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Impact of fluid replacement on heat storage while wearing protective clothing

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This study used partitional calorimetry to determine the influence of fluid replacement on heat storage during uncompensable heat stress. Eight males performed either light (L; level treadmill walking at 0.97 $m \cdot s^{-1}$ (3.5 $km \cdot h^{-1}$) or heavy (H; 1.33 $m \cdot s^{-1}$ (4.8 $km \cdot h^{-1}$) at a 4% grade) exercise at 40°C and 30% relative humidity while wearing nuclear, biological and chemical (NBC) protective clothing. Subjects received either no fluid (NF), or 200 or 250 ml of fluid (F) as warm water at ~35°C immediately before and every 15 min during the L and H trials respectively. Similar reductions in heart rate were observed at both metabolic rates with F but rectal temperature responses were not different between F and NF. Tolerance time was extended during L/F (106.5±22.1 min) compared with L/NF (93.1±20.8 min) but fluid replacement had no influence during H (59.8±9.5 min and 58.3±11.1 min for F and NF respectively). Fluid replacement also had no effect on the rate of heat storage during L (108.2±20.6 $W \cdot m^{-2}$ and 111.0±22.6 $W \cdot m^{-2}$ for F and NF respectively) and H (172.5±11.5 $W \cdot m^{-2}$ and 182.1±15.8 $W \cdot m^{-2}$ for F and NF respectively). However, heat storage expressed per unit of mass was significantly increased during L/F (18.5±4.0 $kJ \cdot kg^{-1}$) compared with the other trials (16.3±4.8 $kJ \cdot kg^{-1}$, 16.6±3.0 $kJ \cdot kg^{-1}$ and 16.7±4.0 $kJ \cdot kg^{-1}$ for L/NF, H/F and H/NF respectively). It was concluded that fluid replacement does not alter the rate of heat storage during uncompensable heat stress but does increase the heat storage capacity during light exercise when tolerance times are >60 min.

1. Introduction

In current industrial or military settings, personnel may be required to wear protective clothing to maintain work schedules in a hazardous environment. Typically, the physical characteristics of the clothing materials limit evaporative heat loss, thereby increasing the rate of heat storage for a given rate of heat production. It is not uncommon, therefore, as ambient temperature increases, for the clothing to create a condition of uncompensable heat stress where the required evaporative cooling exceeds the maximum evaporative potential of the environment (Kraning and Gonzalez 1991).

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It is well documented that maintaining an euhydrated state with fluid replacement during exercise in the heat is associated with lower heart rates and rectal temperatures (T_{re}) compared with the dehydrated condition that occurs when no fluid is provided (Candas *et al.* 1986, Hamilton *et al.* 1991). During compensable heat stress, fluid replacement promotes lower rates of heat storage for a given rate of heat production by maintaining higher rates of skin blood flow and, therefore, heat transfer from the core to the periphery (Montain and Coyle 1992). Under conditions where avenues for heat loss are restricted because of the wearing of protective clothing, it is less clear as to whether fluid replacement will influence rates of heat storage and thereby prolong tolerance time.

During uncompensable heat stress, tolerance time is a function of the initial core temperature, the rate of heat storage and the final core temperature tolerated at exhaustion. Cheung and McLellan (1998a) reported that neither the initial nor final core temperatures were influenced by fluid replacement. Since tolerance times were increased from 93 to 107 min at 40°C during light exercise, these data implied that rates of heat storage were reduced with fluid replacement. In contrast, tolerance was unchanged at 60 min during heavy exercise suggesting that rates of heat storage were unaffected at higher metabolic rates. Unfortunately partitional calorimetric estimates of rates of heat storage were not presented by Cheung and McLellan (1998a) and thus it was not possible to ascribe a functional mechanism to fluid replacement with respect to heat storage.

