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TITLE

INFLUENCE OF HYDRATION STATUS AND FLUID REPLACEMENT ON HEAT TOLERANCE WHILE WEARING NBC PROTECTIVE CLOTHING

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ORIGINAL ARTICLE

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Influence of hydration status and fluid replacement on heat tolerance while wearing NBC protective clothing

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Abstract The purpose of the present study was to investigate the influence of hypohydration and fluid replacement on tolerance to an uncompensable heat stress. Eight healthy young males completed a matrix of six trials in an environmental chamber, set at 40°C and 30% relative humidity, while wearing nuclear, biological, and chemical protective clothing. Subjects performed either light ($3.5\ \mathrm{km \cdot h^{-1}}$, 0% grade, no wind) or heavy ($4.8\ \mathrm{km \cdot h^{-1}}$, 4% grade, no wind) treadmill exercise combined with three hydration states [euhydration with fluid replacement (EU/F), euhydration without fluid replacement (EU/NF), and hypohydration with fluid replacement (H/F)]. Hypohydration of 2.2% body mass was achieved by exercise and fluid restriction on the day preceding the trials. No differences in the endpoint mean skin temperature ($\overline{T}_{sk}$), sweat rate, or rectal temperature (T_{re}) were observed among the hydration conditions for either work rate. During light exercise, the change in T_{re} (ΔT_{re}) was significantly higher with H/F than EU/F after 40 min, and heart rate was greater after 25 min. The heart rate was greater during EU/NF than during EU/F after 60 min. Tolerance times were significantly greater for EU/F than for either EU/NF or H/F. With heavy exercise, no differences in ΔT_{re} were observed across hydration conditions. Compared to EU/F, heart rates were higher after 10 and 30 min for H/F and EU/NF, respectively. Tolerance times were significantly less during H/F than with either of the EU conditions. Stroke volume was significantly decreased in H/F trials compared to EU/F trials for both light and heavy work rates, but no differences in cardiac output were observed. It was concluded that even minor levels of hypohydration significantly impaired exercise tolerance in a severely uncompensable heat stress environment at both light and heavy exercise intensities.

Key words Heat exhaustion · Temperature regulation · Hypohydration · Fluid replacement · Cardiac output

Introduction

Protective clothing such as the nuclear, biological, and chemical (NBC) ensemble worn by military personnel feature low vapour permeability due to the thickness of the clothing and the multi-layered construction. This layering effect results in the trapping of insulative air layers around the body, thus impairing heat transfer to the environment (Holmer 1995). The limited evaporative heat loss through the protective clothing, combined with an increased metabolic heat production and high ambient temperatures can result in situations of uncompensable heat stress, where the evaporative cooling requirements (E_{req}) greatly exceed the possible cooling capacity of the environment (E_{max}; Givoni and Goldman 1972).

It is well documented that fluid replacement and hydration status are important determinants of heat tolerance when evaporative heat loss is not restricted by clothing (Noakes 1993). Core temperature and heart rate (f_C) responses have been shown to increase with progressive severity of hypohydration, while the sweat rate response for a given core temperature decreases (Sawka et al. 1985). At 5% hypohydration, termination of exercise due to subject intolerance has been reported to occur at a significantly lower core temperature than while subjects are euhydrated (Sawka et al. 1992). Evaporative heat loss capacity roughly matches heat loss requirements in these studies, with a heat stress index ($\mathrm{HSI} = E_{req}/E_{max}$) of approximately 1.0. It is less clear, however, what impact hypohydration may have on heat tolerance when protective clothing is worn in the heat, resulting in a HSI of much greater than 1.0 and a more severe uncompensable heat stress environment.

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Fluid replacement during exercise is known to elicit a significant attenuation of cardiovascular and thermal strain compared to the absence of rehydration (Candas et al. 1986). However, ingested fluid must first be emptied from the stomach and absorbed in the intestine before it can enter the body and affect exercise response. Transit time is dependent upon many factors including the volume of fluid ingested, exercise intensity, and ambient temperature (Murray 1987). While wearing protective clothing, it is possible that the influence of fluid replacement may be masked by the high rate of heat storage and short tolerance times at high exercise intensities. At metabolic rates above 500 W, tolerance times converge at approximately 50 min for a range of ambient environments and physiological manipulations (McLellan and Frim 1994). It may be the case that fluid replacement is beneficial only during relatively light exercise, where tolerance time is long enough to allow a significant amount of fluid to enter the body and affect responses before exhaustion occurs due to other factors.

The purpose of the present study was to investigate the influence of hypohydration and fluid replacement on heat and exercise tolerance in an environment of uncompensable heat stress due to the wearing of protective clothing. Subjects wore the NBC protective clothing ensemble in a hot environment and exercised at light and heavy intensities producing a corresponding HSI of 2.5 and 3.5, respectively. Subjects performed exercise in either a euhydrated or a mildly hypohydrated ($\approx$2.5% body weight) state, with the hypohydration level chosen simulate a level typical of voluntary dehydration (Greenleaf 1992). To investigate the effects of fluid replacement during exercise in an uncompensable heat stress environment, subjects in the euhydrated state underwent either a fluid replacement program or refrained from drinking. It was hypothesised that hypohydration and fluid replacement has a major impact on heat tolerance while wearing NBC protective clothing only during light exercise, where tolerance times under normal hydration conditions are expected to approach 2 h.

Methods

Subjects

Eight males volunteered to participate 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. Mean (SD) values for age, height, body mass, peak aerobic power ($\dot{V}O_{2\,peak}$), body fat estimated from skinfolds, and Dubois body surface area were 29.3 (6.4) years 1.78 (0.07) m, 75.6 (9.7) kg, 56.5 (4.4) $ml \cdot kg^{-1} \cdot min^{-1}$, 12.4 (2.8)%, and 1.94 (0.15) m^2. In addition to their relatively high $\dot{V}O_{2\,peak}$, all subjects engaged in regular aerobic activities.

