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INFLUENCE OF SHORT-TERM AEROBIC TRAINING AND HYDRATION STATUS ON TOLERANCE DURING UNCOMPENSABLE HEAT STRESS

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ORIGINAL ARTICLE

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Influence of short-term aerobic training and hydration status on tolerance during uncompensable heat stress

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Abstract The purpose of the present study was to determine the separate and combined effects of a short-term aerobic training program and hypohydration on tolerance during light exercise while wearing nuclear, biological, and chemical protective clothing in the heat (40°C, 30% relative humidity). Males of moderate fitness [$< 50 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ maximal O_2 consumption ($\dot{V}O_{2\max}$)] were tested while euhydrated or hypohydrated by ≈2% of body weight through exercise and fluid restriction the day preceding the trials. Tests were conducted before and after either a 2-week program of daily aerobic training (1 h treadmill exercise at 65% $\dot{V}O_{2\max}$ for 12 days; $n = 8$) or a control period ($n = 7$), which had no effect on any measured variable. The training increased $\dot{V}O_{2\max}$ by 6.5%, while heart rate (f_c) and the rectal temperature (T_{re}) rise decreased during exercise in a thermoneutral environment. In the heat, training resulted in a decreased skin temperature and increased sweat rate, but did not affect f_c, T_{re} or tolerance time (TT). In both training and control groups, hypohydration significantly increased T_{re} and f_c and decreased the TT. It was concluded that the short-term aerobic training program had no benefit on exercise-heat tolerance in this uncompensable heat stress environment.

Key words Heat exhaustion · Temperature regulation · Hypohydration · NBC clothing · Physical fitness

Introduction

It is well known that improvements in aerobic fitness accrued from strenuous long-term training programs or habitual exercise improve an individual's tolerance to heat stress (Gisolfi 1973; Gisolfi and Robinson 1969; Piwonka and Robinson 1967). Fit subjects have also been observed to adapt to heat acclimation more rapidly than non-fit subjects (Pandolf et al. 1977; Shvartz et al. 1977). For the military, soldiers may not have the benefit of time or the facilities to undertake a long-term endurance training or heat-acclimation program in order to prepare for exercise in a hot environment. Recently, however, short-term aerobic training models have been used to elicit a series of cardiodynamic, ventilatory and metabolic adaptations that improve exercise tolerance in a normothermic environment, with significant increases in maximal aerobic power ($\dot{V}O_{2\max}$) and plasma volume and decreases in heart rate (f_c) and glycogen utilization during submaximal exercise following 10–12 consecutive days of training at 59% $\dot{V}O_{2\max}$ (Green et al. 1991a, b). Short-term training has also been found to produce significant improvements in thermal economy and efficiency, with a decrease in core temperature both at rest and during exercise (Shvartz et al. 1974). It would be of interest, therefore, to investigate whether a short-term aerobic training program of 2 weeks or less would have significant benefits in exercise-heat tolerance.

While aerobic training may improve exercise tolerance in a thermoneutral environment, its benefits in a situation of uncompensable heat stress, such as that found while exercising in protective clothing in the heat, are less clear. Due to the limited water vapour permeability of the clothing, it is possible that the increased sweat production in trained subjects may increase physiological strain by promoting a faster rate of dehydration rather than increasing evaporative heat loss (Nunneley 1989). After 8 weeks of aerobic training, no improvements in physiological response or tolerance time (TT) in subjects wearing nuclear, biological and chemical (NBC) clothing have been observed (Aoyagi et al. 1994). However, the metabolic rate used to evaluate the changes in heat tolerance in that study may have produced heat exhaustion before a significant amount of heat transfer could occur through the clothing layers. Thus, the physiological benefit of an

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increased sweating rate with training may have been negated.

The purpose of the present study was to determine, in a group of relatively non-fit subjects, the separate and combined effects of a short-term aerobic training program and hypohydration on heat tolerance during light exercise while wearing NBC clothing. Subjects of low to moderate fitness were tested while euhydrated and also while hypohydrated by ≈2% of body weight. Tests were conducted before and after either a 2-week program of daily aerobic training or a 2-week control period. The training program was hypothesized to result in an improved physiological response in both a euhydrated and hypohydrated state, with a decrease in the magnitude of impairment while hypohydrated following the training program.

Methods

Subjects

Fifteen healthy males between the ages of 18 and 40 years, recruited from the university population or the military community, participated in the study. Subjects underwent a medical examination and were informed of all details of the experimental procedures and the associated risks and discomforts before they provided their consent. The aerobically non-fit subjects for the present study were defined as having an initial $\dot{V}O_{2\max}$ of between 40 and 50 ml · kg^{-1} · min^{-1}, and were either inactive at the time of the study or engaged in physical activity only on an irregular basis. All subjects agreed to abstain from regular aerobic activities for the duration of the experiment.

Experimental design

The experimental protocol and instrumentation used in the present study were approved by the Ethics Review Committees of the University of Toronto and the Defence and Civil Institute of Environmental Medicine (DCIEM). Testing was conducted at DCIEM from January to early May to limit initial heat acclimation through casual exposure to high ambient temperatures. On five separate occasions, each subject performed a heat stress test (HST) which consisted of walking on a motorized treadmill in a hot (40°C, 30% relative humidity, wind speed <0.1 m · s^{-1}) environment while wearing the Canadian Forces NBC protective clothing ensemble. For all subjects, the first session was used as a familiarization trial and the results were discarded. A minimum of 1 week separated experimental trials to avoid the effects of partial heat acclimation.

