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TITLE

EFFECTS OF 6 VERSUS 12 DAYS OF HEAT ACCLIMATION ON HEAT TOLERANCE IN LIGHTLY EXERCISING MEN WEARING PROTECTIVE CLOTHING

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ORIGINAL ARTICLE

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Effects of 6 versus 12 days of heat acclimation on heat tolerance in lightly exercising men wearing protective clothing

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Abstract This study investigated the influence of 6 versus 12 days of heat acclimation on the tolerance of low-intensity exercise in the heat while wearing protective clothing. Sixteen young men were acclimated by treadmill walking (50% of each subject's maximal aerobic power for 60 min·day^{-1}) in a climatic chamber [40 °C dry bulb (db), 30% relative humidity] for either 6 consecutive days or two 6-day periods, separated by a 1-day rest. Before and after heat acclimation, the subjects performed a heat-exercise test (1.34 m·s^{-1}, 0% grade; 40 °C db, 30% relative humidity), either under control conditions [wearing normal light combat clothing (continuous exercise; $n = 5$)] or when wearing protective clothing resistant against nuclear, biological, and chemical (NBC) agents (repeated bouts of 15-min walk + 15-min rest; $n = 8$). Criteria for halting the test exercise were a rectal temperature (T_{re}) of 39.3 °C, a heart rate (f_c) ≥ 95% of the subject's observed maximum, unwillingness of the subject to continue, or the elapse of 150 min. Heat acclimation decreased overall test values of T_{re}, f_c, and mean skin temperature for both control and protective clothing conditions. When wearing normal combat clothing, acclimation responses were about twice as large after 12 than after 6 days, but the response was not increased by longer acclimation when wearing NBC protective clothing. Both 6 and 12 days of acclimation increased tolerance times in NBC protective clothing by about 15 min [from 97 (4) to 112 (6) min and from 108 (10) to 120 (10) min for 6 and 12 days, respectively]. We conclude that the physiological strain and limitation of heat-exercise tolerance imposed by wearing NBC protective clothing are not reduced if heat acclimation is prolonged from 6 to 12 days.

Key words Environmental physiology · Rectal temperature · Skin temperature · Heart rate · Sweat evaporation

Introduction

Human tolerance time in protective clothing appears to be a negative hyperbolic function of both work rate (McLellan et al. 1993) and environmental heat stress (Shvartz and Benor 1971), but the influence of a worsening of ambient conditions upon tolerance time is rapidly reduced as the subject's metabolic rate is increased by exercise (McLellan 1993). Indeed, Tilley et al. (1987) found that the increase in rectal temperature (T_{re}, a critical determinant of tolerance time) was unrelated to the Wet Bulb Globe Temperature Index when subjects wearing full protective equipment exercised at a moderate to heavy rate. In these studies, the expected correlation between the severity of environmental conditions and the physiological response or tolerance time was only observed if fully protected subjects exercised at lower intensities that extended their tolerance time beyond 60 min.

Our previous study (Aoyagi et al. 1994) suggested that a 6-day period of heat acclimation [50% of the individual's maximal aerobic power ($\dot{V}O_{2max}$) for 60 min·day^{-1} at 40 °C dry bulb (db), 30% relative humidity (r.h.)] did not enhance tolerance of work in a hot, dry environment when the subject was wearing heavy clothing that protected against nuclear,

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biological, and chemical (NBC) agents. Evaluations were made at a moderate metabolic rate (42–51% $\dot{V}O_{2max}$), under environmental conditions that allowed approximately 50 min of exercise. Heat acclimation induced an increase in sweat secretion that offset any circulatory gains from an expansion of plasma volume (PV) and it increased thermal discomfort without augmenting body cooling. In such situations, a decrease in resting T_{re} with heat acclimation (which might otherwise increase tolerance time by allowing a greater total heat storage) had no impact on the heat-exercise tolerance.

In an attempt to find a regimen that would increase the heat tolerance of personnel wearing NBC protective clothing, we reduced the intensity of exercise and extended the period of acclimation from 6 to 12 days. We anticipated that benefits might be derived from heat acclimation if the intensity of exercise was low enough to allow a prolonged exposure to the hot environment, with permeation of the acclimation-induced increase of sweat secretion through the protective clothing. Although heat acclimation is a relatively rapid process, it is also possible that our previously adopted 6 days of heat acclimation was insufficient to maximize beneficial responses. An improved control of cardiovascular function, including expanded PV and reduced heart rate (f_c), occurs in 3–6 days, but thermoregulatory adaptations such as increased sweat rate and decreased skin blood flow require up to 14 days before responses are maximized (Armstrong and Maresh 1991).

Therefore, the purpose of this study was to compare the influence of 6 and 12 days of heat acclimation on the performance of light physical work in a hot environment. Evaluations were made when subjects were wearing each of two occupational clothing assemblies: normal combat clothing and NBC protective clothing.

Methods

Subjects

Sixteen male volunteers (military personnel and university students) followed a protocol approved by the Human Ethics Committees of the University of Toronto and the Defence and Civil Institute of Environmental Medicine. A health history and physical examination ensured that there were no medical contraindications to their participation. They were then informed of potential risks and discomforts, and signed a statement of informed consent. Subject characteristics are presented in Table 1.

Preliminary evaluation

Body surface area (A_D) was estimated from body mass and height, using the equation of Du Bois and Du Bois (1916). Body fat was calculated from density (D_b), using the equation of Brožek et al. (1963). D_b was estimated from the logarithm of the sum of skinfold thicknesses at four sites (biceps, triceps, subscapular, and suprailiac), using the equation of Durnin and Womersley (1974) for subjects aged 17–72 years.

$\dot{V}O_{2max}$ was determined on a motor-driven treadmill using an incremental protocol (Aoyagi et al. 1994), with measurement of oxygen consumption ($\dot{V}O_2$) by an open-circuit technique. $\dot{V}O_{2max}$ was defined as the highest observed 30-s $\dot{V}O_2$, based on attainment of a plateau, failure of $\dot{V}O_2$ to increase by 2 ml · kg^{-1} · min^{-1} and/or the attainment of a respiratory exchange ratio >1.00. f_c was monitored throughout the test, using a transmitter/receiver telemetry unit (Sport Tester, Polar Electro PE3000). The highest 5-s average was considered as the individual's maximal f_c ($f_{c,max}$).