Determination of $\dot{V}O_{2\,peak}$

$\dot{V}O_{2\,peak}$ was determined on a motorised treadmill using open-circuit spirometry prior to the series of experiments in the climatic chamber. Following 3 min of running at a self-selected pace, the treadmill grade was increased by 1% each minute to a maximum of 10%. Thereafter, increases in treadmill speed and grade of 0.22 $m \cdot s^{-1}$ (0.8 $km \cdot h^{-1}$) or 1%, respectively, were affected alternately each minute until the subject could no longer continue. Subjects were given verbal encouragement throughout the test. $\dot{V}O_{2\,peak}$ was defined as the highest 30-s oxygen consumption ($\dot{V}O_2$) observed during the incremental test. The subjects f_c was monitored throughout the incremental test, with the aid of a telemetry unit (Polar Vantage XL). The f_c value recorded at the termination of the exercise test was considered to be the individual's maximum f_c.

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 the DCIEM from October to December to limit initial heat acclimation through casual exposure to high ambient temperatures. On seven separate occasions, each subject performed a heat stress test (HST) which consisted of walking on a motorised treadmill in a hot (40°C, 30% relative humidity, no wind) environment while wearing the Canadian Forces NBC protective clothing ensemble. On the afternoons before conducting the sessions, subjects exercised in the heat until they dehydrated by 2.5–3% of their body mass. In all subjects, the first session was used as a familiarisation trial and the results were discarded. A minimum of 1 week separated experimental trials to avoid the effects of partial heat acclimation over the course of the experiment (Barnett and Maughan 1993). The order in which the different conditions were presented were randomised to minimise order effects.

Responses to the HST were evaluated during light (3.5 $km \cdot h^{-1}$, 0% grade) and heavy (4.8 $km \cdot h^{-1}$, 4% grade) exercise while manipulating the subjects' level of hydration. The intensity of the exercise was classified as either light or heavy according to US Army guidelines for work rates below 325 W and above 500 W, respectively (Gonzalez et al. 1993). Following the dehydration protocol, subjects were either rehydrated to baseline body mass overnight (EU) or maintained the decreased body mass overnight (H). A minimum of 15 h elapsed between the end of the dehydration protocol and the HST. During EU sessions, the effects of fluid replacement during exercise in the NBC clothing were tested by the presence (approximately 200 or 250 ml each 15 min during light and heavy exercise, respectively; F) or absence (NF) of water rehydration. Subjects undergoing H trials were tested only in the F condition (i.e. given 200 or 250 ml of water each 15 min) to minimise further losses in body mass. Water temperature was maintained at 37°C to approximate body temperature and to minimise its effect on temperature responses through acting as a heat sink.

The Canadian Forces NBC protective clothing ensemble worn by the subjects in all trials consisted of shorts, T-shirt, socks, combat shirt and trousers, running shoes, and NBC overgarment, rubber gloves and overboots. The total mass of the ensemble is approximately 8.0 kg. This ensemble offers close to 100% protection of the airways. In order to allow some sweat evaporation, there is limited mass penetration of charcoal-filtered air through the fabric. The 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 $m \cdot s^{-1}$, were 0.291 $m^2 \cdot °C \cdot W^{-1}$ (1.88 clo) and 0.33, respectively (Gonzalez et al. 1993).

The E_{req} with the protective clothing in the experimental environment was determined while taking into account the metabolic rate, and radiative and convective heat gains, since the chamber temperature exceeded skin temperature, and net respiratory heat loss using the equations of Givoni and Goldman (1972) and Gonzalez et al. (1993). The E_{max} while wearing the protective clothing was determined using the equation described by Gonzalez et al. (1993), which assumes 100% water vapour saturation at skin temperature. The HSI (E_{req}/E_{max}) was calculated to be about 2.5 for the light exercise and about 3.5 for the heavy exercise.

Dehydration Protocol

Prior to beginning the study, the baseline mass of each subject was determined by taking their average morning nude mass over 5 days. In the afternoons prior to the exercise sessions, subjects reported to the laboratory at $\approx$1330 hours for the dehydration protocol. This allowed approximately 15 h for body fluid compartments to stabilise between the dehydration protocol and the HST. Dehydration sessions took place in the same environmental chamber (40°C, 30% relative humidity) as used for the HST. Both nude and dressed mass (shorts, socks, shoes) were recorded prior to entry into the chamber. Subjects walked on a motorised treadmill at an exercise intensity ($5\ \mathrm{km \cdot h^{-1}}$, 5–7% grade) that induced body mass loss at a rate of $0.8–1.2\ \mathrm{kg \cdot h^{-1}}$. 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. For subjects undergoing EU trials sufficient Gatorade was provided immediately following the dehydration session to replace the amount of body mass loss. Subjects were also instructed to drink $600\ \mathrm{ml \cdot h^{-1}}$ of Gatorade or juices that evening, and at least 600 ml in the morning prior to reporting to the laboratory. Subjects undergoing the H trials were given a total ration of 800 ml of Gatorade, based on expected basal body mass 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 within 90 s of lying down to obtain samples representative of upright exercise (Lundvall and Bjerkhoel 1994). Plasma osmolality was determined in duplicate by freezing point depression (Osmette A, Fisher Scientific), haemoglobin concentration was determined in duplicate by photometry (HemoCue, Hemocue AB, Helsingborg, Sweden) and haematocrit (Hct) was determined in triplicate by microcentrifugation. Hct values were adjusted for blood cell packing and for arterial-venous difference by correction factors of 0.96 and 0.92, respectively (Harrison 1986). Plasma volume changes relative to the EU/F trials were calculated from Hct and haemoglobin values using the equations of Dill and Costill (1974). Both nude and dressed body mass 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 computerised data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer) and the exercise began. Mean values over 1-min periods for T_{re} 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 body mass was recorded within 1 min after exit from the chamber; nude body mass was recorded within 5 min, upon undressing and towelling dry.