Responses to the HST were evaluated while manipulating each subject's level of hydration. Following the dehydration protocol, subjects were either rehydrated to baseline body weight overnight (EU) or the decrease in their body weight was maintained overnight (HY). During all HST, subjects underwent a fluid replacement program consisting of 200 ml of water every 15 min, with the water temperature maintained near 37°C. The order in which the different conditions was presented was randomized to minimize order effects or the effects of partial heat acclimation.

Subjects were randomly assigned to either a training ($n = 8$) or a control ($n = 7$) group. Following an HST in each of the EU and HY conditions, training subjects underwent a 2-week aerobic training program. Six days a week, subjects walked on a motorized treadmill at 60–65% $\dot{V}O_{2\max}$ (4.8 km · h^{-1}, 8–13% grade) in a normothermic (22°C, 40% relative humidity) environment for 1 h. $\dot{V}O_2$ was measured during the first and last training session to ensure that the training intensity was at the desired range. Control subjects also exercised at 60–65% $\dot{V}O_{2\max}$ on the first and last day of the 2-week period. In between, they were asked to maintain their normal daily routines, which did not include aerobic exercise.

Following the 2-week training or control period, all subjects again performed an HST in the EU and HY conditions, with the order of conditions reversed to counterbalance order effects. In between the first and second post-training HST, training subjects performed three to four training sessions to maintain their fitness levels.

NBC protective clothing

The Canadian Forces NBC protective clothing ensemble worn in all trials consisted of shorts, T-shirt, socks, combat shirt and trousers, running shoes, semipermeable NBC overgarment, gas mask and cannister, and impermeable rubber gloves and overboots. The total mass of the ensemble was approximately 8.0 kg. In order to allow some sweat evaporation, there is limited mass penetration of charcoal-filtered air through the fabric. Thermal resistance and the Woodcock vapour permeability coefficient of the ensemble determined on a heated and wetted manikin at a wind speed of 1.12 m · s^{-1} were 0.291 m^2 · °C · W^{-1} (1.88 clo) and 0.33, respectively (Gonzalez et al. 1993).

Individual characteristics

$\dot{V}O_{2\max}$ was determined with the subject on a motorized treadmill using open-circuit spirometry. Following 3 min of running at a self-selected pace, the treadmill grade was increased 1% each minute to a maximum of 10%. Thereafter, increases in treadmill speed and grade of 0.22 m · s^{-1} (0.8 km · h^{-1}) or 2%, respectively, alternated each minute until the subject could no longer continue. Subjects were given verbal encouragement throughout the test. $\dot{V}O_{2\max}$ was defined as the highest 30 s $\dot{V}O_2$ observed during the incremental test. f_c was monitored throughout the incremental test from a telemetry unit (Polar Vantage XL), and the value recorded at the end of the exercise test was considered to be the individual's maximum f_c. $\dot{V}O_{2\max}$ was determined both at the start of the experiment and following the training or control period. Body fatness was estimated from skinfold measurements using a gender-specific regression equation developed from hydrostatic measurements of body density (Forsyth et al. 1984).

Dehydration protocol

A dehydration and overnight protocol identical to that employed in a previous investigation in this laboratory was used, and was found to be effective at manipulating the hydration status of the subjects (Cheung and McLellan 1998). In the afternoons prior to the HST, subjects reported to the laboratory at ≈1330 hours for the dehydration protocol, allowing approximately 15 h for body fluid compartments to stabilize between the dehydration protocol and the HST. Dehydration sessions took place in the same environmental chamber [40°C, 30% relative humidity (RH)] as used for the HST. Both nude and dressed weights (shorts, socks, shoes) were recorded prior to entry into the chamber. Subjects walked on a motorized treadmill at an exercise intensity (4.5–5.5 km · h^{-1}, 3–6% grade) that induced weight loss at a rate of 0.8–1.2 l · h^{-1}. Rectal temperature (T_{re}) and body mass were monitored throughout the dehydration, and subjects were removed from the chamber upon losing 2.5% of their baseline body mass.

Nutrition was controlled for all trials by providing subjects with a set meal plan consisting of PowerBar meal-replacement bars (Power fund Inc. Berkeley CA.). For subjects undergoing EU trials sufficient Gatorade(Quaker Oats Company of Canada, Peterborough, ON) was provided immediately following the dehydration session to replace the amount of weight loss. Subjects were also instructed to drink 600 ml · h^{-1} of Gatorade or juices that evening.

and at least 600 ml in the morning prior to reporting to the laboratory. Subjects undergoing the HY trials were given a total ration of 800 ml of Gatorade. based on expected basal weight losses over a 15-h period.

Dressing and weighing procedure

Subject preparation, insertion of the rectal thermistor, and placement of skin thermistors have been detailed previously (McLellan 1993). Prior to the dressing procedure, subjects remained in an upright posture for 10 min, whereupon a 5 ml blood sample was obtained from an antecubital vein within 90 s of lying down. Plasma osmolality was calculated from plasma concentrations of glucose, sodium, and blood urea nitrogen (Novastat, Nova Biomedical). Both nude and dressed weights were recorded prior to entry into the chamber. Upon entering the chamber, the subject's skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system and the exercise began. Mean values over 1-min periods for core temperature (T_{re}), and a 12-point weighted mean skin temperature ($\bar{T}_{sk}$) (Vallerand et al. 1989) were calculated, recorded, and printed by the data acquisition system. f_c was recorded every 5 min from the Polar Vantage XL unit. After the completion of each trial, dressed weight was recorded within 1 min after exit from the chamber. Nude weight was recorded within 5 min upon undressing and toweling dry.

