_p$ was measured at rest and 90-min acclimation of day 1 and day 5 acclimation. Plasma Sodium concentration $[Na^+]_p$ demonstrated limited change at rest (Δ −0.6: −1 to 0.5 mmol L^{-1}; $p = 0.25$) and 90-min acclimation (Δ 0.3: −0.3 to 1.0 mmol L^{-1}; $p = 0.30$) across the acclimation regime.

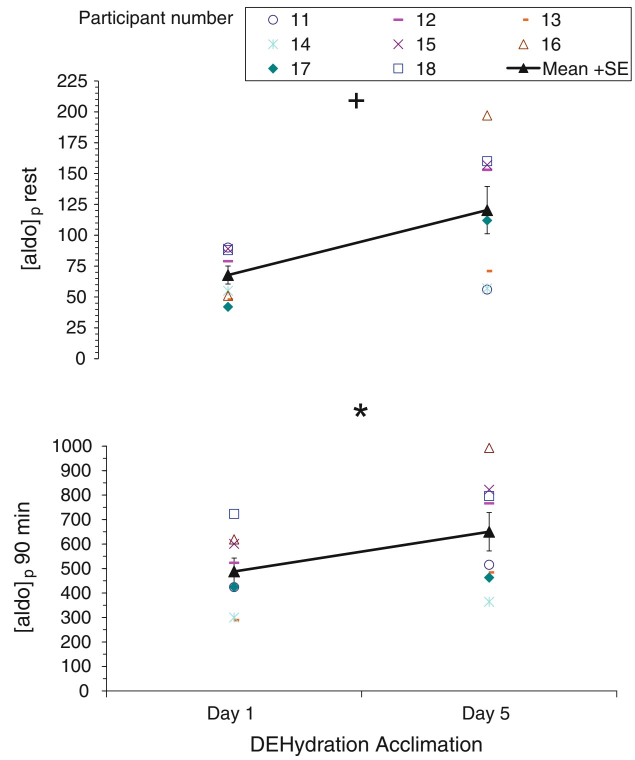

Fig. 8 Plasma aldosterone concentration at rest (*upper panel*) and 90-min acclimation (*lower panel*), on days one and five, undertaken without rehydration during daily heat sessions. Statistically significant change; $^*p < 0.01$ and $^+p < 0.05$) from day 1 to 5 of acclimation. Data mean ± SE are denoted by a *black triangle* and *line* and expressed in pg mL^{-1} for eight highly trained males who undertook the acclimation regime

Exercise performance capacity

Exercise performance capacity (Fig. 9) was measured with a 2,000-m rowing time trial at the end of the 20-min submaximal (~warm up) exercise heat stress test.

Time to complete the 2,000-m performance trial (Fig. 9); decreased by 4 s (time to 2,000 m) across acclimation (Δ −4.0: −6.3 to 0.6 s; $p = 0.02$; Fig. 9) and was lower in six of the eight participants.

Discussion

The majority of heat acclimation literature on humans is based on people who are not highly trained. The principal question in this study was to determine whether highly trained participants, who live in a temperate climate, benefit from a short-term (5-day) heat acclimation protocol with dehydration. Such athletes sometimes require or undertake heat acclimation prior to competition in more heat stressful environments, yet due to their level of conditioning they may already possess many of the

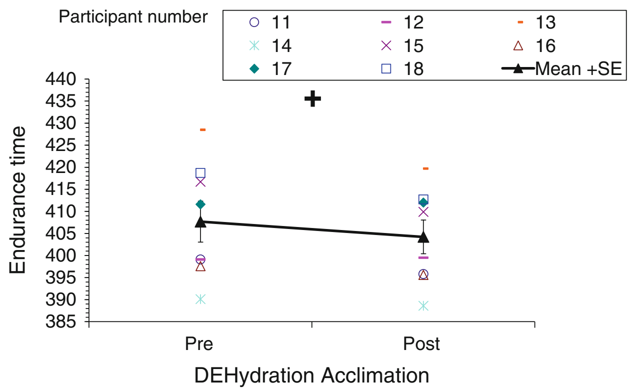

Fig. 9 Exercise endurance performance time after 10-min rowing at 30% maximal work rate and 10 min at 60% maximal work rate and 5-min rest in the heat (35°C, 60% RH), before (pre) and after (post) acclimation, undertaken without rehydration during daily heat sessions. Performance was measured using a 2,000-m rowing trial. Statistically significant change from pre acclimation $^{+}p < 0.05$. Data mean ± SE and expressed in seconds for eight highly trained males who undertook the acclimation regime