Differences in nude and dressed body mass before and after each trial were corrected for respiratory and metabolic body mass losses (see below). The amount of sweat produced was calculated as pre-trial minus post-trial nude body mass (corrected) plus water given (for F conditions). Evaporative sweat loss from the clothing was calculated as pre-trial minus post-trial dressed body mass (corrected) plus water given (for F conditions). Inaccuracy in measurement due to sweat drippage through the mask and mouthpiece was assumed to be minor, with less than 10 g collected through the mouthpiece in pilot trials.

Tolerance Time

Tolerance time 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.

Skin temperature

Skin temperature was measured using heat flux transducers (1A13-18-10P(C), Thermonetics, San Diego, USA). An overall mean skin temperature ($\overline{T}_{sk}$) value that provided a general indication of skin temperature throughout the body was calculated from the weighted averages over 12 sites, using the weightings presented by Vallerand et al. (1989). The sites and weighting factors were as follows: forehead (0.07), chest (0.085), abdomen (0.085), upper back (0.09), lower back (0.09), forearm (0.14), wrist (0.05), front (0.095) and rear thigh (0.095), front (0.065) and rear calf (0.065), and foot (0.07). Mean values over 1-min periods for $\overline{T}_{sk}$ were calculated, recorded, and printed by the data acquisition system.

Gas exchange analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation, $\dot{V}_E$, $\dot{V}O_2$, and CO_2 production ($\dot{V}CO_2$) from a 2-min average obtained every 15 min. An adaptor was attached to the respirator which allowed expired air to be collected. Expired gases were directed into a 5-l mixing box and through a turbine (Alpha Technologies VMM 110 series ventilation module) for determination of $\dot{V}_E$. A sampling line directed dried gases from the mixing box to an O_2 (S-3A Applied Electrochemistry) and CO_2 (CD-3A Applied Electrochemistry) analyser. The gas analysers were calibrated before each test using a precision analysed gas cylinder with known O_2 and CO_2 composition, while the turbine was calibrated using a 3-l syringe. After conversion of the analogue voltage outputs from the ventilation module and the gas analysers into digital signals (Hewlett-Packard 59313 A/D converter), $\dot{V}_E$, $\dot{V}CO_2$, and $\dot{V}O_2$ were calculated and printed on-line every 60 s using appropriate software on a microcomputer (Hewlett-Packard 9825A). Respiratory water loss was calculated using the measured $\dot{V}O_2$ and the equation presented by Mitchell et al. (1972). Metabolic body mass loss was calculated from the $\dot{V}O_2$ and the respiratory exchange ratio using the equation described by Snellen (1966).

Cardiac output

Stroke volume and cardiac output were obtained by impedance cardiography, using the methods first described by Kubicek et al. (1966). Two aluminised mylar band electrodes (IFM Cardiographic Tape, Bionetics, St. Laurent, Quebec, Canada) were each applied around the neck and around the chest. Electrocardiogram electrodes were also applied. Every 15 min during the HST, 6–8 s of cardiac impedance waveforms were obtained. In order to minimise motion and respiratory artifacts, subjects straddled the treadmill and quickly performed an end-expiratory breath hold immediately prior to sampling.

Analysis of the cardiac impedance waveforms was performed on a customised program that permitted the digitisation of individual waveforms. For each timepoint, the waveforms from five cardiac cycles were digitised and averaged. The blood resistivity for each trial was calculated using the adjusted T_{re} and Hct values (Mohapatra and Hill 1975). Stroke volume was calculated using the equations that were derived by Kubicek et al. (1966) and verified by Denniston et al. (1976).

Heat gain

The body heat gain (HG, in kJ) during the heat exposure was calculated using the thermometric method of McLellan and Ducharme (1996). For each subject, the body heat content at thermoneutrality before the trial (HC_N, in kJ) was subtracted from the body heat content at the end of the trial after the heat exposure (HC_H, in kJ), as follows:

$$\mathrm{HG} = \mathrm{HC_H} - \mathrm{HC_N} \qquad (1)$$

$$\mathrm{HC_H} = (0.90T_{\mathrm{re(f)}} + 0.01\overline{T}_{\mathrm{sk(f)}}) \cdot \mathrm{mb_{(f)}} \cdot 3.47 \qquad (2)$$

$$\mathrm{HC_N} = (0.79T_{\mathrm{re(i)}} + 0.21\overline{T}_{\mathrm{sk(i)}}) \cdot \mathrm{mb_{(i)}} \cdot 3.47 \qquad (3)$$

where the mean body temperature before (i) and after (f) the heat exposure was estimated as $0.79T_{\mathrm{re(i)}} + 0.21\overline{T}_{\mathrm{sk(i)}}$ and $0.90T_{\mathrm{re(f)}} + 0.10\overline{T}_{\mathrm{sk(f)}}$, respectively, $\mathrm{mb_{(i)}}$ and $\mathrm{mb_{(f)}}$ represent the nude body mass, and 3.47 is the average specific heat of body tissues (in $\mathrm{kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$).

Statistics

Data are presented as mean values and the standard deviation of the mean. A two-factor (hydration status × time) repeated-measures analysis of variance (ANOVA) was used to compare the changes in T_{re} skin temperature, f_c, gas exchange responses, stroke volume, and cardiac output at a given metabolic rate (light or heavy). A one-factor (hydration) ANOVA was used to analyse differences in tolerance time, body mass changes, sweat rate, evaporative efficiency, heat gain, and plasma osmolality at a given metabolic rate (light or heavy). 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 hydration schedule following the dehydration was successful in either reinstating euhydration or in maintaining hypohydration overnight (Table 1). In EU trials, body mass returned to baseline levels overnight, and were similar for all EU trials. The morning body mass of subjects during the H trials was 2.2% lower than during EU trials for both light and heavy intensity trials, and was similar to their body mass following the dehydration protocol. For both the light and the heavy exercise trials, plasma osmolality during the H trials was significantly higher than during EU trials, while plasma volume was decreased by 5% for light exercise, indicating a hypohydrated state prior to condition H.