The baseline body mass was assumed to be the nude body mass measured prior to the dehydration procedure of the initial EU HST. Differences in nude and dressed weights before and after each trial were corrected for respiratory and metabolic weight losses (see below). The amount of sweat produced was calculated as pre-trial minus post-trial nude weight (corrected) plus water given. Evaporative sweat loss from the clothing was calculated as pre-trial minus post-trial dressed weight (corrected) plus water given.

Tolerance time

Tolerance time (TT) for all trials was defined as the time until T_{re} reached 39.3°C, f_c remained at or above 95% of maximum for 3 min, dizziness or nausea precluded further exercise, either the subject or the experimenter terminated the experiment, or 4 h had elapsed.

Gas exchange analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation, $\dot{V}O_2$, and carbon dioxide production from a 2-min average obtained every 15 min. An adaptor was attached to the respirator which allowed expired air to be collected. Respiratory water loss was calculated using the measured $\dot{V}O_2$ and the equation presented by Mitchell et al. (1972). Metabolic weight loss was calculated from the $\dot{V}O_2$ and the respiratory exchange ratio using the equation described by Snellen (1966).

Statistics

Data are presented as mean values (standard deviation). A three-factor (period × hydration × time) repeated-measures ANOVA was used to compare the T_{re} and T_{sk} and f_c, of the non-fit subjects undergoing the training or control manipulations. A two-factor (period × hydration) repeated-measures ANOVA was used to compare the responses of TT, body weight changes, sweat rate, evaporative efficiency, plasma osmolality, metabolic rate, and respiratory exchange ratio. Following separate data analyses within either the training or control group, a between-group ANOVA was performed between the training and control groups. When a significant F-ratio (corrected for the repeated-measures factor) was obtained, a Newman-Keuls post-hoc analysis was performed to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

Results

The physical characteristics of the subjects are presented in Table 1. The training and control subjects were similar in age, height, body mass, body fat content, and surface area. The short-term training program was effective in significantly increasing $\dot{V}O_{2\,max}$ 6.5% from 43 to 46 $ml \cdot kg^{-1} \cdot min^{-1}$ (Table 1). In contrast, the 2-week control period had no effect on aerobic capacity. Despite the significant increase in aerobic capacity following training, no differences were observed in $\dot{V}O_{2\,max}$ between groups either before or following the manipulation. Comparing the responses between the first and last day of the training program, a significantly lower f_c [from 146.9 (12.9) to 137.3 (5.8) beats $\cdot$ min^{-1}] and T_{re} rise [from 1.26 (0.44) to 1.09 (0.31)°C] at the end of the hour of exercise were observed. The training program did not result in an increased sweating response [0.73 (0.18) to 0.78 (0.22) $l \cdot h^{-1}$] during the training exercise. The control group did not experience any differences in their physiological responses to the two training sessions separated by 2 weeks.

The hydration schedule following the dehydration protocol was successful in either restoring a euhydrated state or maintaining hypohydration overnight (Table 2). In EU trials, body weight returned to baseline levels overnight, and were similar for all EU trials. The average morning weights of training and control subjects during the HY trials ranged from 1.92 to 2.22% less than those during the Pre-EU trial, with no significant

Table 1 Physical characteristics of the subjects in the training and control groups. No significant differences exist between the training and control groups in any of the measured variables. Values are means (SD). ($\dot{V}O_{2max}$ Maximal power output)

Group	Age (years)	Height (m)	Body mass (kg)	Body fat content (%)	Surface area (m^2)	Surface area-to-mass ratio ($m^2 \cdot kg^{-1} \cdot 10^{-2}$)	$\dot{V}O_{2\,max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	
							Pre	Post
Training	30.3	1.77	84.7	19.2	2.02	2.41	43.2	46.0$^+$
(n = 8)	(6.7)	(0.05)	(12.6)	(3.9)	(0.14)	(0.20)	(2.7)	(2.5)
Control	30.6	1.79	80.4	16.3	1.99	2.50	45.3	45.3
(n = 7)	(6.2)	(0.05)	(8.3)	(3.1)	(0.09)	(0.18)	(2.8)	(4.9)

$^+$Significantly different from pre-training values

Table 2 Absolute and relative (to pre-EU) body mass and serum osmolality prior to the heat stress tests (*HST*) before and after the training or control period. The baseline body mass was assumed to be the nude body mass prior to the dehydration procedure of the initial euhydrated HST. Values are means (SD). (*EU* Group in which subjects were rehydrated following dehydration, *HY* group in which the dehydrated state was maintained)

	Training				Control			
	Pre-training		Post-training		Pre-control		Post-control	
	EU	HY	EU	HY	EU	HY	EU	HY
Body mass	84.15	82.15*	84.00	82.09*	80.13	78.22*	79.57	77.91*
(kg)	(12.69)	(12.37)	(12.80)	(12.41)	(8.13)	(8.09)	(8.16)	(8.46)
% Body	0.00	−2.00*	−0.15	−2.06*	0.00	−1.92*	−0.56	−2.22*
mass loss	(0.00)	(0.41)	(0.51)	(0.53)	(0.00)	(0.57)	(0.85)	(0.83)
Osmolality	287.3	293.2*	286.2	291.8*	287.4	291.7*	287.7	292.4*
(mosm · kg^{-1} H_2O)	(5.6)	(3.4)	(2.5)	(3.3)	(2.3)	(3.3)	(2.2)	(3.8)

*Significant main effect of hydration

differences in relative hypohydration within or among groups. Compared to EU trials, serum osmolality was elevated prior to HY trials for both the training and the control groups. These results all indicate that subjects were significantly hypohydrated prior to HY trials.