Experimental design

All trials were conducted during the months of November through March, in order to reduce the likelihood that subjects were initially heat-acclimated. Outdoor temperatures in Toronto during these months average <5 °C.

After 60 min of familiarization [level treadmill walking (1.34 m · s^{-1}) in a controlled environment (40 °C db, 30% r.h.)], subjects

Table 1 Anthropometric, cardiovascular, and circulatory characteristics of subjects before and after 6 days (HA_6) or 12 days (HA_{12}) of heat acclimation. Values are mean (SEM); $n = 8$ for both the HA_6 and HA_{12} groups (A_D body surface area, $f_{c,max}$ maximal heart rate, $\dot{V}O_{2max}$ maximal oxygen intake, *Hct* hematocrit, ΔPV change in plasma volume)

Group	Condition	Age (years)	Height (m)	Body mass (kg)	A_D (m^2)	Body fat (%)
HA_6	Pre-acclimation	29 (2)	1.79 (0.02)	82.6 (3.3)	2.01 (0.04)	18.1 (1.5)
	Post-acclimation	–	–	82.6 (3.2)	2.01 (0.04)	–
HA_{12}	Pre-acclimation	28 (1)	1.78 (0.01)	83.8 (2.6)	2.02 (0.02)	19.8 (1.5)
	Post acclimation	–	–	83.0 (2.4)	2.01 (0.02)	–

Group	Condition	$f_{c,max}$ (b · min^{-1})	$\dot{V}O_{2max}$		Hct (%)	ΔPV (%)
			(l · min^{-1})	(ml · kg^{-1} · min^{-1})		
HA_6	Pre-acclimation	187 (2)	4.08 (0.20)	49.5 (2.2)	46.4 (1.2)	–
	Post-acclimation	186 (2)	3.95 (0.15)	48.1 (1.8)	44.9 (1.2)	6.7 (3.7)
HA_{12}	Pre-acclimation	192 (3)	4.06 (0.17)	48.6 (2.1)	45.3 (0.9)	–
	Post-acclimation	187 (3)	3.90 (0.11)	47.2 (1.7)	45.1 (0.5)	0.8 (3.0)

were assigned to one of two groups; one was heat-acclimated for 6 days (HA_6; $n = 8$) and the other for 12 days (HA_{12}; $n = 8$). Physiological responses to a standard heat-exercise stress were measured twice before and twice no longer than 4 days after acclimation, with a minimum inter-test interval of 2 days. Subjects wore either normal combat clothing or NBC protective clothing in randomly assigned order. All experiments were performed at the same time of day (8.00 a.m.–12.00 noon) to avoid circadian variations of body temperature response (Stephenson and Kolka 1988). There was little variation in pre-test hematocrit (Hct) values, showing that the 2-day inter-test interval was sufficient to restore normal hydration.

Since the issue of primary interest was the development of a regimen that would improve the heat-exercise tolerance of subjects wearing NBC protective clothing, the normal combat clothing experiments served as a control. To provide a roughly equal thermal challenge when wearing the two clothing ensembles, a continuous work schedule was adopted when wearing normal combat clothing and an intermittent work/rest schedule when wearing the NBC protective clothing.

Heat acclimation

Subjects wore jogging shorts and a T-shirt, and were allowed to drink water ad libitum. Heat acclimation was achieved by a daily 1-h bout of treadmill walking ($1.34\,m \cdot s^{-1}$, 3–12% grade) in a hot environment (40 °C db, 30% r.h.). The exposure was repeated on 6 consecutive days for the HA_6 group, and on 12 days (two 6-day periods, separated by a 1-day rest period) for the HA_{12} group. The treadmill elevation was adjusted to induce 45–55% of each subject's $\dot{V}O_{2max}$ during exposures. In 5 of the 16 subjects, it was necessary to increase the slope over the course of acclimation in order to maintain $\dot{V}O_2$ within the prescribed limits.

Protective ensembles

The normal combat clothing ensemble was equivalent to usual indoor occupational wear. It comprised a T-shirt, briefs or shorts, socks, combat shirt and trousers, and leather boots [total mass (including a contribution of about 0.5 kg from the telemetry unit, skin thermistors, and harness) 4.4 kg; insulation 1.4 clo].

The NBC ensemble was the equivalent of the relatively impermeable garments worn in many hazardous industries. Normal combat clothing was supplemented by an NBC overgarment, rubber gloves and overboots, and a respirator (total mass 8.7 kg; insulation 2.4 clo). The cuffs of the overgarment were taped snugly and the hood was drawn tight, as in normal field use of the clothing. In essence, this ensemble offers close to 100% protection of the airways, but in order to allow some sweat evaporation there is limited mass penetration of charcoal-filtered air and water vapor through the fabric.

Heat-exercise test

Immediately after donning either type of clothing, the subjects moved into the climatic chamber and began the heat-exercise test. The chamber was maintained at 40 (0.5) °C db and 30 (1)% r.h., and subjects were not allowed to drink water. They exercised on a treadmill at a level walking speed of $1.34\,m \cdot s^{-1}$, continuously while wearing normal combat clothing and intermittently (15 min of exercise followed by 15 min of sitting rest) while wearing the NBC protective clothing. These schedules demanded an average of approximately 32% of the subject's $\dot{V}O_{2max}$ while wearing normal combat clothing and 23% while wearing NBC protective clothing. Only five of the eight subjects from each group performed continuous walking in normal combat clothing. The other three subjects performed intermittent exercise during which the degree of changes in the measured variables was too small (for example, an increase of $T_{re} < 1.0$ °C in 150 min) to show or differentiate the influence of 6 and 12 days of heat acclimation; their data have thus been excluded from analyses for the normal combat clothing trials.

Sessions lasted for a maximum of 150 min, criteria for earlier halting of a test being (1) a T_{re} of 39.3 °C, (2) $f_c \geq 95\%$ of the subject's $f_{c,max}$, maintained for 3 min, or (3) unwillingness of the subject to continue due to dizziness, nausea, or other reasons.