Compared with the light exercise, the increased rate of heat production during heavy exercise led to higher sweat rates (Table 2). However, the low vapour permeability of the NBC clothing did not permit an increase in evaporative heat loss to the environment, with evaporation rates being similar across exercise intensities, at approximately 0.30 $\mathrm{kg \cdot h^{-1}}$. Thus, the time required for a 1.0°C increase in T_{re} was less during the heavy trials, indicating a greater rate of heat buildup within the body. During the light trials the change in T_{re} (ΔT_{re}) was greater during the H/F conditions after 40 min compared to EU/F (Fig 1). During heavy exercise, there was a slight, but significant increase in evaporation rate in the EU/F condition compared with H/F. However, this increase in evaporation rate did not result in a difference in ΔT_{re} during heavy exercise.

Tolerance to the HST was determined by time, ethically imposed physiological endpoints, or subject exhaustion. None of the trials approached the 4-h time limit. Most of the subjects were very familiar with the NBC clothing and HSTs, with five of the eight subjects having served as subjects in previous heat experiments in this laboratory. The initial familiarisation session served to accustom all subjects to the protocol and any associated discomforts prior to the actual test. All subjects were highly motivated, and little doubt existed about the

Table 1 Nude body mass, relative mass changes, plasma volume changes, and plasma osmolality prior to exercise. Values are the mean (SD) of the values for eight subjects. (*EU/F* Condition of euhydration with fluid replacement, *EU/NF* condition of euhydration with no fluid replacement, *H/F* condition of hypohydration with fluid replacement)

Variable	Light exercise			Heavy exercise		
	EU/F	EU/NF	H/F	EU/F	EU/NF	H/F
Body mass (kg)	75.2* (9.0)	75.1* (9.2)	73.6 (9.3)	75.4* (9.2)	75.3* (9.5)	73.8 (9.2)
% mass loss	0.0* (0.0)	−0.2* (0.6)	−2.2 (1.0)	0.0* (0.0)	−0.2* (0.7)	−2.2 (0.9)
Plasma volume change (%)	0.0* (0.0)	−0.8* (4.9)	−5.8 (5.4)	0.0 (0.0)	0.3 (8.8)	−3.1 (7.1)
Osmolality ($\mathrm{mosm \cdot kg\ H_2O^{-1}}$)	285.1* (2.5)	285.3* (2.8)	293.6 (5.2)	283.9* (2.0)	283.6* (2.6)	291.9 (3.4)

* Significantly different from H/F

Table 2 Average metabolic rate, sweat rate, and evaporation rate. Values are the near (SD) of the values for eight subjects

Variable	Light exercise			Heavy exercise		
	EU/F	EU/NF	H/F	EU/F	EU/NF	H/F
Average metabolic rate ($\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$)***	11.2 (0.6)	11.6 (0.9)	11.6 (1.0)	17.9 (0.7)	17.8 (1.3)	18.3 (1.0)
Average metabolic rate ($\mathrm{W \cdot m^{-2}}$)***	164 (8)	166 (12)	162 (11)	262 (9)	260 (14)	264 (14)
Sweat Rate ($\mathrm{kg \cdot h^{-1}}$)***	1.26 (0.33)	1.17 (0.29)	1.27 (0.28)	1.55 (0.35)	1.53 (0.37)	1.41 (0.38)
Evaporation rate ($\mathrm{kg \cdot h^{-1}}$)	0.33 (0.06)	0.30 (0.05)	0.31 (0.06)	0.34* (0.04)	0.33 (0.04)	0.32 (0.05)

* Significantly different ($P \leq 0.05$) from H/F conditions

*** Light exercise trials significantly different ($P \leq 0.05$) from heavy exercise trials

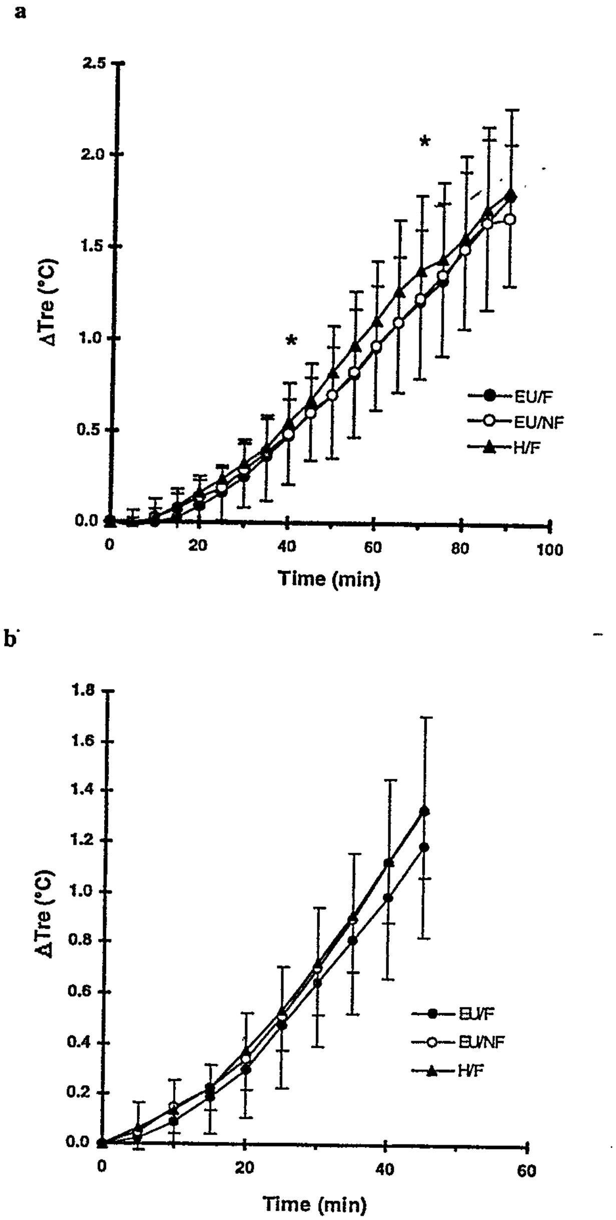

Fig. 1 Changes in rectal temperature (ΔT_{re}) from the value at time = 0 during (**a**) light ($n = 8$ to 50 min, $n = 7$ to 70 min, $n = 6$ to 90 min) and (**b**) heavy ($n = 8$ to 35 min, $n = 7$ to 45 min) exercise. Values are the mean (SD). (EU/F Condition of euhydrated with fluid replacement, EU/NF condition of euhydrated with no fluid replacement, H/F condition of hypohydrated with fluid replacement). * H/F significantly different from EU/F ($n = 7$)

