TITLE

Effects of Dehydration, Hypohydration, and Hyperhydration on Tolerance During Uncompensable Heat Stress

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Tom M. McLellan, Stephen S. Cheung, William A. Latzka, Mike N. Sawka, Kent B. Pandolf, Claire E. Millard, and W. Reg Withey

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Abstract/Résumé

The present study examined the effects of dehydration from prior exercise on subsequent exercise tolerance time (TT) that involved wearing nuclear, biological, and chemical (NBC) protective clothing. It was hypothesised that TT would be reduced in the dehydrated state. Ten men undertook continuous treadmill walking at $4.8\ \text{km} \cdot \text{h}^{-1}$ *at 35 °C and 50% relative humidity, wearing NBC clothing while euhydrated (EU) or dehydrated (D) by 2.3% of body weight. Hydration status had no impact on thermoregulatory or cardiovascular responses during exercise. Also rectal temperature at exhaustion did not differ between EU (38.52 ± 0.39 °C) and D (38.43 ± 0.45 °C). Exercise TT during this uncompensable heat stress was reduced significantly for D (47.7 ± 15.3 min) compared with EU (59.0 ± 13.6 min). It was concluded that prior exercise leading to levels of dehydration to 2.3% of body weight, together with subsequent fluid restriction during exposure to uncompensable heat stress, impaired TT while wearing the NBC protective clothing. The integration of these findings together with other comparable studies that have examined the influence of hypo- and hyperhydration on TT while wearing NBC protective clothing revealed that hydration status has less effect on TT as the severity of uncompensable heat stress increases.*

McLellan and Cheung are with the Defence & Civil Inst. of Environ. Med., PO Box 2000, Toronto, Ont. M3M 3B9. Latzka, Sawka, and Pandolf are with the U.S. Army Res. Inst. of Environ. Med., Natick, MA 01760-5007, USA. Millard and Withey are with the Centre for Human Sciences, Defence Res. Agency, Farnborough, Hampshire GU 146TD, England.

La présente étude analyse les effets de la déshydratation, causés par un exercice préalable, sue le temps de tolérance (TT) à l'effort d'individus portant un vêtement de protection contre des agents nucléaires, biologiques et chimiques (NBC). L'hypothèse initiale indique que la déshydratation réduit le TT. Dix hommes, euhydratés (EU) ou déshydratés (D) de l'équivalent de 2,3% de leur masse corporelle et portant un vêtement NBC, marchent sur un tapis roulant à une vitesse de 4,8 km/h dans les conditions climatiques suivantes: 35 °C, 50% d'humidité relative. Le niveau d'hydratation n'a aucun effet sur les ajustements thermorégulateurs et cardio-vasculaires à l'effort. De plus, la température rectale au point d'épuisement ne diffère pas d'une condition d'hydratation à l'autre: EU (38,52 ± 0,39 °C) et D (38,43 ± 0,45 °C). Le TT au cours de ce stress thermique incompensable est significativement réduit: D (47,7 ± 15,3 min) et EU (50,0 ± 13,6 min). En conclusion, un exercice préalable entraînant une déshydratation équivalente à 2,3% de la masse corporelle réduit le TT d'un effort subséquent chez des individus contraints à boire moins et portant un vêtement NBC en période de stress thermique. Ces observations ainsi que celles d'autres études indiquent que le niveau d'hydratation d'individus portant un vêtement NBC a moins d'effet sur le TT au fur et à mesure que le stress thermique incompensable s'accumule.

Introduction

Protective clothing such as the nuclear, biological, and chemical (NBC) ensemble worn by military personnel features high insulation and low water vapour permeability, due to the thickness and the multilayered fabric design. This layering effect traps insulative air layers around the body and impairs the transfer of heat to the environment. The limited evaporative heat loss allowed by the protective clothing, combined with an increased metabolic heat production and high ambient temperature, can increase the body's core temperature to dangerously high levels. These conditions define uncompensable heat stress, wherein the evaporative cooling requirements (E_{req}) greatly exceed the possible cooling capacity of the environment (E_{max}). The heat strain associated with wearing NBC protective clothing has been defined for many different combinations of ambient temperature, vapour pressure, and metabolic rate (Carter and Cammermyer, 1985; Goldman, 1963; Henane et al., 1979; Kraning and Gonzalez, 1991; McLellan, 1993; McLellan et al., 1993; Montain et al., 1994; Tilley et al., 1981).