Table 3 summarizes some of the physiological responses to the HST. The metabolic rate, and therefore the rate of heat production, was similar for all trials both for the control and the training groups. As expected, responses to the HST were similar in subjects before and following the 2-week control period. Though no change in sweating response occurred while training in a cool environment, the more extreme heat environment of the HST was sufficient to expose a difference in the drive for heat dissipation due to training. One major change as a result of the 2-week aerobic training program was an increased sweat rate during the HST. However, due to the difficulty in water vapour transfer through the NBC ensemble, these adaptations did not result in a significant change in evaporation rate. Overall, no effect of the

Table 3 Sweating and evaporation rate, average metabolic rate, respiratory exchange ratio (RER), rates of ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$), tolerance time, time required for rectal temperature (T_{re}) to increase by 1.0°C, and initial and final T_{re} during heat stress tests before and after the training or control period. Values are means (SD)

	Training				Control			
	Pre-training		Post-training		Pre-control		Post-control	
	EU	HY	EU	HY	EU	HY	EU	HY
Sweat rate	0.87	0.92	1.00^+	1.03^+	0.85	0.90	0.83^{++}	0.88^{++}
($l \cdot h^{-1}$)	(0.27)	(0.26)	(0.29)	(0.25)	(0.16)	(0.19)	(0.18)	(0.18)
Evaporation rate	0.31	0.26	0.29	0.29	0.27	0.24	0.27	0.27
($l \cdot h^{-1}$)	(0.07)	(0.06)	(0.05)	(0.04)	(0.04)	(0.06)	(0.03)	(0.05)
Average metabolic rate	173.9	175.0	171.4	168.8	170.9	163.9	166.5	165.7
($W \cdot m^{-2}$)	(8.3)	(8.3)	(12.8)	(12.2)	(9.8)	(8.3)	(9.0)	(8.2)
RER	0.87	0.84*	0.88	0.83*	0.86	0.83*	0.87	0.83*
	(0.03)	(0.02)	(0.04)	(0.02)	(0.04)	(0.02)	(0.05)	(0.02)
$\dot{V}_E$	21.8	22.0	22.0	21.0	22.8	22.2	22.8	22.8
($l \cdot min^{-1}$)	(2.4)	(2.7)	(2.7)	(3.1)	(2.1)	(2.8)	(1.9)	(3.8)
$\dot{V}O_2$	11.00	11.32	10.85	10.72	11.05	10.85	10.82	11.00
($ml \cdot kg^{-1} \cdot min^{-1}$)	(1.15)	(1.05)	(0.98)	(1.45)	(0.70)	(0.38)	(0.44)	(0.55)
$\dot{V}CO_2$ ($l \cdot min^{-1}$)	0.868	0.848*	0.860	0.823*	0.838	0.774*	0.822	0.788*
	(0.059)	(0.060)	(0.083)	(0.064)	(0.064)	(0.048)	(0.077)	(0.068)
Tolerance time	93.1	75.8*	94.0	80.3*	85.3	74.6*	90.9	79.6*
(min)	(18.9)	(14.4)	(16.2)	(11.7)	(10.2)	(10.1)	(11.9)	(10.3)
ΔT_{re} = 1°C (min)	64.3	57.4	65.1	62.5	65.3	63.3	66.4	64.7
	(8.1)	(11.1)	(9.6)	(9.3)	(10.1)	(6.2)	(7.6)	(5.4)
Initial T_{re} (°C)	37.08	37.18*	36.93	37.20*	36.93	37.04*	36.99	37.19*
	(0.24)	(0.34)	(0.34)	(0.35)	(0.22)	(0.22)	(0.19)	(0.13)
Endpoint T_{re} (°C)	38.70	38.63	38.61	38.60	38.46	38.49	38.60	38.56
	(0.37)	(0.35)	(0.25)	(0.42)	(0.36)	(0.28)	(0.34)	(0.39)

*Significant main effect of hydration

$^+$ Significant main effect of training

$^{++}$ Significant difference between training and control groups training or control period was observed on tolerance time.

Hydration status had a significant effect on responses to exercise-heat tolerance. Hypohydration did not affect the rate of heat production or the drive for heat dissipation, with similar metabolic rates and sweating and evaporation rates for both the training and control groups. Before and after the training or control period, hypohydration resulted in a significantly shorter TT, with the higher initial T_{re} a likely contributing factor. Interestingly, the respiratory exchange ratio was significantly lower during HY trials in both the control and training groups. Serum glucose concentrations prior to the HST were similar across all conditions in both training and control groups, with mean values ranging from 4.5 to 5.5 mmol $\cdot$ l^{-1}. No significant differences were observed in $\dot{V}O_2$, indicating that the difference was due to a decreased CO_2 output.

Comparing the results between the control and training groups, no significant between-group differences were observed in TT, metabolic rate, respiratory exchange ratio, evaporation rate, initial and endpoint T_{re}, and time required for T_{re} to increase by 1.0°C. While the sweating rates were similar prior to the training or control period, the training group had a significantly higher sweat rate compared to control subjects after training.

The $\overline{T}_{sk}$, T_{re}, and f_c responses to the HST are presented in Fig. 1–3, respectively. As expected, the 2-week control period did not influence the responses of the three variables to the HST. The primary effect of the 2-week training program was observed in the $\overline{T}_{sk}$ response, with training resulting in a significantly lower $\overline{T}_{sk}$ (Fig. 1), which may have been brought about by the increased sweating and skin wettedness following training. Training did not significantly alter the T_{re} or f_c response to the HST.