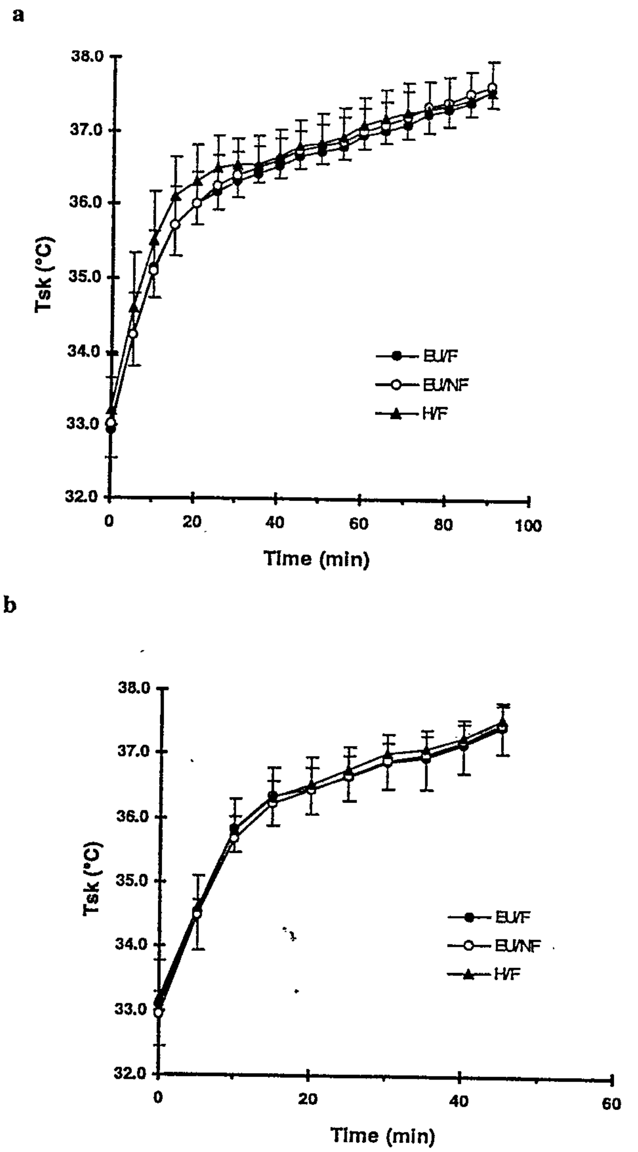

Fig. 2 Changes in skin temperature (T_{sk}) during (**a**) light ($n = 8$ to 50 min, $n = 7$ to 70 min, $n = 6$ to 90 min) and (**b**) heavy ($n = 8$ to 35 min, $n = 7$ to 45 min) exercise. Values are the mean (SD)

presence of exhaustion and imminent collapse. Of the 48 test trials, 30 were terminated due to exhaustion. Of the remainder, 15 were terminated due to the T_{re} reaching 39.3°C, and 3 due to the f_c reaching 95% of maximum. In all of these cases, subjects reported that they were very near the point of collapse.

With light exercise, the tolerance time for EU/F was significantly longer than either EU/NF or H/F (Table 3), demonstrating an impairment in exercise tolerance due to hypohydration, and a beneficial effect due to fluid replacement during exercise. No difference was observed between EU/NF and H/F trials. For heavy exercise trials, fluid replacement during exercise produced no additional benefit for tolerance time. A decreased tolerance time was observed during H/F compared to either of the EU trials, indicating a slight impairment due to hypohydration even at higher work rates with their shorter tolerance times. No differences were observed in the endpoint T_{re} at which the exercise sessions were terminated across either of the exercise intensities or hydration conditions.

For both light and heavy exercise, the body heat gain was significantly less during EU/NF than during either EU/F or H/F (Table 3). During light exercise, the heat gain during EU/F was also greater than during H/F.

Table 3 Tolerance time, time required for a 1.0°C increase in rectal temperature (T_{re}) starting and ending T_{re}, and total heat storage in t body during exercise with and without accounting for the fluid consumed. Values are the mean (SD) of the values for eight subjects

Variable	Light exercise			Heavy exercise		
	EU/F	EU/NF	H/F	EU/F	EU/NF	H/F
Tolerance time (min)***	106.5*,** (22.1)	93.1 (20.8)	87.1 (14.2)	59.7* (9.5)	58.3* (11.1)	53.3 (8.9)
Time (min) for 1.0°C increase in T_{re}***	62.5* (14.3)	63.6* (12.2)	54.9 (14.7)	42.0 (8.3)	37.1 (4.9)	37.1 (7.8)
T_{re} start (°C)	36.85 (0.28)	36.89 (0.29)	36.96 (0.31)	36.94 (0.27)	36.88 (0.21)	37.01 (0.25)
T_{re} at endpoint (°C)	38.90 (0.40)	38.74 (0.68)	38.76 (0.46)	38.69 (0.62)	38.71 (0.43)	38.74 (0.47)
Heat storage (kJ)	570.8*,** (132.8)	413.3 (98.5)	508.2** (109.0)	554.9** (142.2)	464.1 (104.7)	546.8** (103.8)
Heat storage discounting fluid (kJ)	407.1 (124.0)	413.3 (98.5)	378.0 (89.1)	432.8 (121.8)	464.1 (104.7)	433.5 (97.3)

* significantly different ($P \leq 0.05$) from H/F
** Significantly different ($P \leq 0.05$) from EU/NF
*** Light exercise significantly different ($P \leq 0.05$) from heavy exercise

Fluid replacement may benefit heat tolerance by maintaining body mass and providing a greater mass for heat storage. When heat gain was recalculated by discounting the fluid consumed (the amount of fluid given was subtracted from $mb_{(f)}$) during exercise, no significant differences were observed between any of the hydration conditions.