It is well documented that fluid replacement and hydration status are important determinants of exercise tolerance time (TT) when evaporative heat loss is not restricted by clothing (Noakes, 1993). The importance of hydration status during uncompensable heat stress, however, is less well defined. Sawka et al. (1992) reported that the termination of exercise due to intolerance occurred at a significantly lower core temperature with hypohydration of 5% body weight. In addition, TT was reduced from 120 min during euhydrated trials to 55 min when subjects were hypohydrated. Evaporative heat loss roughly matched heat loss requirements in that study, with a heat stress index ($HSI = E_{req} \cdot E_{max}^{-1}$) of approximately 1.0. Recently, Cheung and McLellan (1998a) studied the effects of a milder level of hypohydration (2.5% body weight) during more severe uncompensable heat stress conditions. They found that core temperature at exhaustion was not affected by this level of hypohydration. They also observed that both hypohydration and the restriction of fluid during exercise had a greater impact during light exercise (metabolic rate less than 350 W) in which TT was extended to approximately 90 min compared with heavy exercise (heat production greater than 500 W) with a shorter TT of 60 min.

Both studies (Cheung and McLellan, 1998a; Sawka et al., 1992) controlled the level of hypohydration by having subjects exercise the day prior to heat-stress exposure and maintaining the desired level of hydration overnight. Both studies also evaluated the impact of hypohydration on TT with fluid replacement during exercise. From a research design perspective, it is important to allow subjects enough time to recover from the prior exercise before studying the effects of hypohydration on thermoregulation. However, in a military scenario, personnel may experience voluntary dehydration during exercise in a compensable heat stress environment and then have to continue exercise in an uncompensable heat stress environment that involves wearing NBC protective clothing. Further, the replacement of fluid while wearing the protective clothing is difficult and not always possible when a respirator is worn. Thus there is a need for information that documents the severity not only of beginning exercise in a dehydrated state but also the effects of further dehydration while wearing the protective clothing.

It was the purpose of the present study, therefore, to establish the effects of prior exercise leading to mild dehydration of approximately 2.5% body weight on subsequent TT during uncompensable heat stress that also led to further dehydration due to fluid restriction. A second purpose was to integrate the findings of the present study with those of Sawka et al. (1992) and Cheung and McLellan (1998a, 1998b), along with a recent study by Latzka et al. (1998) that compared glycerol and water hyperhydration, in order to clarify the importance of hydration status on TT and the core temperature tolerated at exhaustion in an uncompensable heat-stress environment.

Methods

SUBJECTS AND EXPERIMENTAL DESIGN

Ten men volunteered to participate in the study. Subjects were informed of all details of the experimental procedures and the associated risks and discomforts in the presence of a medical officer before they provided their written consent. Respective mean values (±*SD*) for age, height, weight, body fatness estimated from skinfolds, and Dubois body surface area were 26.0 ± 3.1 yrs, 1.76 ± 0.08 m, 76.6 ± 8.9 kg, 14.5 ± 2.8%, and 1.93 ± 0.15 m^2.

Testing was conducted in March and subjects were not heat acclimated prior to the experiment. The order of trials was randomised to eliminate any order effect and bias for the extent of the partial heat acclimation that may have been acquired with the repeated testing. On two afternoons while wearing the United Kingdom's NBC clothing, each subject underwent a heat stress test (HST) that involved walking on a motorised treadmill at 4.8 km · h^{-1} for a maximum of 100 min in a hot (35 °C dry bulb and globe temperature, 50% rel. humidity) environment with a wind speed of 1.1 m · s^{-1} while either euhydrated (EU) or dehydrated (D) by approximately 2.5% of body weight. On the morning of each experimental session, subjects walked at 4.8 km · h^{-1} in the heat wearing shorts and a T-shirt for a maximum of 3 hours. During this period, fluid was either provided to maintain euhydration or restricted until subjects became dehydrated by 2.5% of their body weight. Following the morning session, subjects were hydrated to achieve the desired hydration condition (either EU or D). Approximately 2.5 hrs elapsed between the end of the morning protocol and the afternoon HST. No fluid was provided during the afternoon HST. Trials were separated by 48 hrs.