Temperature measurement

A computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer) processed data from T_{re} and skin temperature (T_{sk}) sensors at 1-min intervals. T_{re} was measured using a flexible vinyl-covered probe (Pharmaseal APC 400 Series) inserted approximately 12 cm beyond the anal sphincter. Local T_{sk} was measured at 12 locations, using uncovered thermistors (Yellow Springs Instruments thermistor bead 44004). The mean T_{sk} ($\bar{T}_{sk}$) was calculated by weighting the 12 readings, according to the equation of Vallerand et al. (1989).

f_c measurement

f_c was monitored utilizing a telemetry unit, clipped to an elasticized electrode belt that was fitted around the chest. The receiver, taped to the outside of the clothing, provided a continuous display of f_c, and averaged values were recorded every 5 min.

Gas exchange analysis

Open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), $\dot{V}O_2$, and carbon dioxide output ($\dot{V}CO_2$) during the last 120 s of every 15 min. An adaptor attached to a low-resistance Hans-Rudolf respiratory valve (for normal combat clothing) or a respirator (for NBC protective clothing) directed expired gases into a 5-l mixing box and then through a ventilation module (Alpha Technologies VMM 110 Series) for the determination of $\dot{V}_E$. A sampling line passed an aliquot of dried expired gases to an O_2 and CO_2 analyzer (Ametek Instruments S-3A and CD-3A, respectively). The ventilation meter was calibrated with a 3-l syringe, and the gas analyzers were calibrated using precision-analyzed cylinder mixtures. After analogue-to-digital conversion (Hewlett-Packard 59313A A/D converter), $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$ and respiratory gas exchange ratio (R) were calculated and printed on-line every 30 s for $\dot{V}O_{2max}$ and every 60 s for submaximol effort, using a microcomputer (Hewlett-Packard 9825A). Metabolic heat production was determined by the equation of Gagge and Nishi (1983), using measured $\dot{V}O_2$ and R values.

Sweat measurement

An electronic scale (Electroscale, model 921) sensitive to the nearest 10 g was used to weigh subjects nude (but fitted with the T_{re} thermistor and connecting cable) and when dressed (also fitted with the rectal probe) before and immediately after the heat-exercise tests. Sweat lost by dripping onto the floor was negligible under the conditions of this experiment. The loss from insensible perspiration was assumed to be a uniform $20\,g \cdot h^{-1}$ (McArdle et al. 1991). Weight losses due to respiratory evaporation (m_e) and CO_2-O_2 exchange (m_r) were estimated using the equations of Mitchell et al. (1972) and Snellen (1966), respectively. Values for m_e and m_r were subtracted from the nude and dressed weight losses to estimate sweat production (SP, the sum of sweat evaporated plus sweat still soaking the clothing) and the weight loss due to sweat evaporation (SE) alone, respectively. Evaporative efficiency was calculated as $(SE \cdot SP^{-1}) \cdot 100$.

Blood analysis

Finger-prick blood samples were obtained with subjects standing before beginning each of the heat-exercise tests, and on days 1 and 6 or 12 of heat acclimation. The Hct was measured in triplicate, using a microhematocrit centrifuge (Autocrit III model 575). Assuming no change of red cell volume with exercise or heat (Aoyagi et al. 1994), the acclimation-related changes in PV were calculated from Hct values, using the equation of Van Beaumont (1972).

Statistical analysis

Data are presented as mean values and standard errors of the mean (SEM). Paired or non-paired *t*-tests were used as appropriate to analyze or compare the influence of 6- and 12-day acclimation on anthropometric and physiological variables, respectively. Multifactor [subject, acclimation (and group)] repeated measures analysis of variance was used to assess changes in cardiorespiratory and thermoregulatory variables for each clothing ensemble. When a significant *F* value was obtained for the time × acclimation (× group) interaction (after adjustment for repeated measures by the Greenhouse-Geisser method), the post hoc Newman-Keuls multiple comparisons procedure was used to locate significant differences. All statistical contrasts were accepted at the 0.05 level of significance.

Results

Subject characteristics

Appropriate *t*-tests showed no significant changes in anthropometric or physiological variables over the 6- or 12-day periods of heat acclimation (Table 1).

Gas exchange

Heat acclimation significantly decreased the overall exercise $\dot{V}CO_2$ in the HA_6 group and *R* in the HA_{12} group when wearing normal combat clothing (Table 2). When wearing NBC protective clothing, individual values of $\dot{V}_E$ were reduced at 15, 75, and 90 min and $\dot{V}CO_2$ at 15 min in the HA_{12} group, and the magnitudes of the acclimation-induced decrements of $\dot{V}_E$ at 15 and 75 min were significantly greater in the HA_{12} than in the HA_6 group.

Sweat

When subjects undertook the heat-exercise stress challenge in normal combat clothing, neither the HA_6 nor HA_{12} group showed any significant change in sweat production or evaporative efficiency after heat acclimation (Table 3). When wearing NBC protective clothing, both 6 and 12 days of heat acclimation significantly increased sweat production (+13%), although sweat evaporation did not increase. Moreover, the duration of acclimation did not influence the sweat data significantly.

Rectal temperature

Heat acclimation induced a significant 0.1–0.6 °C reduction of resting and overall heat-exercise stress T_{re}, irrespective of the duration of acclimation that was undergone or the type of clothing that was worn (Fig. 1). Further, the rate of increase in T_{re} during all trials tended to be slightly ($0.1–0.2 °C \cdot h^{-1}$) slower after acclimation. When the HA_{12} group wore NBC

Table 2 Gas exchange data of subjects wearing normal combat or NBC protective clothing before and after HA_6 or HA_{12}. Values are means pooled over an entire session (SEM). In both the HA_6 and HA_{12} groups, $n = 5$ for the normal combat clothing trial (continuous exercise) and $n = 8$ for the NBC protective clothing trial (intermittent exercise) ($\dot{V}_E$ expired minute ventilation, $\dot{V}O_2$ oxygen consumption, $\dot{V}CO_2$ carbon dioxide production, *R* respiratory gas exchange ratio, *M* metabolic heat production)