Recently the present authors developed a model that allows skin vapour pressure and evaporative heat loss to be estimated from humidity sensors and temperature thermistors placed above the skin surface and over the combat clothing layer of the NBC ensemble (Cain and McLellan 1998). This method allows for a more definitive assessment of rates of heat storage during uncompensable heat stress (McLellan *et al.* 1996, 1999). Using partitional calorimetry and this method to determine evaporative heat loss, it was the purpose of the present study to determine the impact of fluid replacement during uncompensable heat stress on the rate of heat storage. The data for these analyses were extracted from the findings presented previously by Cheung and McLellan (1998a). It was hypothesized that fluid replacement would lower rates of heat storage during longer exposures by maintaining higher rates of evaporative heat loss through the clothing ensemble.

2. Methods

2.1 *Subjects*

Eight non heat-acclimatized males volunteered to participate in the study after the proposal obtained approval from the Institute's Ethics Committee. Means (±SD) for age, weight, height, Dubois body surface area (A_D) and peak aerobic power were 29.3±6.4 years, 75.6±9.7 kg, 1.78±0.07 m, 1.94±0.15 m^2 and 56.5±4.4 $ml \cdot kg^{-1} min^{-1}$ respectively. All subjects were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiment, each subject gave their written informed consent before the first day of data collection.

Cheung and McLellan (1998a) have reported a more detailed explanation of the procedures followed during this study. A brief overview of the methods pertinent to the present analyses and a detailed explanation of the equations used to determine rates of heat storage are presented below.

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the equation presented by Mitchell *et al.* (1972). Metabolic weight loss was calculated from $\dot{V}O_2$ and the respiratory exchange ratio using the equation described by Snellen (1966).

2.5. *Heat storage*

The rate of heat storage (S in $W \cdot m^{-2}$) was calculated from the heat balance equation:

$$\dot{S} = \dot{M} - \dot{W} \pm (\dot{C} + \dot{R}) \pm \dot{C}_{resp} - \dot{E}_{resp} - \dot{K}_{H_2O} - \dot{E}_{sk} \tag{1}$$

The rate of metabolic heat production, $\dot{M}$, was determined from the measured $\dot{V}O_2$, the respiratory exchange ratio, RER, and A_D, as (Nishi 1981):

$$\dot{M} = 352(0.23 \cdot \text{RER} + 0.77)(\dot{V}O_2 \cdot A_D{}^{-1}) \tag{2}$$

The external rate of work performed ($\dot{W}$) was considered to be zero during the light exercise since the subjects walked on a level treadmill. $\dot{W}$ was calculated for the heavy exercise condition using the treadmill speed, V ($m \cdot s^{-1}$), the grade fraction (0.04), and the dressed body mass, m_d (kg), as (Givoni and Goldman 1972):

$$\dot{W} = 9.8 \cdot (0.04) \cdot V \cdot m_d \cdot A_D{}^{-1} \tag{3}$$

During exposure to 40°C, the rate of radiative and convective heat exchange, R and C, contributed to a positive heat storage since the chamber temperature exceeded skin temperature. R and C were estimated using the total insulative value of the NBC clothing ensemble, I_T, of 0.291 $m^2 \cdot {}^\circ C \cdot W^{-1}$ (or 1.88 clo) determined at a wind speed of 1.12 $m \cdot s^{-1}$ on a heated and dry articulating copper manikin (Gonzalez *et al.* 1993), and the difference between the chamber temperature of 40°C and $\bar{T}_{sk}$ averaged over each 5-min interval, as (Gonzalez *et al.* 1997):

$$\dot{R} + \dot{C} = (40 - \bar{T}_{sk}) \quad 0.291^{-1} \tag{4}$$

Respiratory evaporative heat loss, E_{resp}, and convective heat gain, C_{resp}, were calculated from the chamber vapour pressure, P_a, of 2.21 kPa for 40°C and 30% relative humidity, and the respired vapour pressure, P_{resp}, of 5.32 which assumes 100% saturation of expired air at a mouth temperature, T_{resp}, of 34°C at 40°C ambient temperature (Livingstone *et al.* 1994), as (Fanger 1970):