NBC PROTECTIVE CLOTHING

The protective clothing ensemble consisted of shorts, T-shirt, socks, combat shirt and trousers, combat boots, two-piece overgarment, rubber gloves and overboots, and respirator with canister. Total mass of the ensemble was approximately 9.0 kg. Total thermal resistance and the Woodcock water vapour permeability coefficient of the NBC ensemble determined on a heated and wetted manikin at a wind speed of 1.12 $m \cdot s^{-1}$ were 0.271 $m^2 \cdot °C \cdot W^{-1}$ and 0.29, respectively (Gonzalez et al., 1993). Slightly different values have been determined for the Canadian (0.291 $m^2 \cdot °C \cdot W^{-1}$ and 0.33) and U.S. Army (0.327 $m^2 \cdot °C \cdot W^{-1}$ and 0.32) NBC ensembles (Gonzalez et al., 1993).

DRESSING AND WEIGHING PROCEDURES

Both nude and dressed weights of the subjects were recorded prior to entering the chamber and as soon as possible after exiting from it. T_{re} was measured at 5-min intervals with a thermistor inserted 0.12 m beyond the anal sphincter, and a 4-point weighted average from the chest, forearm, thigh, and calf was used to estimate mean skin temperature ($\bar{T}_{sk}$) (Ramanathan, 1964). Heart rate was recorded every 5 min from an ECG monitor.

Differences in nude and dressed weights pre- and posttrial were not corrected for respiratory and metabolic weight losses. The amount of sweat produced was calculated as pretrial minus posttrial nude weight. Evaporative sweat loss from the clothing was calculated as pretrial minus posttrial dressed weight. Sweat rates and evaporation rates were calculated from measured changes in nude and dressed weight, respectively, divided by tolerance time.

TOLERANCE TIME AND GAS EXCHANGE ANALYSES

Tolerance time for all trials was defined as the time until T_{re} reached 39.2 °C, HR exceeded 180 $b \cdot min^{-1}$, dizziness or nausea precluded further exercise, or 100 min had elapsed.

During each trial, open-circuit spirometry over a 60-sec period using Douglas bags was employed to determine expired minute ventilation, oxygen consumption, and carbon dioxide production after 5 min and then at 30-min intervals. The metabolic rate was calculated using the equation described by Weir (1949).

STATISTICS

Data are presented as mean values and standard deviation of the mean. A two-factor (hydration status × time) repeated-measures ANOVA was used to compare the changes in rectal and skin temperature, heart rate, and gas exchange responses. Paired *t*-tests using the Bonferroni adjustment for multiple comparisons were performed to isolate differences among treatment means. A paired *t*-test also was used to analyse differences in tolerance time, body weight changes, sweat rate, and evaporative sweat loss. For all statistical analyses, the 0.05 level of significance was used. Descriptive cumulative statistics were used to generate heat strain tolerance curves from the data of the present study together with individual subject data from studies by Cheung and McLellan (1998a) and Latzka et al. (1998).

Results and Discussion

Body weights were significantly reduced by 2.3% prior to Condition D (74.2 ± 8.6 kg) compared with EU (76.0 ± 8.7 kg). Fluid loss from the body and the clothing, and TT were significantly greater during EU than D (Table 1). Hydration status did not affect the average metabolic rate or the initial or final T_{re}. The overall change in T_{re}, however, was significantly greater for EU (1.49 ± 0.49 °C) than for D (1.33 ± 0.58 °C). Although T_{re} was higher during Condition D than during EU (Figure 1), these differences were not statistically significant. Similarly, hydration status had no impact on the $\bar{T}_{sk}$ (Figure 2) or heart rate (Figure 3) response during the heat-stress exposure in the NBC clothing.

The results of the present study indicated that TT was significantly decreased when subjects were dehydrated prior to exposure to uncompensable heat stress. However, the rate of T_{re} increase, increases in $\bar{T}_{sk}$, and the heart rate response were not affected by beginning the exercise in a dehydrated condition. These findings are in agreement with recent data from Cheung and McLellan (1998a), who examined the impact of mild hypohydration (2.5% body weight) during uncompensable heat stress. These authors also observed similar T_{re} and $\bar{T}_{sk}$ responses during heavy (greater than 500 W) exercise despite small but significant reductions in TT when exercise began in a hypohydrated state. Tolerance times were reduced from 60 min in the euhydrated condition to 53 min when hypohydrated by 2.5% body weight.