Figure 2 presents the changes in $\overline{T}_{sk}$ throughout the exercise sessions. Subjects in all conditions exhibited the similar pattern of a rapid increase in $\overline{T}_{sk}$ during the initial 15 min of exercise followed by a much slower rate of increase. Hydration status or restricting fluid replacement had no impact on the increase in $\overline{T}_{sk}$ during either light or heavy exercise.

The changes in f_c throughout HST for the light and heavy exercise are presented in Fig. 3. During light exercise, f_c was significantly higher for H/F compared with EU/F trials after 25 min, and remained elevated for the remainder of the exercise. Fluid replacement elicited a significantly lower f_c in the EU trials after 60 min of exercise. During heavy exercise, higher f_c values were observed after 10 min of walking for H/F compared with either of the EU conditions. After 30 min of walking, the consumption of fluid during exercise produced an attenuation in f_c rise, with a significantly higher f_c being observed for EU/NF compared with EU/F.

Stroke volume changes throughout the HST are presented in Fig. 4. Stroke volume decreased steadily over the course of the exercise for all hydration conditions and exercise intensities. During light exercise, there was a main effect of hydration condition on stroke volume, with a lower stroke volume during H/F (average of 55.0 ml) compared to both EU/F and EU/NF (averages of 64.2 and 63.0 ml, respectively). During heavy exercise, EU/F stroke volumes (average of 72.7 ml) were higher than EU/NF and H/F (64.9 and 60.6 ml, respectively).

Figure 5 presents the changes in cardiac output throughout the exercise sessions. The decrease in stroke volume during exercise was more than compensated f by the increase in f_c, and cardiac output increased ov the course of the HST concomitant with the increase i $\dot{V}O_2$. During both light and heavy exercise, no signif cant differences were observed in the cardiac output f any of the hydration conditions.

Discussion

The wearing of protective clothing during exercise in th heat is known to cause a significant increase in energ expenditure and physiological strain to the individua (Smolander et al. 1984; Duggan 1988; Candas and Hoef 1995; Holmer 1995; Patton et al. 1995). The combinatio of the limited vapour permeability of the protectiv clothing, the treadmill exercise, and the hot environmen result in an environment of uncompensable heat stres where the requirement for evaporative heat loss greatl exceeds the capacity, defined by the vapour pressure of th environment and the characteristics of the clothing (Givoni and Goldman 1972). For the light and heavy exercis intensities used in the present study, the HSI (E_{req}/E_{max} was 2.5 and 3.5, respectively. This was a more severe environment than used in previous studies that have examined the influence of hydration status on uncompensabl heat stress, where the HSI approached a maximum o about 1.0 (Sawka et al. 1985; Sawka et al. 1992). In addition, the present study was unique in investigating th separate effects of hypohydration and fluid replacemen during exercise in the heat specifically while wearin protective clothing. The results of the present study indicate that, under these conditions of uncompensable hea stress, tolerance time is significantly affected by the hydration status of the subject prior to beginning the exercis bout. The rate of T_{re} increase during light exercise wa significantly higher for H/F compared to EU/F, indicating a beneficial thermoregulatory effect of maintainin

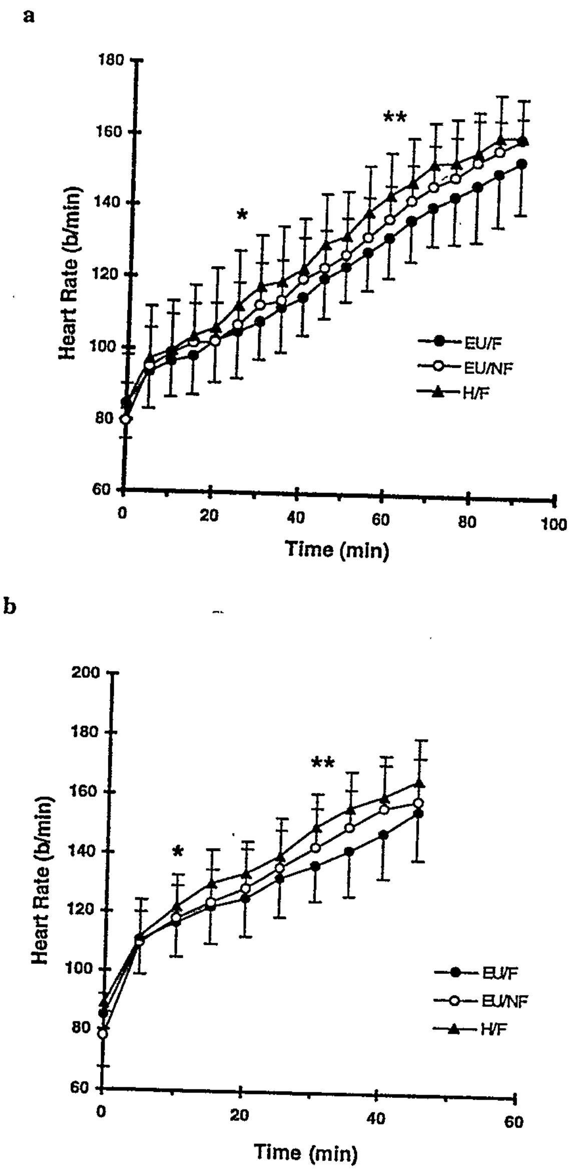

Fig. 3 Changes in heart rate during (a) light ($n = 8$ to 50 min, $n = 7$ to 70 min, $n = 6$ to 90 min) and (b) heavy ($n = 8$ to 35 min, $n = 7$ to 45 min) exercise. Values are the mean (SD)* H/F significantly different from EU/F to the end of the session. ** EU/NF significantly different from EU/F to the end of the session