$$\dot{E}_{resp} = 0.0173 \quad \dot{M} \cdot (P_{resp} - P_a) \tag{5}$$

and

$$C_{resp} = 0.0014 \quad M \cdot (T_a - T_{resp}) \tag{6}$$

Heat loss through conduction from the body to the ingested volume of water, $\dot{K}_{H_2O}$, was estimated from the total volume of water ingested, m_{H_2O} in kg, the difference in temperature between the water (estimated at 35°C) and the average T_{re} throughout the exposure, the heat capacity of water of 4.18 $kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}$ and tolerance time, as:

$$\dot{K}_{H_2O} = m_{H_2O} \cdot (T_{re} - 35) \quad 4.18 \quad 1000 \cdot (60 \cdot \text{time})^{-1} \quad A_D{}^{-1} \tag{7}$$

Evaporative heat loss from the skin, E_{sk}, was determined from a model that determined mass flow rates of water vapour through the clothing layers using the skin and garment vapour pressures measured from the humidity sensors positioned above the skin surface and over the combat clothing layer together with the thermal resistances of the clothing and air layers (McLellan *et al.* 1996, Cain and McLellan 1998).

Heat storage capacity, S ($kJ \cdot kg^{-1}$), was calculated from $\dot{S}$, tolerance time and the post-nude mass, m_{pn} as:

$$S = \dot{S} \quad A_D \cdot m_{pn}^{-1} \quad (60 \cdot time) \cdot 1000^{-1} \qquad (8)$$

2.6 *Statistical analyses*

Data are presented as mean ± SD of the mean. A two-factor (metabolic rate and fluid replacement) repeated measures ANOVA evaluated any differences among the trials for sweat production, initial, final and delta T_{re}, rate and capacity of heat storage, and tolerance time. A three-factor (metabolic rate, fluid replacement, time) repeated measures ANOVA was performed for evaluating the changes in heart rate and T_{re} during the exposures. When a significant *F*-ratio was obtained, a Newman–Keuls post-hoc analysis isolated differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

3. Results

3.1 *Rates of dehydration*

Sweat rates were significantly greater during H ($1.54 \pm 0.35\ kg \cdot h^{-1}$) compared with L ($1.21 \pm 0.31\ kg \cdot h^{-1}$) but sweat rates were not affected by fluid replacement. Total fluid provided was greater during L (1.22 ± 0.29 l) compared with H (0.91 ± 0.17 l). Fluid replacement did not prevent a decrease in body mass for both L (1.42 ± 0.71%) and H (0.91 ± 0.41%) but the decreases in body mass with fluid replacement were significantly less than the changes observed following no fluid replacement (2.49 ± 0.76% and 2.06 ± 0.49% for L and H respectively)

3.2. *Heart rate*

Figure 1 presents the changes in heart rates during L and H with and without fluid replacement. During L, heart rates were significantly lower with fluid replacement at 30 min and from 40 min to the end of the heat exposure. Heart rates were also significantly reduced with fluid replacement during H after 30 min of exercise.

3.3. *Rectal temperature*

Figure 2 depicts the T_{re} response during the heat exposure. Data are not presented to exhaustion in this figure because of individual differences in tolerance times. Fluid replacement had no impact on the change in T_{re} during either the L or H exercise trials. There were no differences among the trials for either the initial (36.85 ± 0.28°C, 36.89 ± 0.28°C, 36.94 ± 0.27°C and 36.88 ± 0.21°C for the L/F, L/NF, H/F and H/NF trials respectively) or final (38.90 ± 0.40°C, 38.74 ± 0.68°C, 38.69 ± 0.62°C and 38.71 ± 0.43°C) T_{re}. However, the change in T_{re} from the beginning to the end of the trial was significantly greater for L/F (2.05 ± 0.58°C) compared with the other trials (1.85 ± 0.62°C, 1.75 ± 0.58°C and 1.84 ± 0.48°C for the L/NF, H/F and H/NF conditions respectively)

3.4. *Tolerance time*

Fluid replacement during L significantly extended tolerance time (106.5 ± 22.1 min and 93.1 ± 20.8 min for the F and NF trials respectively) but fluid replacement had no impact during H (59.8 ± 9.5 min and 58.3 ± 11.1 min for F and NF respectively).