Table 1 Thermoregulatory and T_{re} Response and Tolerance Time While Wearing United Kingdom NBC Clothing

	Euhydrated	Dehydrated
Avg metab. rate ($W \cdot m^{-2}$)	161.2 ± 15.0	158.7 ± 19.5
Sweat rate ($kg \cdot h^{-1}$)	1.30* ± 0.37 (*n* = 8)	0.95 ± 0.41 (*n* = 8)
Evaporation rate ($kg \cdot h^{-1}$)	0.39* ± 0.12 (*n* = 8)	0.28 ± 0.10 (*n* = 8)
Initial T_{re} (°C)	37.03 ± 0.26	37.10 ± 0.23
Final T_{re} (°C)	38.52 ± 0.39	38.43 ± 0.45
Tolerance time (min)	59.0* ± 13.6	47.7 ± 15.3

No fluid was given during any trials. Values are mean ± *SD* for $n = 10$ unless otherwise stated.
*Significantly different from dehydrated.

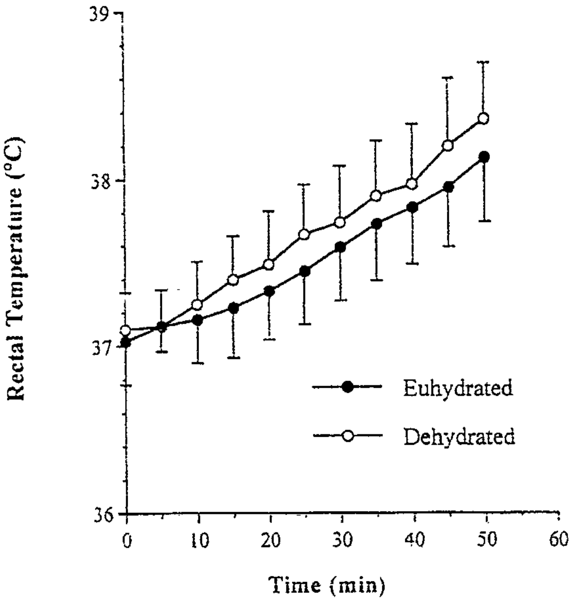

Figure 1. Rectal temperature during the euhydrated or dehydrated trials while wearing the United Kingdom NBC protective clothing. Values are mean ± *SD*.

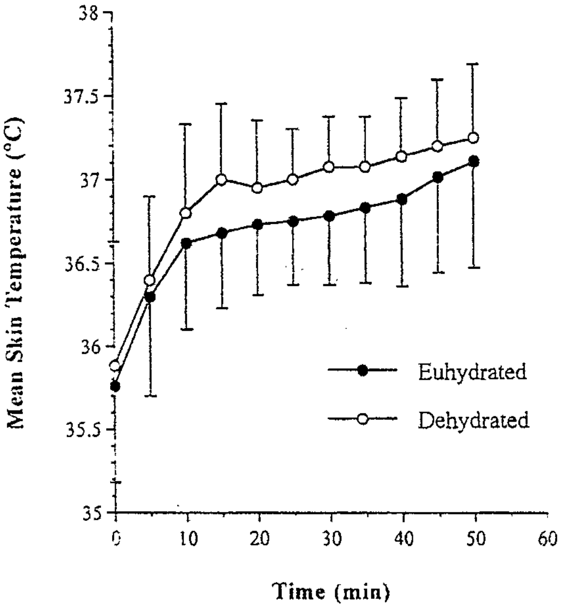

Figure 2. Mean skin temperature during the euhydrated or dehydrated trials while wearing the United Kingdom NBC protective clothing. Values are mean ± *SD*.