Hydration status had a significant effect on thermal and cardiovascular responses to the HST. In both the control and training groups, hypohydration resulted in a significantly higher T_{re} throughout the HST, with the primary factor being an elevated initial T_{re} (Fig. 2). The f_c response to the HST was influenced by hydration status (Fig. 3). Hypohydration elicited a significantly higher rise in f_c after 5 and 15 min in the training and control groups, respectively, contributing to a higher overall f_c with hypohydration in both groups. In contrast, $\overline{T}_{sk}$ was not influenced by hydration status in either the control or training group (Fig. 1). No overall differences in T_{re}, $\overline{T}_{sk}$ or f_c response were observed between the control and training groups.

Discussion

A period of physical training elicits adaptations in the body that are similar to those produced by a period of repeated heat exposures, including increases in blood volume (Green et al. 1991a; Harrison 1986), a lower resting core temperature (Shvartz et al. 1974), and improvements in the sweating responses (Henane et al. 1977; Nadel et al. 1974). Long-term fitness has also been associated with an increased tolerance to exercise in the heat in both longitudinal training (Avellini et al. 1982; Gisolfi and Robinson 1969) and cross-sectional (Piwonka and Robinson 1967) studies. For these reasons, improvements in aerobic fitness have been associated with a reduction in physiological strain and increased performance time during exercise in the heat, and physical training programs have been used as a method of heat acclimation (Armstrong and Pandolf 1988).

The design of the short-term training model employed in the present study attempted to simulate a

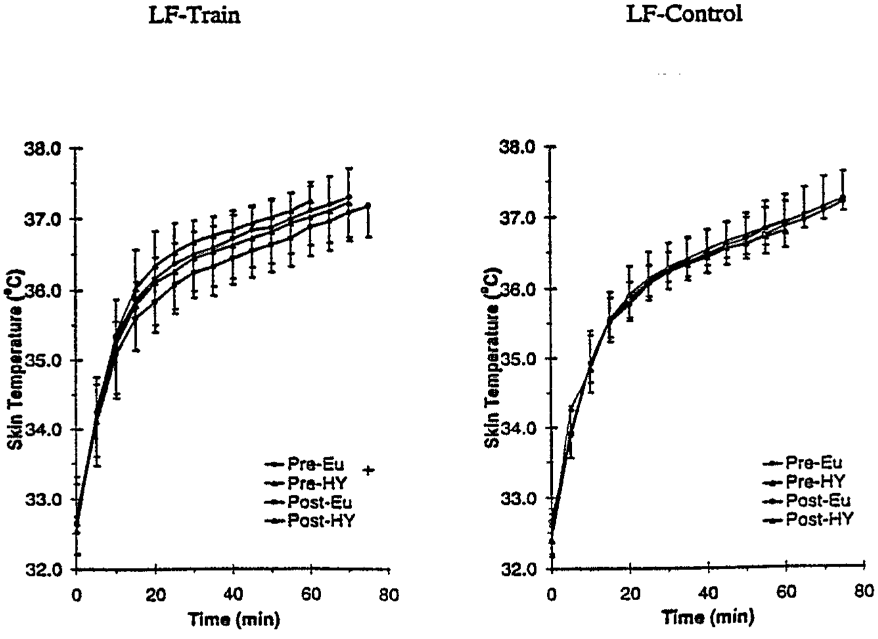
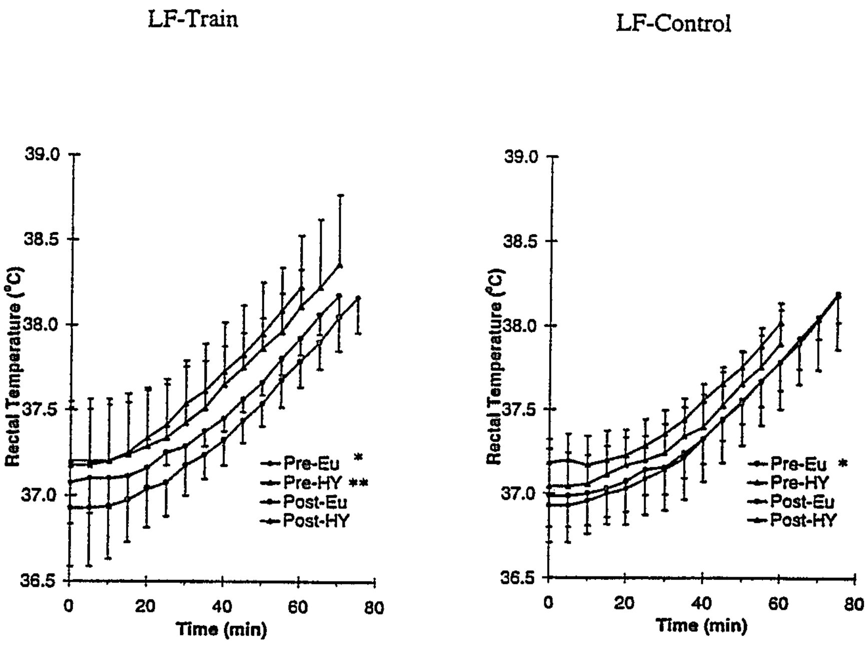