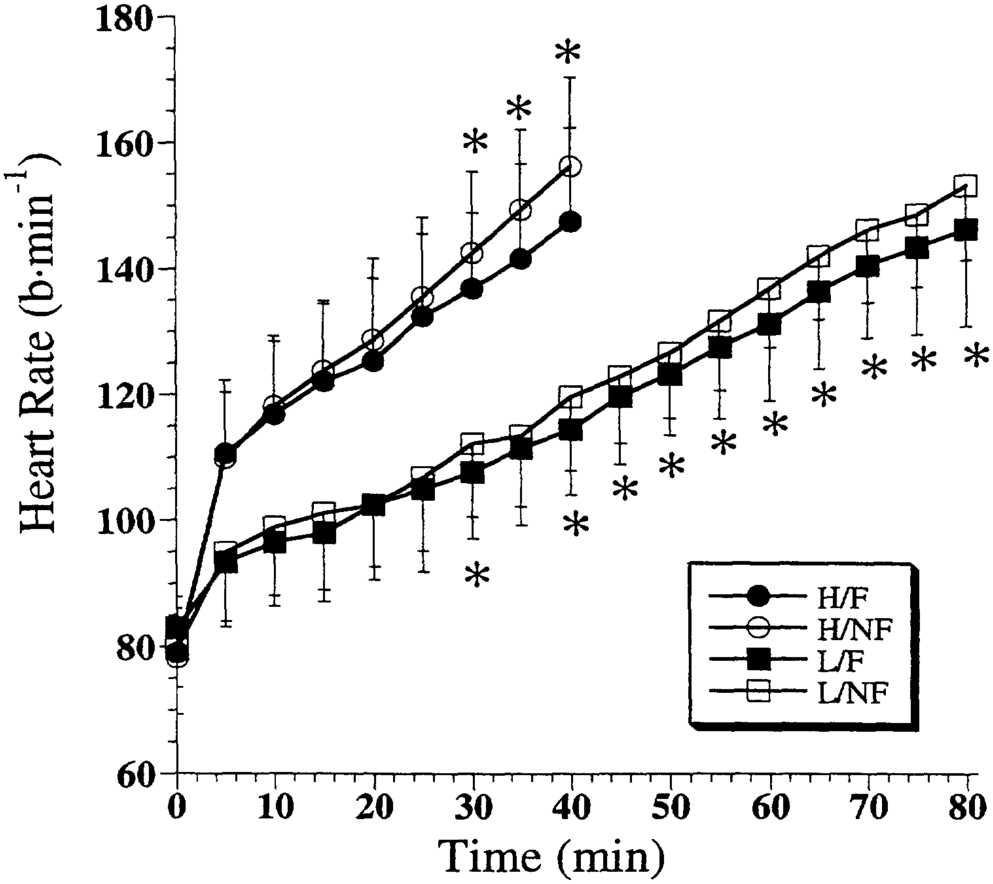

Figure 1. Changes in heart rate during the light (L) and heavy (H) exercise with (F) or without (NF) fluid replacement at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble Values are mean ± SD for $n = 8$ except during L from 55 to 80 min, where $n = 7$. *Significant effect for fluid replacement

3.5 *Heat storage*

The results from the partitional calorimetry are presented in table 1. With the exception of the heat transfer due to the heat capacity of the ingested water, fluid replacement did not affect the terms of the heat balance equation. Thus, the metabolic rate, radiative and convective heat gain, respiratory heat loss and evaporative heat loss were not different for the F and NF trials during either L or H. Although rates of heat storage were lower overall for F (140.3 ± 37.0 $W \cdot m^{-2}$) compared with NF (146.5 ± 41.4 $W \cdot m^{-2}$). these differences were not significant ($p < 0.06$). Total heat storage expressed relative to body mass was significantly greater for L/F compared with the other trials.