Clothing	Group	Condition	$\dot{V}_E$ ($l \cdot min^{-1}$)	$\dot{V}O_2$ ($l \cdot min^{-1}$)	$\dot{V}CO_2$ ($l \cdot min^{-1}$)	*R*	*M* ($kJ \cdot m^{-2} \cdot h^{-1}$)
Normal	HA_6	Pre-acclimation	27.4 (1.9)	1.31 (0.06)	1.12 (0.06)	0.86 (0.02)	781 (32)
		Post-acclimation	27.2 (1.6)	1.27 (0.06)	1.07 (0.04)*	0.84 (0.02)	753 (23)
	HA_{12}	Pre-acclimation	29.7 (2.8)	1.37 (0.11)	1.18 (0.09)	0.87 (0.02)	829 (57)
		Post-acclimation	25.6 (1.2)	1.23 (0.07)	1.01 (0.05)	0.83 (0.02)*	739 (33)
Protective	HA_6	Pre-acclimation	21.6 (1.0)	0.95 (0.06)	0.88 (0.05)	0.96 (0.02)	589 (28)
		Post-acclimation	21.3 (0.8)	0.92 (0.04)	0.85 (0.04)	0.95 (0.01)	572 (17)
	HA_{12}	Pre-acclimation	21.2 (1.3)	0.92 (0.05)	0.84 (0.05)	0.93 (0.01)	569 (28)
		Post-acclimation	19.0 (1.0)**,***	0.88 (0.04)	0.78 (0.03)**	0.09 (0.02)	540 (20)

* Significant decrease in mean value pooled over an entire session following acclimation ($P < 0.05$)
** Significant decrease in mean value during a given phase of exercise or rest (change in response pattern) following acclimation ($P < 0.05$)
*** Significantly greater rate of decrease in mean value during a given phase of exercise (rate of change in response pattern) following a longer period of acclimation ($P < 0.05$)

Table 3 Sweat data of subjects wearing normal combat or NBC protective clothing before and after HA_6 or HA_{12}

Clothing	Group	Condition	Sweat production ($kg \cdot h^{-1}$)	Sweat evaporation ($kg \cdot h^{-1}$)	Evaporative efficiency (%)
Normal	HA_6	Pre-acclimation	0.84 (0.06)	0.64 (0.02)	77.5 (4.5)
		Post-acclimation	0.89 (0.08)	0.66 (0.02)	75.7 (4.4)
	HA_{12}	Pre-acclimation	0.97 (0.10)	0.67 (0.04)	69.5 (3.1)
		Post-acclimation	0.90 (0.10)	0.64 (0.04)	71.7 (3.5)
Protective	HA_6	Pre-acclimation	0.94 (0.12)	0.27 (0.02)	31.7 (3.7)
		Post-acclimation	1.06 (0.12)*	0.29 (0.02)	29.0 (2.5)
	HA_{12}	Pre-acclimation	1.00 (0.10)	0.28 (0.02)	30.0 (2.9)
		Post-acclimation	1.13 (0.10)*	0.30 (0.02)	27.2 (1.6)

* Significant increase in sweat production following acclimation ($P < 0.05$)

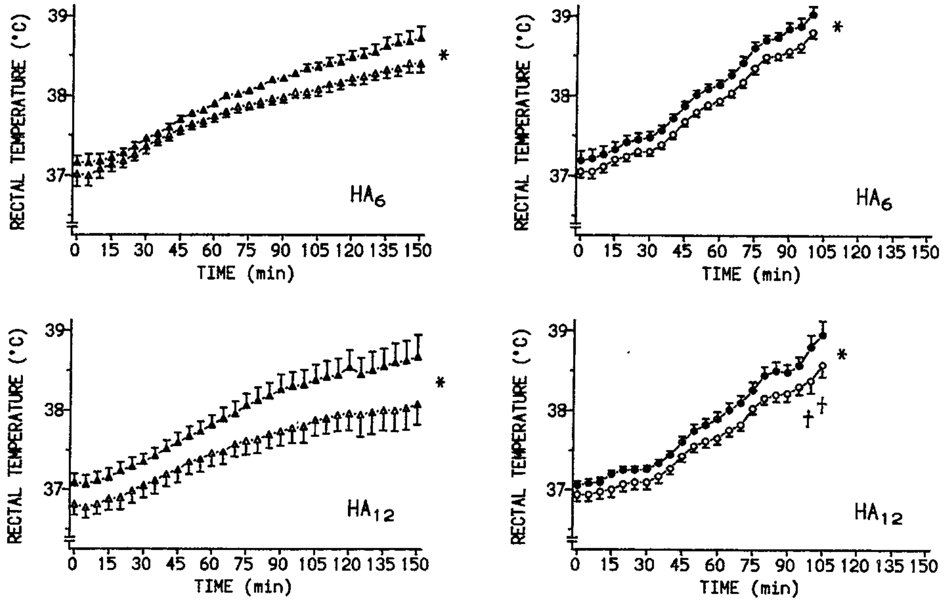

Fig. 1 Changes in rectal temperature during the heat-exercise test for subjects wearing normal combat clothing (*triangles*) or NBC protective clothing (*circles*) before (*filled*) and after (*unfilled*) 6 days (HA_6) or 12 days (HA_{12}) of heat acclimation. Values are mean (SEM). In the HA_6 group, $n = 5$ for the normal combat clothing trial (continuous exercise) and $n = 8$ until 75 min; $n = 7$ at 80 min; $n = 6$ at 85 min; $n = 5$ at 90 min; and $n = 4$ at 95 and 100 min for the NBC protective clothing trial (intermittent exercise). In the HA_{12} group, $n = 5$ until 120 min and $n = 4$ from 125 until 150 min for the normal combat clothing trial (continuous exercise) and $n = 8$ until 65 min; $n = 7$ from 70 until 85 min; $n = 6$ at 90 and 95 min; and $n = 4$ at 100 and 105 min for the NBC protective clothing trial (intermittent exercise). * Significant difference in mean value pooled over an entire session between pre- and post-acclimation ($P < 0.05$) and † significant difference in the rate of increase in mean value between pre- and post acclimation ($P < 0.05$)

protective clothing, this change was statistically significant at 100 and 105 min.

Mean skin temperature

With one exception (the HA_6 group in NBC protective clothing), the average $\bar{T}_{sk}$ pooled over the course of a given heat-exercise stress challenge decreased significantly (by 0.2–0.4°C) after heat acclimation (Fig. 2). During the NBC protective clothing trial, a trend to a further 0.2 °C reduction in $\bar{T}_{sk}$ with 12 versus 6 days of acclimation was not statistically significant ($P = 0.07$).