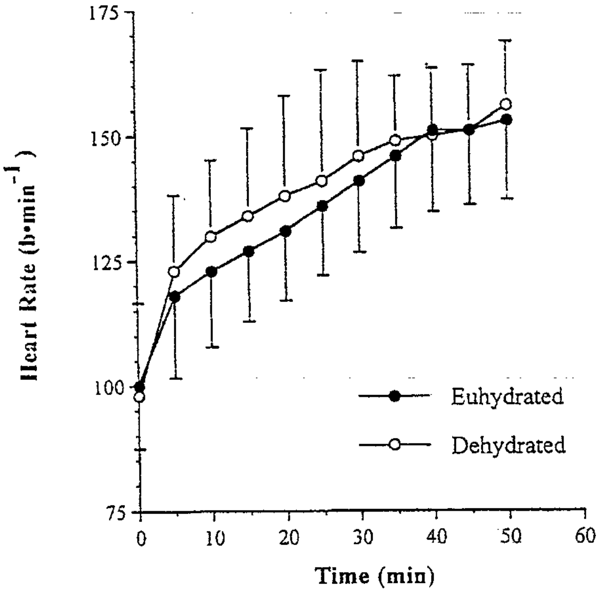

Figure 3. Heart rate during the euhydrated or dehydrated trials while wearing the United Kingdom NBC protective clothing. Values are mean ± *SD*.

Thus, for exercise lasting approximately 1 hour, there is a minor beneficial effect for maintaining a euhydrated state prior to exercising in an uncompensable heat stress environment.

INTEGRATION OF FINDINGS

The results of the present study can be compared with others that studied the impact of hydration on TT during uncompensable heat stress (Cheung and McLellan, 1998a, 1998b; Latzka et al., 1998; Sawka et al., 1992). These other investigations created uncompensable heat stress conditions either with NBC protective clothing and environmental conditions (Cheung and McLellan, 1998a, 1998b; Latzka et al., 1998) similar to those used in the present study, or with higher ambient temperatures to create a heat stress index close to 1.0 while not wearing the NBC clothing (Sawka et al., 1992). Aerobic fitness levels of subjects in all these studies were comparable, with mean values of 50–55 ml · kg^{-1} · min^{-1}. The subjects in Sawka et al. (1992) and Latzka et al. (1998) were heat acclimated prior to being exposed to the heat stress, but this was not the case in the present investigation nor in Cheung and McLellan (1998a, 1998b). Nevertheless, recent findings have shown that acclimation to a hot dry environment has only a minor effect on TT and does not affect the core temperature tolerated at exhaustion (Cheung and McLellan, 1998b; McLellan and Aoyagi, 1996).

When integrating these studies, it becomes apparent that as the severity of uncompensable heat stress increases, hydration status has less impact on TT when wearing the protective clothing. For example, Latzka et al. (1998) examined the effects of water or glycerol hyperhydration during uncompensable heat stress and found a 13% improvement in TT during heavy exercise (800 W) with glycerol hyperhydration compared with the control condition (which represented the euhydrated state with restriction of fluid during exercise). This significant relative improvement represented an absolute increase of only 4 minutes from 30 to 34 min, or an additional distance covered of 400 m walking up a 4–9% grade on a treadmill. Similarly, beginning heavy exercise in a mild state (2.5% body weight) of hypohydration decreased TT significantly by about 10%, from 59 to 53 minutes (Cheung and McLellan 1998a), which decreased walking distance about 500 m up a 4% grade. In the present study, fluid restriction leading to additional dehydration of 3.5% body weight decreased TT a further 10% to 48 minutes, which decreased walking distance a further 400 m.

As the severity of uncompensable heat stress is reduced with lower metabolic rates and/or lower ambient temperatures or vapour pressures, hydration status exerts a greater impact on the duration of work performance. Either beginning exercise in a hypohydrated state of 2.5% body weight, or restricting fluid during exercise that began in a euhydrated condition and led to a dehydrated state of 2.5% body weight, increased the physiological strain of exercise and decreased TT about 15%, or 15 min, while wearing the protective clothing (Cheung and McLellan, 1998a). These differences translated into a decreased walking distance of 800 m. These findings are consistent regardless of fitness level or state of heat acclimation (Cheung and McLellan, 1998b). Thus, in an environment of uncompensable heat stress, rehydration during light exercise lasting at least 90 min is of equal importance to euhydration in maintaining TT.