4. Discussion

To our knowledge this is the first study that has addressed the impact of fluid replacement on heat storage during uncompensable heat stress. Our initial

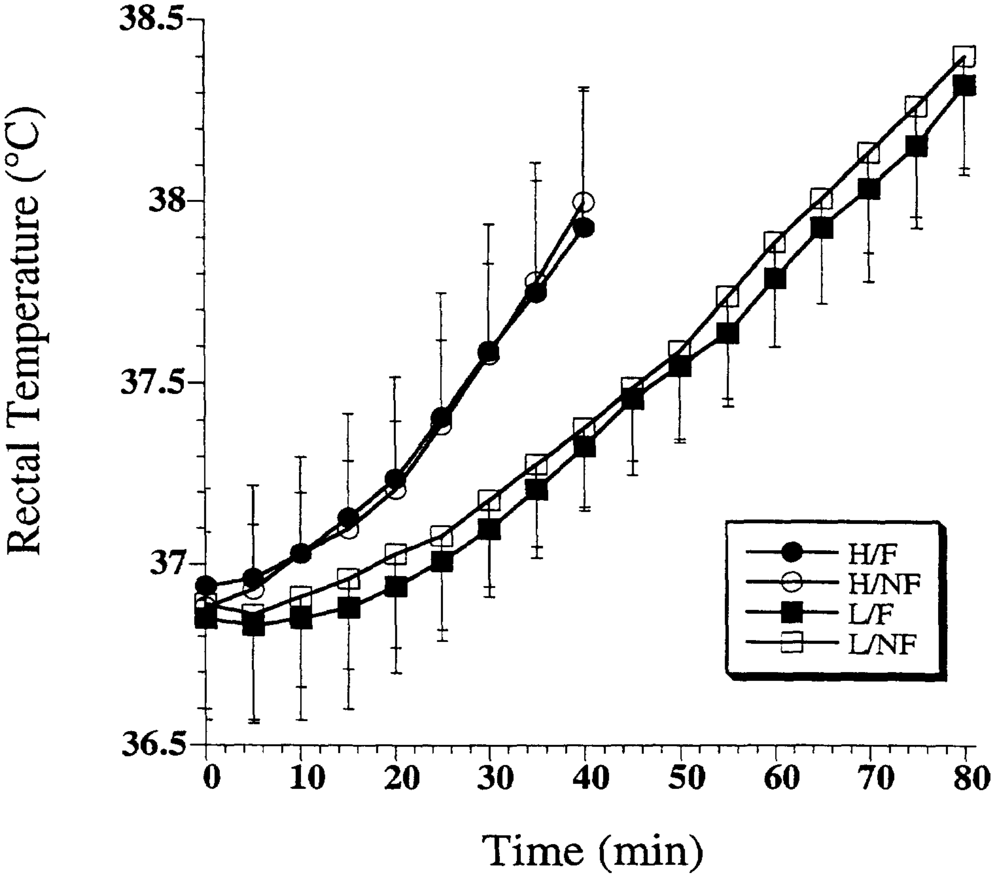

Figure 2 Changes in rectal temperature during the light (L) and heavy (H) exercise with (F) or without (NF) fluid replacement at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble. Values are mean ± SD for $n=8$ except during L from 55 to 80 min, where $n=7$.

hypothesis proposed that fluid replacement would promote greater evaporative heat loss through the clothing ensemble during longer heat exposures and thereby decrease the rate of heat storage. This hypothesis is not supported by the present findings. The present analyses have revealed that fluid replacement has only a marginal influence on the rate of heat storage during uncompensable heat stress. Further, any differences in rates of heat storage that were observed could not account for the inconsistent effect of fluid replacement on tolerance time when light and heavy exercise were compared. In addition, the extended tolerance times during light exercise were attributed to a greater heat storage capacity per unit of mass rather than due to a lowered rate of heat storage.