Heart rate

Heat acclimation significantly reduced the resting and overall heat-exercise stress f_c by 5–26 $beats \cdot min^{-1}$, irrespective of the duration of acclimation that was undergone or the type of clothing that was worn (Fig. 3). When wearing normal combat clothing, the average decrease of f_c for the heat-exercise stress was

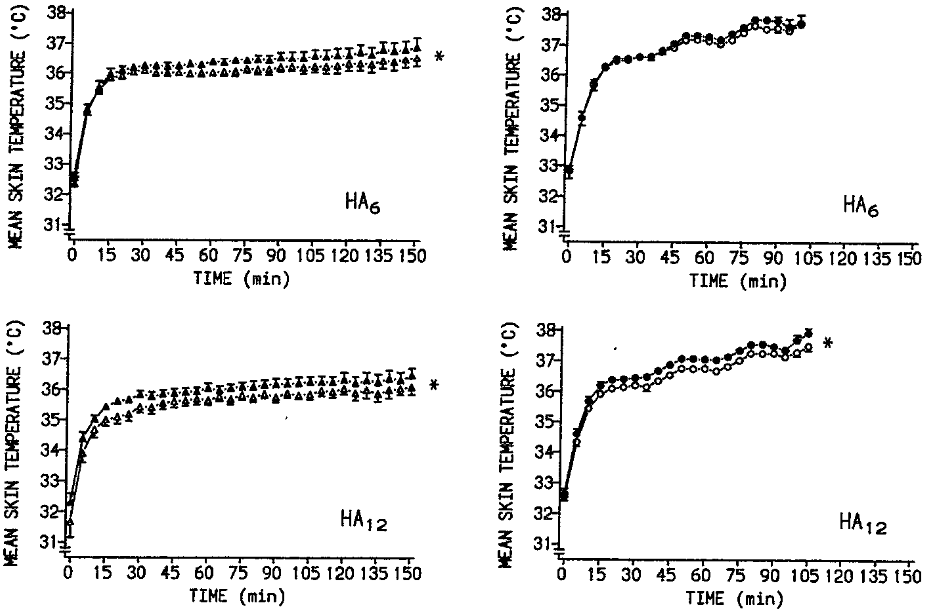

Fig. 2 Changes in mean skin temperature during the heat-exercise tests. * Significant difference in mean value pooled over an entire session between pre- and post-acclimation ($P < 0.05$)

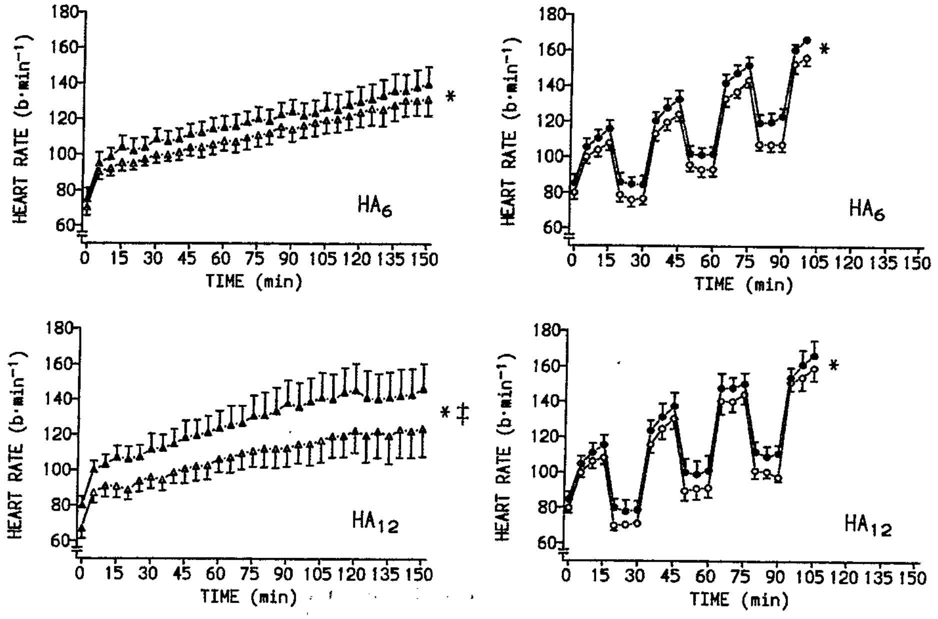

Fig. 3 Changes in heart rate during the heat-exercise tests. ‡ Significantly greater rate of decrease in mean value pooled over an entire session following a longer period of acclimation ($P < 0.05$)

significantly greater for 12 days of acclimation (about -19 beats·min^{-1}) than for 6 days (about -8 beats·min^{-1}). On the other hand, when f_c data for NBC protective clothing were pooled over an entire session, the HA$_6$ and HA$_{12}$ groups showed a similar acclimation-induced reduction of about 8 beats·min^{-1}.

Tolerance time

The test protocol in normal combat clothing did not allow an assessment of heat-exercise tolerance time, since all except one subject in the HA$_{12}$ group completed the 150-min test (Table 4). On the other hand, when wearing NBC protective clothing, heat acclimation significantly increased the tolerance time, by 15 min for the HA$_6$ group and by 12 min for the HA$_{12}$ group (difference between HA$_6$ and HA$_{12}$ not significant).

Discussion

In contrast with earlier studies at high work rates (Aoyagi et al. 1994), in this study heat acclimation

Table 4 Heat-exercise tolerance time and reasons for test termination of subjects wearing normal combat or NBC protective clothing before and after HA_6 or HA_{12}. Range of observations is shown in square brackets. Figures for *reason for test termination* are the number of subjects [T_{re} rectal temperature (39.3 °C), f_c heart rate ($\geq 95\%$ $f_{c,max}$ for 3 min), *SV* subject's volition, *TL* time limit (150 min)]

Clothing	Group	Condition	Heat-exercise tolerance time (min)	Reason for test termination			
				T_{re}	f_c	SV	TL
Normal	HA_6	Pre-acclimation	150 (0)	0	0	0	5
		Post-acclimation	150 (0)	0	0	0	5
	HA_{12}	Pre-acclimation	146 (4) [120–150]	0	0	1	4
		Post-acclimation	150 (0)	0	0	0	5
Protective	HA_6	Pre-acclimation	97 (4) [78–115]	3	0	5	0
		Post-acclimation	112 (6)* [84–130]	4	0	4	0
	HA_{12}	Pre-acclimation	108 (10) [65–140]	4	1	3	0
		Post-acclimation	120 (10)* [69–150]	1	1	4	2

*Significant increase in tolerance time following acclimation ($P < 0.05$)

offered some benefit to individuals in NBC protective clothing when they exercised in the heat at a low metabolic rate. This benefit was not increased by extending the acclimation period to 12 days when wearing NBC protective clothing (in contrast to the situation in normal combat clothing, where reductions in physiological strain were about twice as great after 12 than after 6 days of heat acclimation). The more limited benefit from heat acclimation when wearing NBC protective clothing is explained in part by the hotter and wetter microenvironment within this type of garment (Kakitsuba et al. 1988; Sullivan and Mekjavić 1992). On the whole, the present results are consistent with the classic finding that the major physiological adaptations occur in the first few days of heat acclimation (Armstrong and Maresh 1991).