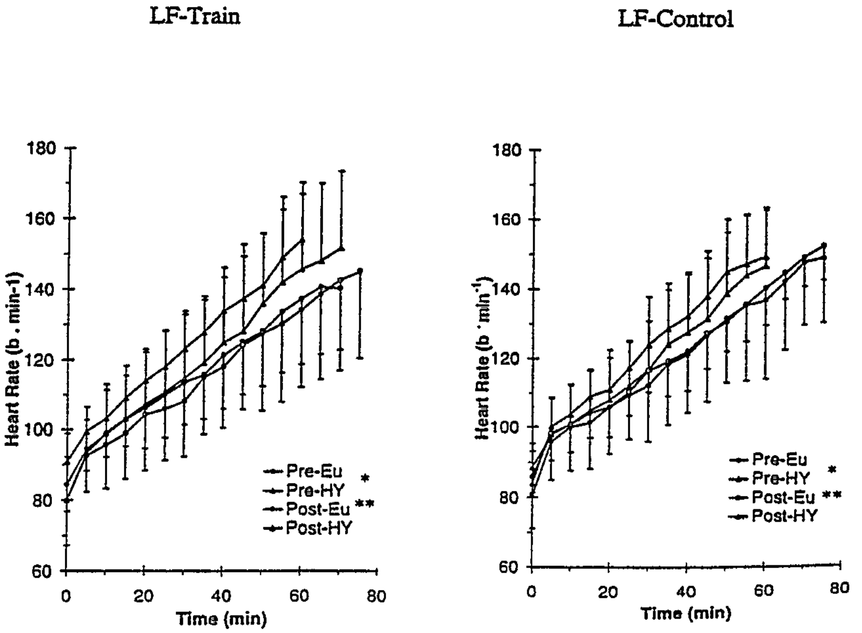
Fig. 1 Mean skin temperature ($\overline{T}_{sk}$) response to the heat stress test while either euhydrated (*EU*, *circles*) or hypohydrated (*HY*, *triangles*), before (*filled symbols*) and after (*open symbols*) 2 weeks of training ($n = 8$) or control ($n = 7$). Values are mean (SD). $^+$ Significant main effect of training

Fig. 2 Rectal temperature (T_{re}) response to the heat stress test while either euhydrated (*EU, circles*) or hypohydrated (*HY, triangles*), before (*filled symbols*) and after (*open symbols*) 2 weeks of training ($n = 8$) or control ($n = 7$). Values are mean (SD). *Significant main effect of hydration. **Significant hydration × time interaction



military scenario in which individuals could be adapted relatively quickly in a temperate environment prior to deployment to a hot environment. Treadmill exercise was chosen for its lack of requirement for specialized equipment and as an unskilled task to control for any learning component. Training also had to be of sufficient intensity to elicit adaptation, yet be light enough that the untrained and relatively unfit subjects could perform the entire protocol. TT for untrained and non-fit subjects cycling at 70–75% $\dot{V}O_{2\max}$ has been reported to be approximately 50 min (McLellan and Skinner 1985), while Green et al. (1991a) have stated that not all previously untrained subjects could complete 2 h of continuous cycling at 59% $\dot{V}O_{2\max}$ for the initial few days of a 10 to 12-day training program. Therefore, we chose an exercise intensity of approximately 65% $\dot{V}O_{2\max}$ in order to allow all subjects to exercise continuously for at least 1 h daily throughout the 2-week period. Responses to either the EU or HY HST before or following the control period were identical for all measured variables. Therefore, we are confident that any adaptations in the training group can be attributed to the training manip-

Fig. 3 Heart rate response to the heat stress test while either euhydrated (*EU, circles*) or hypohydrated (*HY, triangles*), before (*filled symbols*) and after (*open symbols*) 2 weeks of training ($n = 8$) or control ($n = 7$). Values are mean (SD). *Significant main effect of hydration. **Significant hydration × time interaction



ulation, as opposed to either a learning effect or partial acclimation from the periodic exposures to heat over the course of the study.

Short-term training in the present study resulted in a series of adaptations during exercise in a thermoneutral environment, including a lower level in f_c and a decrease in ΔT_{re} as seen with other training programs (Armstrong and Pandolf 1988; Shvartz et al. 1974). The training program did not result in the significant improvement in the overall sweating response seen with a higher-intensity program (Henane et al. 1977). However, while the total sweating rate was similar, the decrease in ΔT_{re} with training implies an effect on the relationship between sweat rate and core temperature changes (Nadel et al. 1974). Despite a degree of adaptation during exercise in a thermoneutral environment, the only significant alleviation of physiological strain during exposure to uncompensable heat stress post-training was an increased sweat rate and decreased $\bar{T}_{sk}$, with no improvement in TT or in f_c or T_{re} response.

The efficacy of a physical training program for improving heat tolerance is not a universal finding (Shvartz et al. 1973). Factors such as the design of the training program and the environment to be encountered must also be considered. The intensity of the training stimulus is a major determinant of the magnitude of adaptation following training (Armstrong and Pandolf 1988), and the training program employed in the present study may have been of insufficient intensity to produce significant heat adaptations. Henane et al. (1977) suggest that training must increase $\dot{V}O_{2\,max}$ by approximately 15% to induce a level of physiological strain that would result in significant adaptations to heat. The degree of adaptation to heat stress may also depend on both the magnitude and the duration of hyperthermia in the body (Avellini et al. 1982; Fox et al. 1963). Subjects in the present study did increase their T_{re} approximately 1.2°C over the hour of exercise, though with a relatively short time at a maintained state of hyperthermia. Despite these objections, the decrease in f_c and ΔT_{re} during the final exercise session and the significant increase in sweating rate and decrease in skin temperature in the HST post-training demonstrate that a moderate degree of cardiorespiratory and thermal adaptation was achieved.