Studies to date have conclusively shown the benefits of fluid replacement during exercise in compensable heat stress conditions, with lower heart rates and core temperatures being observed compared with trials that restrict fluid intake (Costill *et al.* 1970, Candas *et al.* 1986, Hamilton *et al.* 1991, Montain and Coyle 1992). González-Alonso *et al.* (1997) were able to identify separate and interactive effects of

Table 1. Sources of heat gain or loss during the light and heavy exercise at 40°C with or without fluid replacement while wearing nuclear, biological and chemical protective clothing. Values are means (SD) for $n = 7$ in $\mathrm{W\ m^{-2}}$

	Light exercise		Heavy exercise	
	Fluid	No fluid	Fluid	No fluid
*Metabolic rate (M)	167.5 (8.9)	171.9 (12.3)	261.6 (12.6)	268.7 (5.7)
*External power (W)	0	0	22.4 (0.7)	22.4 (0.7)
Radiative and convective heat gain (R + C)	11.9 (0.9)	12.1 (1.4)	11.8 (1.6)	12.2 (1.0)
*Respiratory convective heat gain (C_{resp})	1.4 (0.1)	1.4 (0.1)	2.2 (0.1)	2.3 (0.1)
*Respiratory evaporative heat loss ($\dot{E}_{resp}$)	8.7 (0.3)	9.2 (0.7)	14.1 (0.7)	14.4 (0.3)
Skin evaporative heat loss (E_{sk})	62.7 (11.7)	65.2 (13.2)	63.7 (4.3)	64.2 (13.7)
*Heat loss to the ingested water‡ (K_{H_2O})	2.2 (0.2)	0	2.9 (0.5)	0
*Rate of heat storage (S)	108.2 (20.6)	111.0 (22.6)	172.5 (11.5)	182.1 (15.8)
Heat storage (S in $\mathrm{kJ \cdot kg^{-1}}$)	18.5† (4.0)	16.3 (4.8)	16.6 (3.0)	16.7 (4.0)

*Significant difference between light and heave exercise.
‡Significant difference between fluid and no fluid.
†Significantly different from the other trials.

core temperature and body fluid balance on the cardiovascular changes observed during exercise in the heat with no fluid replacement. Their findings revealed that both hyperthermia and dehydration lowered stroke volume by ~8% and increased heart rate sufficiently to prevent a decline in cardiac output. However, when dehydration and hyperthermia occurred together, the changes in stroke volume were greater than the separate effects and cardiac output decreased (González-Alonso *et al.* 1997). In the present study, the core temperature response was similar with or without fluid replacement. Thus, the lower heart rates that were observed after 30–40 min at both metabolic rates most likely reflect the influence of fluid replacement on blood volume. It is interesting that at both metabolic rates, significant reductions in heart rate were observed following sufficient time for the absorption of ~500 ml of fluid.

According to Montain and Coyle (1992), during compensable heat stress fluid replacement augments skin blood flow and, therefore, heat transfer from the core to the periphery. The lower rates of heat storage with fluid replacement, therefore, were explained by a greater dry heat exchange to the environment since whole body sweat rates were not affected by fluid ingestion (Montain and Coyle 1992). However, under the uncompensable heat stress conditions studied in the present investigation, there was no evidence that fluid replacement altered any component of the heat balance equation other than by providing an increased heat capacity due to the volume and temperature of the ingested fluid (table 1). Indeed, since the environmental temperature exceeded skin temperature (data not shown), dry heat transfer represented a source of heat gain and thus this mechanism could not account for a beneficial effect of fluid replacement on temperature regulation in the present heat stress environment.

Sweat rates were unaffected by the presence or absence of fluid and thus evaporative heat loss was controlled by the water vapour permeability of the clothing layers rather than by any change in the vapour pressure at the skin surface. Similar rates of evaporative heat loss have been reported in our previous studies (McLellan *et al.* 1999) that have estimated skin vapour pressures using the method described by Cain and McLellan (1998) under identical environmental conditions.