Metabolic responses

In agreement with earlier investigations (Aoyagi et al. 1994; Sawka et al. 1983; Young et al. 1985), heat acclimation tended to induce a small decrease in the metabolic cost of the test exercise; this change was larger for the longer period of heat acclimation (−7% vs −3%) and for the clothing with a (normal) vapor permeability (−7% vs −4%). When wearing NBC protective clothing, the benefits of the 12-day acclimation period (for instance, lessening of hyperventilation) were also more marked during treadmill walking than during sitting rest. One primary physiological mechanism contributing to a decreased metabolism after heat acclimation is probably a Q_{10} effect due to parallel reductions in T_{re} and $\bar{T}_{sk}$ (and vice versa; see Aoyagi et al. 1994 and Young 1990 for details). There may also be more efficient walking in the final trial, due to both a learning of techniques of walking in NBC protective clothing and a lessening of fatigue in the final minutes of the trial.

Thermoregulatory responses

Acclimation or acclimatization to heat typically increases sweating capacity (Roberts et al. 1977; Wenger 1988; Wyndham 1967) : (1) sweating begins at a lower threshold of T_{re} and $\bar{T}_{sk}$, (2) the slope relating sweat rate to T_{re} is steeper, and/or (3) plateauing of the sweat rate/T_{re} relationship occurs at a higher sweat rate. However, acclimation-induced changes in sweating do not always lead to an increase in the total volume of sweat secreted in the face of a given environmental challenge (Aoyagi et al. 1994). The benefits of a decrease in the threshold T_{re} and $\bar{T}_{sk}$ may be offset by a reduction in the resting T_{re} and $\bar{T}_{sk}$. The advantage of an increase in sweat rate at a given T_{re} may also be negated by a slower increase of T_{re} in a given environment, secondary to reduced metabolic heat production and/or enhanced evaporative cooling. Finally, any benefit from a later plateauing of sweat rate may not be realized because the maximum duration of the trial is predetermined by the investigator. The interaction of these various factors could explain why our heat acclimation programs allowed an equivalent SP at a lower T_{re} and $\bar{T}_{sk}$ in normal combat clothing and an increased SP only when the subjects were wearing NBC protective clothing.

Heat exchange mechanisms

In trials where sweat secretion was increased by heat acclimation, there was a slight trend (statistically not significant) to a $0.02\ \mathrm{kg \cdot h^{-1}}$ increase in the volume of sweat evaporated. Assuming a latent heat of evaporation of $2.43\ \mathrm{kJ \cdot g^{-1}}$, an average specific heat $3.47\ \mathrm{kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$ for lean body tissues and a lean body mass of 67 kg, the rate of increase in T_{re} could have been some $0.2\ \mathrm{{}^{\circ}C \cdot h^{-1}}$ less after heat acclimation. Such a small decrease of metabolic heat production (by $17\text{–}29\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}}$) would have slowed heat storage by an additional $0.1\text{–}0.2\ \mathrm{{}^{\circ}C \cdot h^{-1}}$. Given little change in other components of the heat balance equation (Aoyagi et al. 1995), heat acclimation should have slowed the increase in T_{re} by 0.3–0.4 °C $\cdot$ h^{-1}, irrespective of the type of clothing that was worn.

The observed rate of increase in T_{re} was at most 0.2 °C $\cdot$ h^{-1} less after heat acclimation. A previous study under similar ambient conditions (Aoyagi et al. 1994) suggested that even when wearing normal combat clothing, evaporative cooling was severely restricted if the sweat evaporation rate exceeded 0.65 kg $\cdot$ h^{-1}. Thus, during the normal combat clothing trial, sweating may already have reached a useful ceiling prior to heat acclimation, and the decrease of metabolic rate could account for all of the slower increase in T_{re} that was seen after acclimation.

When wearing NBC protective clothing, it is less clear whether the slower increase in T_{re} after heat acclimation was due to a decreased metabolic rate, an increased sweat evaporation, or both. Under any given set of ambient conditions, the rate of sweat evaporation during the NBC protective clothing trial appeared to be largely independent of the rate of sweat secretion. Thus, any differences in sweat production between the present study (0.94–1.13 kg $\cdot$ h^{-1}) and our previous trial in the same environment (1.10–1.49 kg $\cdot$ h^{-1}; Aoyagi et al. 1994) did not yield corresponding differences in the rate of sweat evaporation (0.27–0.30 vs 0.29–0.33 kg $\cdot$ h^{-1}). Nevertheless, the $\bar{T}_{sk}$ at a given T_{re} (especially during the latter part of the NBC protective clothing trial) was 0.2–0.3°C lower in the present than in the previous study, irrespective of the acclimation status of the subjects. More sweat was evaporated, largely because the exposure was more prolonged, and the time for mass flow of vapor through the outer protective garment was increased. The larger total volume of sweat that was evaporated increased overall evaporative cooling, even though the rate of sweat evaporation in unit time was similar for the two patterns of exercise. However, $\bar{T}_{sk}$ is influenced not only by sweating, but also by skin blood flow. As in many military settings, our subjects were not allowed to drink water during the trial. This constraint undoubtedly reduced the degree of cutaneous vasodilation with rising T_{re} (Fortney et al. 1981; Johnson 1992; Nadel et al. 1980). Although the sweat rate was smaller (by about 20%) in the present study than in our earlier experiment, the cumulative dehydration was more severe, because the average trial continued for about twice as long. Therefore, the lower $\bar{T}_{sk}$ at a given T_{re} may have been due in part to a lower skin blood flow.