One explanation for the lack of a significant post-training effect on exercise-heat tolerance is the uncompensable hot-wet microenvironment created within the NBC clothing during exercise in the heat. The wearing of protective clothing impairs the dissipation of metabolic heat (Holmer 1995), resulting in a significant impairment of cardiorespiratory and thermoregulatory responses (Smolander et al. 1984) which may overwhelm any physiological manipulations. Comparing three methods of acclimating to subsequent exposure to dry heat, Shvartz et al. (1973) observed no improvement in exercise-heat tolerance following aerobic training, whereas either hot-dry or hot-wet heat acclimation produced substantial improvements in response. In hot-wet environments, Strydom et al. (1966) and Strydom and Williams (1969) found only partial adaptation through physical conditioning compared with heat acclimation. The $\dot{V}O_{2\,max}$ of a group of untrained and unfit individuals (Aoyagi et al. 1994) increased by 16% following 8 weeks of aerobic training, yet no significant improvements in exercise-heat tolerance while wearing NBC clothing in the heat were observed. However, the high rate of metabolic production used resulted in TT values of only about 50–60 min, with only the rare trial exceeding 70 min. McLellan (1993) has proposed that TT in the severe uncompensable heat stress environment of NBC clothing is primarily independent of ambient conditions or any physiological manipulations at these rates of heat production, due to an insufficient amount of time for significant heat transfer through the clothing before the onset of exhaustion from other factors. The present study suggests that, while wearing NBC clothing, the adaptations with moderate endurance training may be insufficient to improve exercise-heat tolerance even at low metabolic rates.

It is interesting to compare the results of the present study with a related study using the identical hypohydration protocol and HST with a group of fitter individuals with a $\dot{V}O_{2\,max}$ above $55\ ml \cdot kg^{-1} \cdot min^{-1}$ (Cheung and McLellan 1998). The magnitude of impairment with hypohydration was similar across fitness groups, with an approximate 18% decrease in TT with hypohydration. In addition, a non-significant trend of an approximate 10-min increase in TT during either EU or HY trials existed in the fitter group compared to the non-fit individuals in the present study, supporting the contention of Gisolfi and Robinson (1969) and Piwonka and Robinson (1967) of a benefit from long-term fitness on responses to exercise in the heat.

One interesting and unexpected observation in the present study was that hydration status appeared to impact on energy metabolism during exercise in the heat. The decrease in the respiratory exchange ratio during HY trials was consistent in both the training and control groups pre- and post-manipulation. Similar findings have been presented by Sawka et al. (1985), who observed a progressive decrease in respiratory exchange ratio with increasing severity of hypohydration during exercise in the heat but did not elaborate on any possible mechanisms. The finding of a decrease in respiratory exchange ratio with hypohydration in the heat is surprising, and the underlying mechanism is not readily apparent. Substrate availability does not appear to be impaired by hypohydration, as no differences have been observed in the rate of glycogen resynthesis overnight (Neufer et al. 1991) relative to that in a euhydrated state. Diet was controlled in the present study during the period following the dehydration protocol until the HST the next morning. Thus, there would be no reason to expect muscle glycogen stores to be different at the start of the HST during the hypohydration trials. The lack of a hydration effect on serum glucose levels prior to the HST in either group also supports the contention that the shift in the respiratory exchange ratio was not due to dietary influences. CO_2 output was significantly decreased during the HY trial, suggesting that the decrease in respiratory exchange ratio was due to a shift in substrate utilization to an increased reliance on lipid metabolism (Holloszy 1973). The finding of a decreased respiratory exchange ratio during hypohydration in the heat is different from that observed in thermoneutral environments, where hypohydration did not elicit any differences in $\dot{V}O_2$ or the respiratory exchange ratio during submaximal exercise (Neufer et al. 1989; Dengel et al. 1992). It is possible that the stress of heat exposure may interact with hypohydration to produce the downward shift in the respiratory exchange ratio, as a significant decrease in this parameter during exercise in a hot compared to a thermoneutral environment was noted by Young et al. (1985). However, a recent study presented conflicting data, observing hyperglycemia and an increased respiratory exchange ratio during exercise in the heat, brought about by an elevation in plasma cortisol and catecholamines and an increased hepatic glucose release (Hargreaves et al. 1996).

In summary, a 2-week program of aerobic exercise produced a moderate but significant training effect and improvements in physiological strain during exercise in a thermoneutral environment in a group of untrained and relatively non-fit subjects. The short-term training program elicited an increase in $\dot{V}O_{2\max}$, along with a significant decrease in f_c and rise in T_{re}. These adaptations were moderately successful in alleviating physiological strain during light exercise in an uncompensable heat stress environment, with an increase in sweat rate and a decrease in T_{sk} suggesting an increased sweating response and drive for evaporative heat loss. However, the adaptations due to training were ultimately unsuccessful in significantly prolonging exercise-heat tolerance in either a euhydrated or mildly hypohydrated state in an uncompensable heat stress environment.