Although initial and final core temperatures were not affected by fluid replacement or metabolic rate, the overall increase in T_{re} from the beginning to the end of the heat exposure was significantly greater during the L/F condition. Consistent with this finding was the greater capacity during L/F to store heat, expressed per unit of mass, when this value was calculated from the partitional calorimetric estimates of rates of heat storage. Thus, one is left to try to explain why fluid replacement allowed a greater increase in body heat content only during heat exposures that lasted for >60 min. One explanation could focus on the greater absolute volume of fluid ingested during L and the possible influence this volume might have on maintaining cardiovascular stability with longer heat exposures. However, given that stroke volume and cardiac output data are not consistent with this theory (Cheung and McLellan 1998a) and that heart rates were reduced with fluid replacement during both L and H, it is unlikely that the additional 300 ml of fluid provided during L could account for this differential effect of fluid replacement during light and heavy exercise. Also, the additional heat storage capacity of the 300 ml of water cannot account for the $\sim 2 \text{ kJ} \cdot \text{kg}^{-1}$ increase in heat content.

Another possibility consistent with previous findings with heat acclimation (Aoyagi *et al.* 1994 and 1995), is that other factors, perhaps psychological, associated with the discomfort of heavy exercise limit tolerance time when protective clothing is worn (Aoyagi *et al.* 1998). Thus, physiological manipulations such as heat acclimation and endurance training (Aoyagi *et al.* 1994), fluid replacement (Cheung and McLellan 1998a) or water hyperhydration (Latzka *et al.* 1998) are ineffective means of increasing tolerance during the uncompensable heat stress associated with performing heavy exercise while wearing NBC protective clothing. Conversely, at lower metabolic rates, where perhaps the discomfort of higher sweat rates is reduced (Aoyagi *et al.* 1998), heat acclimation (Aoyagi *et al.* 1995), aerobic fitness (Cheung and McLellan 1998b) and fluid replacement (Cheung and McLellan 1998a) have been shown to benefit tolerance time when the NBC clothing ensemble is worn.

Of interest within the context of the present analyses is the possible influence of greater volumes of ingested fluid on tolerance time during light exercise. Certainly manipulations of the volume and temperature of the ingested fluid could provide an additional avenue for heat loss from the body. For example, the ingestion of 2 l of 10°C water to maintain an euhydrated state during the light exercise condition could enable an additional 240 kJ of heat loss with a body temperature close to 39°C, i.e. from equation (7), $240 \text{ kJ} = (4.18 \text{ kJ} \enspace \text{kg}^{-1} \cdot {}^{\circ}\text{C}^{-1}) \enspace (2 \text{ kg}) \cdot (39 - 10^{\circ}\text{C})$. This additional avenue for heat loss could slow the rate of total body heat storage by $\sim 20 \text{ W} \cdot \text{m}^{-2}$ during 100 min of heat stress. In theory, slowing the rate of heat storage from 110 to 90 $\text{W} \enspace \text{m}^{-2}$ would extend tolerance times to ~ 130 min if the heat storage capacity of $18.5 \text{ kJ} \enspace \text{kg}^{-1}$ (table 1) were attainable under these conditions, i.e. $130 \text{ min} = (18\ 5 \text{ kJ} \enspace \text{kg}^{-1} \cdot 75 \text{ kg}) \cdot (90 \text{ W} \enspace \text{m}^{2} \enspace 1.94 \text{ m}^{2} \cdot 60 \text{ s} \cdot \text{min}^{-1} \enspace 1000^{-1})^{-1}$, as determined from equation (8). It should be remembered that in the present study, however, fluid replacement conferred an advantage for heat storage that had little, if any, to do with the added heat storage capacity of the ingested fluid. Thus, it is conceivable that tolerance times would actually exceed this value of 130 min. The mechanism(s) responsible for this additional effect of fluid replacement was not evident from the partititional calorimetric analyses of heat storage.

5. Conclusion

In summary, the present study has revealed that fluid replacement does not alter the rate of heat storage during light and heavy exercise while wearing NBC protective clothing in the heat. Fluid replacement does allow, however, a greater heat storage capacity expressed per unit of mass when the rate of heat production is low. The reason for this improved heat storage capacity has yet to be elucidated.

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