Circulatory responses

Heat acclimation is generally accompanied by a progressive, hormonally regulated expansion of PV (for example, an activation of the arginine-vasopressin and renin-angiotensin-aldosterone systems; Armstrong and Maresh 1991; Fellmann 1992; Francesconi 1988; Harrison 1985). In the present study, the resting PV tended to expand (+7%; $P = 0.11$) after 6 days of heat acclimation, but was unchanged after the 12-day period. The time course and amount of expansion depends upon initial fitness (Aoyagi et al. 1994; Fortney and Senay 1979) and the pattern of the acclimation program (Rowell 1974; Wenger 1988). If acclimation is continued for 2 weeks or more, the early increase of resting PV may be followed by a secondary return toward pre-acclimation levels (Wyndham et al. 1968). However, the secondary change does not impair the ability to exercise in the heat, because of an enhanced hemodilution response during exercise (Senay 1979; Senay et al. 1976). Wenger (1988) suggests that an increase in PV probably plays a more important role in reducing f_c and circulatory strain than the effects of an increase in venous tone and a decrease in T_{re} and $\bar{T}_{sk}$.

In our previous trial of NBC protective clothing (Aoyagi et al. 1994), any circulatory gains from the acclimation-induced 8% expansion of pre-test PV tended to be offset by a 13% increase in sweat rate. However, a similar increase in sweat rate occurred over the present study, raising the question why f_c decreased over the present series of NBC protective clothing experiments. Because exercise was of lower intensity but longer duration, the $\bar{T}_{sk}$ was lower at a given T_{re}, thus allowing a smaller skin blood flow to achieve a given core-to-skin heat transfer (Sawka and Wenger 1988). Furthermore, the lighter physical work reduced the blood flow demands of the exercising muscles. A reduction in peripheral pooling secondary to a lower skin and/or muscle blood flow would have improved cardiac filling and alleviated circulatory strain. In this regard, Fortney et al. (1983) indicated that pooling of blood in veins might be quantitatively more important than plasma water loss as a cause of reduced cardiac filling pressures in the heat.

Tolerance times

Regardless of acclimation status, all subjects except one completed the full 150 min in the normal combat clothing trials. However, we were able to show clear-cut reductions in T_{re}, $\bar{T}_{sk}$, and f_c after heat acclimation, allowing a comparison of the magnitude of physiological changes induced by the 6- and 12-day periods.

When the subjects were tested wearing NBC protective clothing, heat acclimation not only reduced the physiological strain, but also extended the heat-exercise tolerance time (by 15 min for the HA_6 group and by 12 min for the HA_{12} group). Although heat acclimation induced similar decrements of resting T_{re} (and the rate of increase in T_{re}) in our previous study (Aoyagi et al. 1994), acclimation did not increase tolerance time in that trial, where subjects were exercising at a higher metabolic rate (1.53–1.59 l $\cdot$ min^{-1}, 42–51% $\dot{V}O_{2max}$)

Table 5 Prediction of increase in tolerance time with reductions in T_{re}. ΔRest, change in resting T_{re} and ΔSlope, change in the rate of increase in T_{re}. Estimates are calculated as $(\Delta\text{Rest} + (\text{Time} \cdot 60^{-1}) \cdot \Delta\text{Slope}) \cdot \{[2.0 \cdot (\text{Time} \cdot 60^{-1})^{-1} - \Delta\text{Slope}] \cdot 60^{-1}\}^{-1}$

ΔRest (°C)	ΔSlope (°C·h^{-1})	Initial tolerance time (min)															
		30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
0.0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	−0.1	1	1	2	3	4	6	7	9	11	13	16	18	21	25	28	32
	−0.2	2	3	5	7	9	12	16	20	25	30	36	43	50	58	67	77
−0.1	0.0	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9
	−0.1	2	3	5	6	8	10	12	15	17	20	23	26	30	34	38	42
	−0.2	3	5	7	10	13	17	21	26	31	38	44	52	60	69	79	90
−0.2	0.0	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	−0.1	4	6	7	9	12	14	17	20	23	27	30	34	39	43	48	53
	−0.2	5	7	10	13	17	22	26	32	38	45	53	61	70	80	91	103

but for a shorter period (47–52 min). Why would heat acclimation increase the tolerance time in NBC protective clothing only if the individual was exercising at a low rate (0.88–0.95 l·min^{-1}, 23% $\dot{V}O_{2max}$) for a long time (97–120 min)?

As in the previous study (Aoyagi et al. 1994), a half of the subjects voluntarily terminated the NBC protective clothing trials in less than the prescribed time limit. Thermal discomfort resulting from a T_{re}-to-$\bar{T}_{sk}$ difference of <1 °C and a wetted skin area of $>40\%$ are known to shorten tolerance times (Goldman 1985, 1988). In the present study, although the sweat rate tended to be less than in our earlier trial, a longer test session allowed a larger proportion of secreted sweat to be evaporated. Thus, there was a less marked convergence of T_{re} and $\bar{T}_{sk}$ (Δ1.1–1.2 °C in the present study, as compared with Δ0.7–0.8 °C in the previous trial), while a greater fraction of secreted sweat accumulated within the NBC protective overgarment. On the other hand, a lower percentage of subjects reached the f_c criterion for test termination, and a higher percentage reached the T_{re} criterion. In other words, more subjects tolerated the T_{re} ceiling when they were exercising at a lower intensity.

Assuming that an increase in T_{re} of 2.0 °C (37.3–39.3 °C) is permitted during each trial, Table 5 describes a simplified model to predict increases in tolerance time with reductions in resting T_{re} and the rate of increase in T_{re} following heat acclimation. Given an 0.1 °C lower initial T_{re} and an 0.1 °C·h^{-1} slower increase of T_{re} after acclimation, the time to the 39.3 °C ceiling is extended by 15 min for the HA_6 group (initial tolerance ~100 min) and by 17 min for the HA_{12} group (initial tolerance ~110 min). The predicted increases are closely compatible with the observed data. One weakness of Table 5 is an overestimation of the acclimation-induced gains in shorter exposures (< 60 min), because of the sluggish variation of T_{re} in the early stages of exercise and the predominance of other reasons for test termination in such trials.