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References

Aoyagi Y, McLellan TM, Shephard RJ (1994) Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. Eur J Appl Physiol 68:234–245

Armstrong LE, Pandolf KB (1988) Physical training, cardiorespiratory physical fitness and exercise-heat tolerance. In: Pandolf KB, Sawka MN, Gonzalez RR (eds) Human performance physiology and environmental medicine in terrestrial extremes. Benchmark, Indianapolis, pp 199–226

Avellini BA, Shapiro Y, Fortney SM, Wenger CB, Pandolf KB (1982) Effects on heat tolerance of physical training in water and on land. J Appl Physiol 53:1291–1298

Cheung SS, McLellan TM (1998) Influence of hydration status and fluid replacement on tolerance during uncompensable heat stress. Eur J Appl Physiol 77:139–148

Dengel DR, Weyand PG, Black DM, Cureton KJ (1992) Effect of varying levels of hypohydration on responses during submaximal cycling. Med Sci Sports Exerc 24:1096–1101

Forsyth RD, Plyley MJ, Shephard RJ (1984) Estimation of body fatness of Canadian Forces. Can J Appl Sports Sci 9:5P

Fox RH, Goldsmith R, Kidd DJ, Lewis HE (1963) Blood flow and other thermoregulatory adaptations with acclimation to heat. J Physiol (Lond) 166:548–562

Gisolfi CV (1973) Work-heat tolerance derived from interval training. J Appl Physiol 35:349–354

Gisolfi CV, Robinson S (1969) Relations between physical training, acclimatization, and heat tolerance. J Appl Physiol 26:530–534

Gonzalez RR, Levell CA, Stroschein LA, Gonzalez JA, Pandolf KB (1993) Copper manikin and heat strain model evaluations of chemical protective ensembles for the technical cooperation program (TTCP). US Army Research Institute of Environmental Medicine, Technical Report T94-4

Green HJ, Goates G, Sutton JR, Jones S (1991a) Early adaptations in gas exchange, cardiac function and haematology to prolonged exercise training in man. Eur J Appl Physiol 63:17–23

Green HJ, Jones S, Ball-Burnett ME, Smith D, Livesey J, Farrance BW (1991b) Early muscular and metabolic adaptations to prolonged exercise training in humans. J Appl Physiol 70:2032–2038

Hargreaves M, Angus D, Howlett K, Conus NM, Febbraio M (1996) Effect of heat stress on glucose kinetics during exercise. J Appl Physiol 81:1594–1597

Harrison MH (1986) Heat and exercise: effects on blood volume. Sports Med 3:214–223

Henane R, Flandrois R, Charbonnier JP (1977) Increase in sweating sensitivity by endurance conditioning in man. J Appl Physiol 43:822–828

Holloszy JO (1973) Biochemical adaptations to exercise: aerobic metabolism. In: Wilmore JH (ed) Exercise and sports sciences reviews. Academic, New York, pp 45–71

Holmer I (1995) Protective clothing and heat stress. Ergonomics 38:166–182

McLellan TM (1993) Work performance at 40°C with Canadian Forces biological and chemical protective clothing. Aviat Space Environ Med 64:1094–1100

McLellan TM, Skinner JS (1985) Submaximal endurance performance related to the ventilation thresholds. Can J Appl Sports Sci 10:81–87

Mitchell JW, Nadel ER, Stolwijk JAJ (1972) Respiratory weight loss during exercise. J Appl Physiol 32:474–476

Nadel ER, Pandolf KB, Roberts MF, Stolwijk JAJ (1974) Mechanisms of thermal acclimation to exercise and heat. J Appl Physiol 37:515–520

Neufer PD, Young AJ, Sawka MN, Quigley MD, Levine L, Latzka WA (1989) Substrate levels and muscle metabolism while hypohydrated (abstract). FASEB J 21:S19

Neufer PD, Sawka MN, Young AJ, Quigley MD, Latzka WA, Levine L (1991) Hypohydration does not impair skeletal muscle glycogen resynthesis after exercise. J Appl Physiol 70:1490–1494

Nunneley SA (1989) Heat stress in protective clothing: interactions among physical and physiological factors. Scand J Work Environ Health 15 [Suppl 1]:52–57

Pandolf KB, Burse RL, Goldman RF (1977) Role of physical fitness in heat acclimatization, decay and reinduction. Ergonomics 20:399–408

Piwonka RW, Robinson S (1967) Acclimatization of highly trained men to work in severe heat. J Appl Physiol 22:9–12

Sawka MN, Young AJ, Francesconi RP, Muza SR, Pandolf KB (1985) Thermoregulatory and blood responses during exercise at graded hypohydration levels. J Appl Physiol 59:1394–1401

Shvartz E, Saar E, Meyerstein N, Benor D (1973) A comparison of three methods of acclimatization to dry heat. J Appl Physiol 34:214–219

Shvartz E, Magazanik A, Glick Z (1974) Thermal responses during training in a temperate climate. J Appl Physiol 36:572–576

Shvartz E, Shapiro Y, Magazanik A, Meroz A, Birnfeld H (1977) Heat acclimation, physical fitness, and responses to exercise in temperature and hot environment. J Appl Physiol 43:678–683

Smolander J, Louhevaara V, Tuomi T, Korhonen O, Jaakkola J (1984) Cardiorespiratory and thermal effects of wearing gas protective clothing. Int Arch Occup Environ Health 54:261–270

Snellen JW (1966) Mean body temperature and the control of thermal sweating. Acta Physiol Pharmacol 14:99–174

Strydom NB, Williams CG (1969) Effect of physical conditioning on state of heat acclimatization of Bantu laborers. J Appl Physiol 27:262–265

Strydom NB, Wyndham CH, Williams CG, Morrison JF, Bredell GAG, Benade AJS, von Rahden M (1966) Acclimatization to humid heat and the role of physical conditioning. J Appl Physiol 21:636–642

Vallerand AL, Limmer R, Schmegner IF (1989) Computer acquisition and analysis of skin temperature and heat flow data from heat flux transducers. Comp Methods Prog Biomed 30:279–282

Young AJ, Sawka MN, Levine L, Cadarette BS, Pandolf KB (1985) Skeletal muscle metabolism during exercise is influenced by heat acclimation. J Appl Physiol 59:1929–1935

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