Also, from the present study, it appears that fluid restriction while in a dehydrated state has an additional negative impact on TT, since work times were reduced 20% versus the 10% reduction observed when fluid was provided while hypohydrated and performing heavy exercise (Cheung and McLellan 1998a). Greater absolute differences in TT would be expected as the HSI decreased further toward 1.0 by lowering the rate of heat production or increasing the rate of evaporative heat loss by removing layers of clothing. More severe hypohydration would also be expected to have a greater impact on TT during light exercise (Sawka et al., 1985; 1992), as would be the case with the mild level of dehydration used in the present study if fluids were restricted, leading to greater levels of dehydration throughout exercise. Sawka et al. (1992) reported that TT decreased from 120 to 55 min when subjects were hypohydrated by 5% of body weight prior to exercising at 45% $\dot{V}O_{2\,peak}$ in a hot and dry environment (49 °C, 20% rel. humidity) that produced an HSI close to 1.0. One might also expect that conditions of water or glycerol hyperhydration might exert a greater beneficial effect on TT with HSI values closer to 1.0.

IMPACT OF HYDRATION STATUS ON HEAT TOLERANCE

The individual data from the present study, together with the subject data provided from Cheung and McLellan (1998a) and Latzka et al. (1998), presents an opportunity to address the impact of hydration status on heat tolerance, defined here as the core temperature tolerated at exhaustion. All of these studies involved subjects of comparable aerobic fitness levels wearing NBC protective clothing with similar

Table 2 Number of Cases That Defined Termination of Heat Stress Test as a Function of Final Rectal Temperature

	Reason for termination					
Rectal temp. (°C)	Fatigue	Ataxia or dizziness	Dyspnea	Muscle cramp	Heart rate cut-off	Rectal temp. cut-off
38.0	6		1			
38.1	4				2	
38.2	4			1	1	
38.3	5	1	1		1	
38.4	1	1				
38.5	5	2	1			
38.6	3	2	1			
38.7	3					
38.8	2	1				
38.9	2	4				
39.0	5	4			1	
39.1	1	1				
39.2	4	3				
39.3	1					15
39.4						
39.5		1				
39.6						
39.7	1					
Total	47	20	4	1	5	15

Note: Data represent subject responses from the present study, Cheung and McLellan (1998a), and Latzka et al. (1998).

insulative and water vapour permeability characteristics (Gonzalez et al., 1993). Table 2 summarizes the individual reasons for termination of heat-stress exposure for these studies.

The majority of sessions were terminated by the subjects due either to dizziness or fatigue. In the trials that were terminated due to the subject reaching an ethically imposed upper limit of 39.3 °C for T_{re} (Cheung and McLellan 1998a), subjects reported being very near the point of voluntary termination. Figures 4 and 5 depict heat strain tolerance curves that compare the effects of hypohydration and hyperhydration, respectively, with the euhydrated condition. Subjects who terminated their trial due to dyspnea, muscle cramps, or reaching the heart rate limit are not included in these figures.

The importance of fluid replacement during exercise is evident in Figure 4, which reveals that many subjects can tolerate higher core temperatures at exhaustion if given fluid during the euhydrated trials. The figure also shows that beginning exercise in a euhydrated condition but restricting fluid during the subsequent

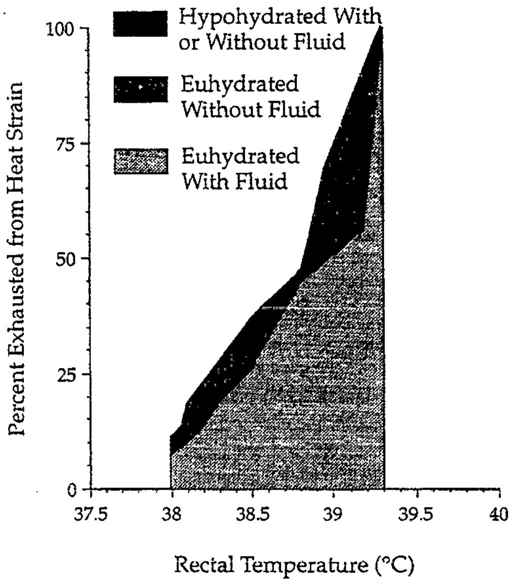

Figure 4. Heat strain tolerance curves for hypohydrated (includes dehydrated trials) with fluid or w/o fluid replacement ($n = 22$), euhydrated w/o fluid replacement ($n = 30$), and euhydrated with fluid replacement ($n = 16$) during exercise in a hot environment while wearing the Canadian (Cheung and McLellan, 1998a), United Kingdom (present study), or United States (Latzka et al., 1998) NBC protective clothing.