In conclusion, when wearing NBC protective clothing, the extension of acclimation from 6 to 12 days does not reduce the physiological strain further. However, the tolerance of a standard exercise and heat stress challenge can be extended by adopting a schedule of light intermittent exercise (an average metabolic rate < 1.0 l·min^{-1}, 25% $\dot{V}O_{2max}$) that allows sufficient time for mass flow of sweat through the outer NBC protective garment.

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References

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

Aoyagi Y, McLellan TM, Shephard RJ (1995) Determination of body heat storage in clothing: calorimetry versus thermometry. Eur J Appl Physiol 71:197–206

Armstrong LE, Maresh CM (1991) The induction and decay of heat acclimatization in trained athletes. Sports Med 12:302–312

Brožek J, Grande F, Anderson JT, Keys A (1963) Densitometric analysis of body composition:revision of some quantitative assumptions. Ann NY Acad Sci 110:113–140

Du Bois D, Du Bois EF (1916) Clinical calorimetry:a formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871

Durnin JVGA, Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 32:77–97

Fellmann N (1992) Hormonal and plasma volume alterations following endurance exercise: a brief review. Sports Med 13:37–49

Fortney SM, Senay LC Jr (1979) Effect of training and heat acclimation on exercise responses of sedentary females. J Appl Physiol Respir Environ Exerc Physiol 47:978–984

Fortney SM, Nadel ER, Wenger CB, Bove JR (1981) Effect of acute alterations of blood volume on circulatory performance in humans. J Appl Physiol Respir Environ Exerc Physiol 50:292–298

Fortney SM, Wenger CB, Bove JR, Nadel ER (1983) Effect of blood volume on forearm venous and cardiac stroke volume during exercise. J Appl Physiol Respir Environ Exerc Physiol 55:884–890

Francesconi RP (1988) Endocrinological responses to exercise in stressful environments. In: Pandolf KB (ed) Exercise and sport sciences reviews, vol 16. Macmillan, New York, pp 255–284

Gagge AP, Nishi Y (1983) Heat exchange between human skin surface and thermal environment. In: Lee DHK (ed) Handbook of physiology: reactions to environmental agents. American Physiological Society, Bethesda, pp 69–92

Goldman RF (1985) Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF (eds) Protecting personnel at hazardous waste sites. Butterworth, Boston, pp 215–266

Goldman RF (1988) Standards for human exposure to heat. In: Mekjavić IB, Banister EW, Morrison JB (eds) Environmental ergonomics: sustaining human performance in harsh environments. Taylor and Francis, Philadelphia New York London, pp 99–136

Harrison MH (1985) Effects of thermal stress and exercise on blood volume in humans. Physiol Rev 65:149–209

Johnson JM (1992) Exercise and the cutaneous circulation. In: Holloszy JO (ed) Exercise and sport sciences reviews, vol 20. Williams and Wilkins, Baltimore, pp 59–97

Kakitsuba N, Gaul K, Michna H, Mekjavić IB (1988) Dynamic moisture permeation through clothing. Aviat Space Environ Med 59:49–53

McArdle WD, Katch FI, Katch VL (1991) Vitamins, minerals, and water. In: Exercise physiology: energy, nutrition, and human performance, 3rd edn. Lea and Febiger, Philadelphia, pp 44–67

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

McLellan TM, Jacobs I, Bain JB (1993) Continuous vs. intermittent work with Canadian Forces NBC clothing. Aviat Space Environ Med 64:595–598

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

Nadel ER, Fortney SM, Wenger CB (1980) Effect of hydration state on circulatory and thermal regulations. J Appl Physiol Respir Environ Exerc Physiol 49:715–721

Roberts MF, Wenger CB, Stolwijk JAJ, Nadel ER (1977) Skin blood flow and sweating changes following exercise training and heat acclimation. J Appl Physiol Respir Environ Exerc 43:133–137

Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal stress. Physiol Rev 54:75–159

Sawka MN, Wenger CB (1988) Physiological responses to acute exercise-heat stress. In: Pandolf KB, Sawka MN, Gonzalez RR (eds) Human performance physiology and environmental medicine at terrestrial extremes. Benchmark, Indianapolis, pp 97–151

Sawka MN, Pandolf KB, Avellini BA, Shapiro Y (1983) Does heat acclimation lower the rate of metabolism elicited by muscular exercise? Aviat Space Environ Med 54:27–31

Senay LC Jr (1979) Effects of exercise in the heat on body fluid distribution. Med Sci Sports 11:42–48

Senay LC, Mitchell D, Wyndham CH (1976) Acclimatization in a hot, humid environment: body fluid adjustments. J Appl Physiol 40:786–796

Shvartz E, Benor D (1971) Total body cooling in warm environments. J Appl Physiol 31:24–27

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

Stephenson LA, Kolka MA (1988) Effect of gender, circadian period and sleep loss on thermal responses during exercise. In: Pandolf KB, Sawka MN, Gonzalez RR (eds) Human performance physiology and environmental medicine at terrestrial extremes. Benchmark, Indianapolis, pp 267–304

Sullivan PJ, Mekjavić IB (1992) Temperature and humidity within the clothing microenvironment. Aviat Space Environ Med 63:186–192

Tilley RI, Standerwick JM, Long GJ (1987) Ability of the Wet Bulb Globe Temperature Index to predict heat stress in men wearing NBC protective clothing. Mil Med 152:554–556

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

Van Beaumont W (1972) Evaluation of hemoconcentration from hematocrit measurements. J Appl Physiol 31:712–713

Wenger CB (1988) Human heat acclimatization. In: Pandolf KB, Sawka MN, Gonzalez RR (eds) Human performance physiology and environmental medicine at terrestrial extremes. Benchmark, Indianapolis, pp 153–197

Wyndham CH (1967) Effect of acclimatization on the sweat rate/rectal temperature relationship. J Appl Physiol 22:27–30

Wyndham CH, Benade AJA, Williams CG, Strydom NB, Goldin A, Heyns AJA (1968) Changes in central circulation and body fluid spaces during acclimatization to heat. J Appl Physiol 25:586–593

Young AJ (1990) Energy substrate utilization during exercise in extreme environments. In: Pandolf KB, Holloszy JO (eds) Exercise and sport sciences reviews, vol 18. Williams and Wilkins, Baltimore, pp 65–117

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

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