heat-related adaptations. However, the present results obtained using highly trained rowers undergoing short-term heat acclimation of daily controlled hyperthermia, with dehydration indicate that they experienced adaptation to the heat. This was indicated by the characteristic features of acclimation: end-exercise f_c (Fig. 4, lower panel) decreased 14 b min^{-1} (7.5%) and T_{re} decreased 0.3°C (0.8%) (Fig. 5, lower panel). This is despite that endurance-trained athletes behave physiologically as if they are already heat acclimatised (Taylor 2000) and hence the lower adaptive response (Taylor and Cotter 2006). This could not be dismissed with the results from the present study as some of the highly trained individuals demonstrated a lesser adaptive response. However, there was a 4.5% resting PV expansion, decreased perceived body temperature at rest and an increase in endurance exercise capacity, as 2,000 m rowing performance decreased by 4 s (1.5%; Fig. 9). The increased resting PV expansion with highly trained athletes is a unique contribution to the literature, especially as six of the participants had previously demonstrated high basal levels of PV (Creasy 2002). The high level of aerobic conditioning of the trained participants was reflected in their training regime—consistently training up to 14 h per week and able to perform at 90% of world record pace in the 2,000-m rowing ergometer performance test. Furthermore, although $\dot{V}O_{2peak}$ is a useful marker of endurance performance potential (Secher 1993; Steinmacker 1993), rowing requires several important physiological adaptations, such as the ability to tolerate high levels of acidity in the working muscle, especially in the 2,000-m rowing event (Schabort et al. 1999; Smith 2003). Therefore, in this study the adaptations and responses for the highly trained participants were of a similar magnitude to that seen in moderately trained (Garrett et al. 2009; Patterson et al. 2004) and untrained (Turk and Worsley 1974; Weller and Harrison 2001) individuals. For example, Patterson et al. (2004) used short-term (7-day) heat acclimation with the controlled hyperthermia technique and recorded decreased end-exercise f_c (6.8%), T_{re} (0.5%), PV expansion (9.8%) and increased work capacity (8.3%). More recently, using a similar acclimation protocol described in this study, Garrett et al. (2009) reported similar findings of decreased end-exercise f_c (7%), T_{re} (0.7%), PV expansion (4.2%) and increased work capacity (14%) among lesser trained participants.

Acclimation significantly lowered exercising but not resting T_{re} (Fig. 5, upper panel). This lack of reduction in resting T_{re} is in contrast to some studies (Buget et al. 1988; Houmard et al. 1990; Shvartz et al. 1973). However, the absence of an acclimation-induced, reduced resting T_{re} may reflect the findings on animals (Sakurada et al. 1994) and humans (Shido et al. 1999), (Shido et al. 1999) that resting T_{re} measurements are only attenuated at the time of day the heat exposures typically occur. Therefore, in the present study resting T_{re} was not substantially lowered and may be explained by the timing of the measurement. The heat stress testing was in the morning (9.00–12.00), whereas acclimation bouts were in the late afternoon (15.00–17.00), mainly because of timetable constraints of participants and experimentation. Thus, it is suggested that the acclimation-induced effects of reducing resting body temperature would have been more pronounced if the heat stress test had been in the afternoon, but it may also have required more than a 5-day acclimation (Buono et al. 1998; Sakurada et al. 1994; Shido et al. 1999). Second, as the exercise duration was relatively short (20-min) to mimic the ecological validity of the warm-up and performance in elite rowing (Ingham et al. 2002; Secher 1993; Steinmacker 1993), it may be that T_{re} may have been slow to respond and not the most valid index of core temperature which maybe a limitation of this study. However, T_{re} after acclimation is both a reliable and valid index of the effect of acclimation on body core temperature (T_c), for a combination of reasons. First, a rapid lowering of resting and exercising T_c—as seen here in exercise—is a common and rapidly adapting phenotypic attribute of heat acclimation (Buono et al. 1998; Nielsen et al. 1993; Shido et al. 1999). However, it should be noted that less information is available that this phenotype can be applied to elite performers. Second, T_{re} is heavily influenced by the heat production of lower-body exercise, relative to oesophageal temperature (T_{es}), which also reflects upper-body heat production (Gass et al. 1988) and evaporative and convective heat loss from cutaneous perfusion (Kenny et al.

2003). The rowers in the present study were highly familiar with rowing ergometry and were thus rowing at the same rate of heat production in pre- versus post-acclimation trials. Thus, the observed lowering of exercising T_{re} post acclimation would, if anything, have been an underestimation of the effect on other core tissue T_c. Third, whilst T_{es} may have rapid kinetics and a close representation of arterial temperatures it is not without its own problems. For example, the temperature of the gastrointestinal temperature is an important consideration in exercising heat stress by virtue of its involvement in GI permeability (which is presumably more related to T_{re} than T_{es}). Oesophageal thermistors—in our experience—are more uncomfortable and intrusive devices during exertion and are less well tolerated by athletes, which can in itself impair the validity of findings. Thus, we felt that T_{re} was the preferred measure to use in this cohort, especially since comparisons were within athletes, in the same stress test before and after intervention. In relatively short, performance-based, exercise trials, the use of T_{re} as a measure of core temperature for 20-min cycle ergometer exercise, in a thermo-neutral and hot environment has previously been reported by Hettinga et al. (2007). Similarly, in heat stress conditions T_{re} has been used in a 20 km (~25–30 min) cycling time trial with trained participants (Tucker et al. 2004) and a 30-min cycling time trial with elite cyclists (Tatterson et al. 2000). In the present study, the decreased T_{re} at 20-min exercise across acclimations (Fig. 5, lower panel), despite the lack of reduction in resting temperature, demonstrates that adaptation to heat stress from short-term acclimation was similar to that seen in moderately trained (Creasy 2002; Garrett et al. 2009; Patterson et al. 2004; Regan et al. 1996; Taylor et al. 1995) and untrained (Turk and Worsley 1974; Weller and Harrison 2001) participants. The lower T_{re} may allow individuals to exercise longer or harder in the heat before a critical temperature (Nielsen et al. 1993) and the central drive to exercise is reduced (Bruck and Olschewski 1987; Nielsen et al. 1990). The lower exercising core temperature might lessen or delay hyperthermic effects such as increased catecholamines (Febbraio et al. 1994), glycogenolysis (Febbraio et al. 1994) and cellular permeability in vasoconstricted tissues such as the gastrointestinal tract (Moseley et al. 1994).