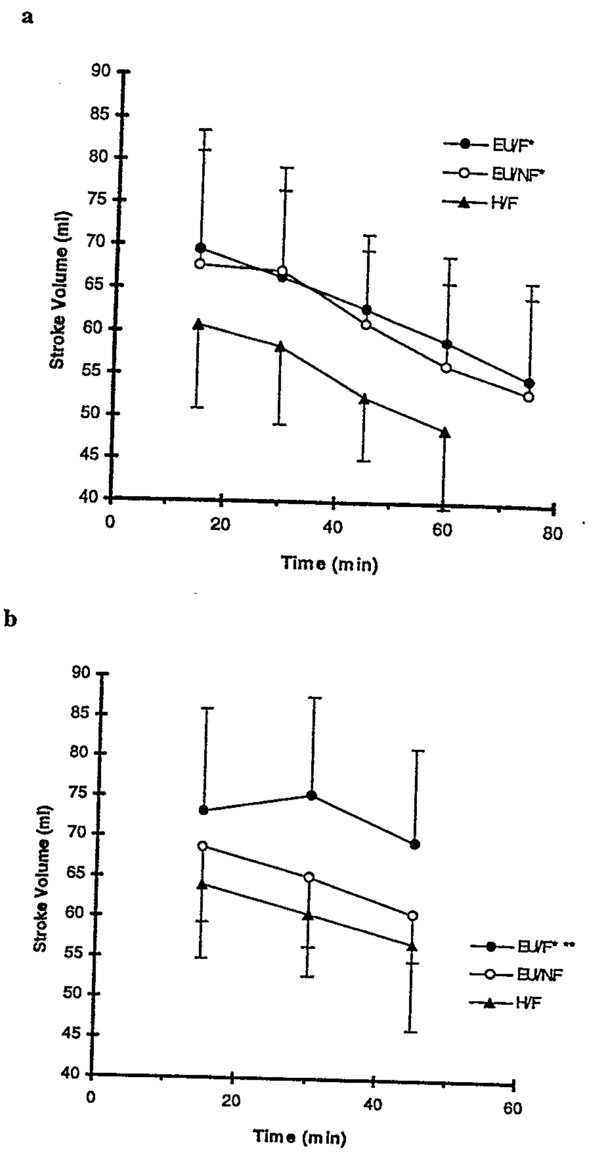

Fig. 4 Changes in stroke volume during (a) light ($n = 8$ to 45 min, $n = 7$ to 75 min) and (b) heavy ($n = 8$ to 30 min, $n = 7$ to 45 min) exercise. Values are the mean (SD) * H/F significantly different from EU/F. ** EU/NF significantly different from EU/F

euhydration prior to exercise. However, no significant difference between the EU/NF and H/F conditions was observed. This suggests that, in an environment of uncompensable heat stress, fluid replacement during light exercise is of equal importance to euhydration in maintaining performance. During heavy exercise there was a small, but significant reduction in tolerance time during H/F compared with EU/F or EU/NF, indicating a minor beneficial effect from maintaining a euhydrated state prior to exercise.

Decreased sweating has been suggested to be the main contributor to the excessive rise in core temperature that occurs during hypohydration (Greenleaf and Castle 1971). Hydration status may affect thermoregulatory or cardiovascular responses to exercise via alterations of body fluid volumes or tonicity (Nielsen 1974), or through the direct impairment of sweat gland function (Taylor 1986). Increasing levels of hypohydration result in a graded increase in the threshold temperature for the onset of sweating and a graded decrease in the sensitivity of the sweating response during exercise in a warm environment (Montain et al. 1995). In the present study, 2.2% hypohydration caused a significant increase in serum osmolality prior to both exercise conditions. No differences were observed in whole-body sweat rates among hydration conditions. However, for the light exercise, core temperature was elevated during the hypohydration trial, implying that the relationship between core temperature and sweat rate was altered,

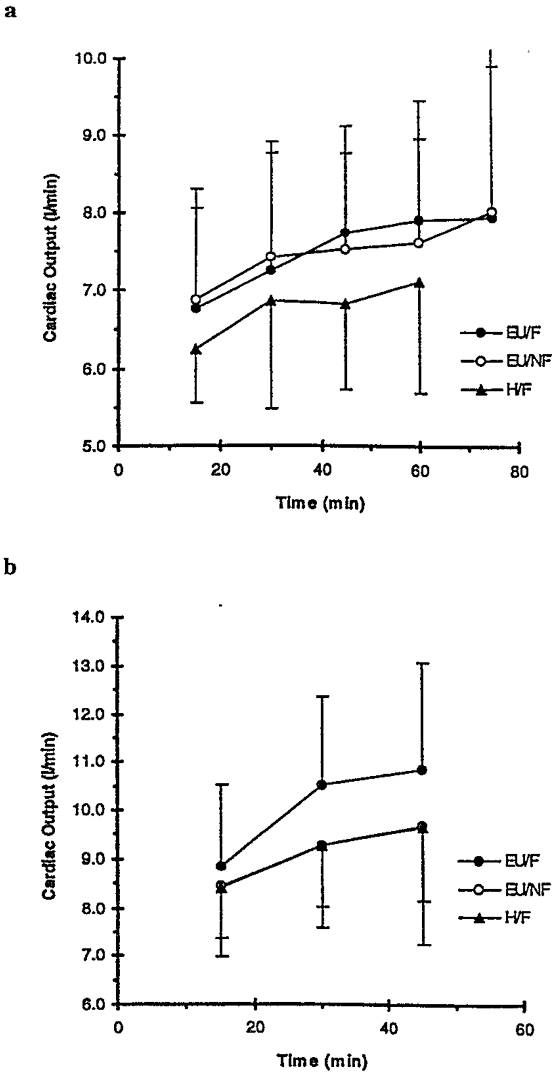

Fig. 5 Changes in cardiac output during (**a**) light ($n = 8$ to 45 min, $n = 7$ to 75 min) and (**b**) heavy ($n = 8$ to 30 min, $n = 7$ to 45 min) exercise. Values are the mean (SD)

although our method of estimating whole-body sweat rates from changes in nude body mass did not allow us to isolate the nature of the change.