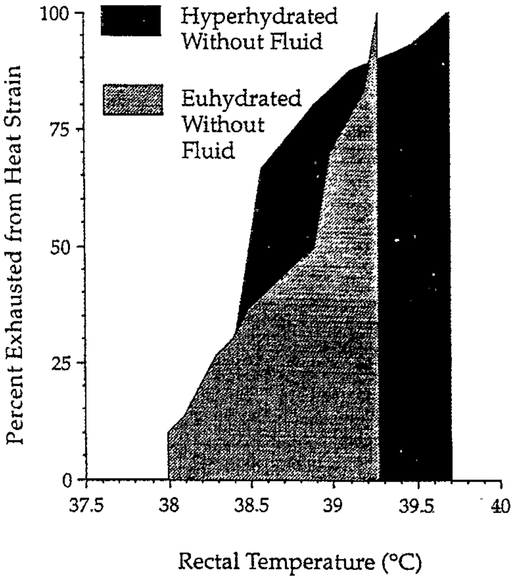

Figure 5. Heat strain tolerance curves for euhydrated w/o fluid replacement ($n = 30$) or hyperhydrated with water or glycerol but w/o fluid replacement ($n = 16$) during exercise in a hot environment while wearing the Canadian (Cheung and McLellan, 1998a), United Kingdom (present study), or United States (Latzka et al., 1998) NBC protective clothing.

exercise session produces a heat tolerance response similar to the hypohydrated or dehydrated condition. The effects of hyperhydration are less apparent due to the fact that some subjects included in the euhydrated curve were stopped when Tre reached 39.3 °C whereas subjects during the hyperhydration trials were allowed to continue exercising until Tre reached 40 °C. Certainly there is no evidence to suggest that beginning exercise in a hyperhydrated condition will improve one's tolerance to elevated core temperatures if exhaustion occurs at a Tre below 39.3 °C.

Interestingly, despite the differences in levels of hydration and TT, no significant differences were observed in the Tre at which subjects terminated the euhydrated or dehydrated trials in the present study, nor in other studies that examined mild levels of hypohydration (Cheung and McLellan, 1998a, 1998b). The similarity in the endpoint Tre was in contrast to studies that observed a significantly lower Tre endpoint with hypohydration (Sawka et al., 1985; 1992). However, the reduced TT and lower Tre endpoints were only observed with significantly greater (5–7%) levels of hypohydration than those in the present study, with no differences observed at 3% hypohydration (Sawka et al., 1985). This suggests that mild hypohydration does not necessarily reduce the core temperature that may be tolerated in the NBC clothing before exhaustion occurs. There was some indication, however, that providing fluid during exercise in the euhydrated state would increase the Tre at exhaustion for many subjects (see Figure 4). It is noteworthy that Sawka et al. (1992) reported higher Tre at exhaustion for euhydrated than for hypohydrated (5% body weight) trials in which hydration levels were maintained with fluid replacement during the HST.

Hyperhydration also does not alter the physiological strain tolerated at exhaustion during uncompensable heat stress. Exhaustion from heat strain occurred at the same core temperature, core temperature increase, heart rate, and skin temperature during each trial in Latzka et al. (1998). Previous research has demonstrated that core temperature provides the "best" physiological index of thermal tolerance (Montain et al., 1994; Nielsen et al., 1993; Sawka et al., 1992). In the present study, exhaustion from heat strain occurred at a mean core temperature of 38.5 ± 0.5 °C; this compares favorably to values reported by other studies examining uncompensable heat stress (McLellan et al., 1996; Montain et al., 1994; Nielsen et al., 1993; Sawka et al., 1992). However, Table 2 shows there is considerable individual variation in the Tre value tolerated at exhaustion. This value ranged from a low of 38.0 °C to a high of 39.7 °C. Factors that may influence this index of thermal tolerance include body composition and aerobic fitness (Cheung and McLellan, 1998b; McLellan, 1998).

Conclusions

In summary, mild levels of dehydration together with fluid restriction during exercise significantly impair exercise TT in an uncompensable heat stress environment. The impairment of hydration becomes more evident as the duration of exercise increases at lower metabolic rates. Fluid ingestion during uncompensable heat stress beginning in a euhydrated state prolongs TT only at light work intensities. Heat tolerance, defined as the highest core temperature tolerated at exhaustion, is not affected by dehydration or hypohydration to 3.5% of body weight, nor is it affected by water or glycerol hyperhydration.

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