The physiological adaptation observed in the present study, indicated by the reduced end-exercise f_c (Fig. 4, lower panel) and T_{re} (Fig. 5, lower panel) with 4.5% PV expansion, will have presumably supported the increased endurance performance capacity (1.5%; Fig. 9) after short-term (5 day) heat acclimation. For example, there is evidence to suggest that exercise-induced hypervolaemia mediated by PV expansion (Harrison 1985; Senay et al. 1976) has the beneficial effect of enhancing cardiovascular and thermoregulatory responses to exercise, resulting in greater cardiac stability (Fellman 1992). There was an increased response of plasma aldosterone both at rest (Fig. 8, upper panel) and at 90-min (Fig. 8, lower panel) across acclimation bouts. However, there was limited response in plasma sodium at rest and after 90-min acclimation. This is surprising as the principle effects of aldosterone are the retention of Na^+ and therefore also water from the urine output to maintain extracellular fluid volume and thus also blood volume. Increased Na^+ and water retention at the distal tubules (Morris 1981) are important mediators of the rapid PV expansion during the initial hours to days after exercise (Nagashima et al. 1999, 2001). However, the increased fluid retention observed in this study by the 4.5% PV expansion may reflect why the Na^+ concentration may not have increased. Furthermore, it may be that the increased response in plasma aldosterone at rest and the limited response in plasma sodium at rest and end 90-min acclimation bout on day 1 and 5 may have reflected a residual sodium deficit (Allsopp et al. 1998) for the highly trained athletes. This is possibly due to the level of training undertaken immediately prior to the pre-competition training camp itself (Fig. 1). The observed increased plasma aldosterone at 90-min end acclimation bout was expected, as it has been demonstrated that it may be more systematically altered after dehydration acclimation and it has previously been shown that a state of euhydration will blunt the release of aldosterone in exercising and ambient heat stress (Brandenberger et al. 1986, 1989; Kenefick et al. 2007; McConell et al. 1997).

The 2,000 m rowing performance trial resulted in a reduction in time of 4 s which equates to a 1.5% increase in performance. This small relative change may actually indicate a substantial increase in performance, especially using highly trained athletes in the sport of rowing. The power versus velocity relation in rowing is such that power is related to velocity by an exponent of 3, meaning that disproportionate gains in power must be made to obtain similar increases in speed. Therefore, 1–2% change in performance velocity due to change in power output at high level in rowing has been demonstrated as functionally significant (Hopkins et al. 2001). It has been demonstrated that highly trained athletes behave physiologically as if they were already heat acclimatised (Taylor 2000) and the higher the background adaptation, the lower the adaptation response (Taylor and Cotter 2006). Therefore, the absolute magnitude of physiological or performance changes will be lower in comparison with moderately or untrained participants. This study further suggests that the adaptation to heat stress for highly trained participants may have been enhanced using the controlled hyperthermia technique during acclimation. This technique maintains strain across acclimation and allows an increase in work output as the individual adapts to the heat stress (Fig. 2) and hence, it may offer a more complete adaptation (Taylor 2000). Nevertheless, the important point is that the highly trained rowers obtained functionally significant and meaningful adaptation in physiological strain and performance across the relatively brief heat acclimation regime; indicating that—at least using this regime—they stand to benefit from acclimation procedures that have been studied using lesser adapted humans (Garrett et al. 2009).

In summary, the adaptations in this study indicate improved cardiovascular stability after short-term (5-day) heat acclimation with dehydration. Furthermore, endurance performance capacity was improved by dehydration acclimation. The greater endurance performance capacity is consistent with the lower strain during fixed-load exercise, indicated by f_c and T_{re} and the PV response across acclimation. Therefore, this study has contributed to the very limited information available on adaptation to heat stress for highly trained participants.

Conclusions

Highly trained participants, who live in a temperate climate, benefit from a short-term (5-day) heat acclimation protocol with dehydration via enhanced thermoregulatory and cardiovascular responses to exercise in the heat.

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