Hypohydration placed an additional strain on the cardiovascular system during exercise in the NBC clothing. During both light and heavy exercise, f_{c} was significantly increased while subjects were hypohydrated than while they were euhydrated with fluid replacement over the course of the HST. Sawka et al. (1985) observed progressive increases in plasma osmolality and decreases in plasma volume with increasing levels of hypohydration, resulting in progressive elevations in f_{c} and core temperature, with core temperature increasing by 0.15°C and f_{c} by 4 beats$\cdot$min^{-1} for each percentage increase in hypohydration. In the present study, f_{c} was increased during hypohydration in order to compensate for the decreased stroke volume, which presumably reflected a decreased blood volume and end-diastolic ventricular volume (Gonzalez-Alonso et al. 1995). In the present experiment, stroke volume was significantly decreased by hypohydration during both light and heavy exercise. However, the elevated f_{c} response was successful in maintaining a similar cardiac output during both EU/F and H/F conditions.

With the light exercise in the present study, the increased tolerance time during EU/F compared with EU/NF was likely to be due to the beneficial effects of fluid replacement on maintaining adequate plasma and blood volume and central venous return. The tolerance times during the light exercise were of sufficient length to allow the ingested fluids to be emptied from the stomach and absorbed from the intestines, thus producing a benefit in plasma or blood volume. It has been reported that heat stress and hypohydration reduces the rate of gastric emptying in fit subjects during treadmill running at 50% maximum $\dot{V}O_2$ (Neufer et al. 1989). However, the rate of fluid consumption in the present study during the light exercise trials was lower than the gastric emptying rate observed by Neufer et al. (1989), so it is unlikely that gastric emptying was significantly slowed in the present study. Fluid replacement during exercise may also have delayed or prevented significant fluid loss from the intracellular fluid compartment. The f_{c} for subjects in the EU/NF condition was increased at 60 min ($n = 7$) compared with EU/F. Fluid replacement during exercise also afforded subjects a greater tolerance to heat build-up, since heat storage within the body was significantly greater for EU/F than with EU/NF at the point of exhaustion.

It is possible that the majority of the ingested fluids remained in the digestive tract at the time of exhaustion. Indeed, ingesting fluids during the heavy exercise may have increased subject discomfort due to increased stomach volume and gastric residue (Mitchell and Voss 1991). This may have been a particular problem in the H/F trial, where the subjects were already discomforted by the hypohydration. However, although fluid absorption rates were not measured, the rate of fluid replacement was likely to be sufficient to completely empty from the digestive tract, since the rate of fluid replacement during heavy exercise corresponded with the gastric emptying rate observed during hypohydrated exercise in the heat (Neufer et al. 1989). It would appear that, during heavy exercise, even if the ingested fluid was emptied and absorbed from the digestive tract fast enough to counteract body fluid shifts and decreases in plasma volume due to exercise and sweat loss, other factors limited exercise tolerance.

Similar to previous studies in this laboratory investigating exercise tolerance while wearing the full NBC ensemble in a hot environment, "heavy" workrates of approximately 18 ml$\cdot$kg$^{-1}\cdot$min^{-1} or 500 W resulted in tolerance times of approximately 50–60 min, with a greater variation in tolerance times evident only during lighter exercise (McLellan 1993). Because of the increased rate of heat production with heavy exercise, few subjects in the present study were able to exercise for more than 65–70 min regardless of hydration status prior to exercise or the presence of fluid during exercise. Thus, it appears that physiological manipulations are ineffective for improving heat tolerance while wearing the protective clothing at higher exercise intensities.

Interestingly, despite the differences in sweat rates, rates of T_{re} increase, and tolerance times between the light and heavy work rates, no differences were observed in the T_{re} at which subjects terminated the trials. The majority of sessions were terminated by the subjects due to exhaustion. In the trials that were terminated due to the subject reaching the ethically imposed upper limit for T_{re} or f_c, subjects reported that they were very near the point of voluntary termination. The similarity in the endpoint T_{re} was in contrast to studies in which a significantly lower T_{re} at exhaustion with hypohydration was observed (Sawka et al. 1985; Sawka et al. 1992). However, the reduced tolerance times and lower T_{re} endpoints were only observed with significantly greater (5–7%) levels of hypohydration than in the present study, with no differences observed at 3% hypohydration (Sawka et al. 1985). It would appear that the mild hypohydration that was induced in the present study does not necessarily reduce the core temperature that may be tolerated before exhaustion occurs while wearing the NBC clothing. Despite a slower response time, T_{re} was likely to be representative of the overall core temperature, since Kraning and Gonzalez (1991) reported nearly identical T_{re} and esophageal temperatures after ≈30 min of exercise during similar uncompensable heat stress conditions.

From the present study, it was concluded that, at both light and heavy exercise intensities, minor levels of hypohydration significantly impaired exercise tolerance in a severely uncompensable heat stress environment. Hypohydration decreased plasma volume and increased plasma osmolality, which may have inhibited peripheral blood flow and the sweating response, resulting in an increased rate of heat storage. Fluid ingestion during exercise was successful in prolonging exercise tolerance only at light exercise intensities. At high exercise intensities, fluid replacement had no effect on the body fluid compartments before exhaustion due to other factors occurred.

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