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EFFECTS OF METABOLIC RATE AND AMBIENT VAPOUR PRESSURE ON HEAT STRAIN IN PROTECTIVE CLOTHING

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ORIGINAL ARTICLE

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Effects of metabolic rate and ambient vapour pressure on heat strain in protective clothing

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Abstract Studies have shown that variations in ambient water vapour pressure from 1.7 to 3.7 kPa have little effect on heat tolerance time at a metabolic rate above 450 W while wearing protective clothing. With lighter exercise, where tolerance times exceed 60 min, variations in vapour pressure have a significant impact on evaporative heat loss and, therefore, heat tolerance. The present study has examined whether these findings extend to conditions with more extreme variations in vapour pressure. Twelve males performed light (L, 350 W) and heavy (H, 500 W) exercise at 40 °C in a dry (D, 1.1 kPa) and humid (H, 4.8 kPa) environment while wearing a semi-permeable nuclear, biological and chemical protective clothing ensemble ($0.29\ \mathrm{m}^2 \times {}^{\circ}\mathrm{C}^{-1} \cdot \mathrm{W}^{-1}$ or 1.88 clo; Woodcock vapour permeability coefficient, $i_m = 0.33$). Partitional calorimetry was used to determine the rate of heat storage ($\dot{S}$) with evaporative heat loss from the skin ($\dot{E}_{sk}$) calculated from changes in dressed mass or the physical properties of the clothing and the vapour pressure gradient between the skin and the environment. Skin vapour pressure was predicted from measurements of water vapour pressure above the skin surface and in the clothing with humidity sensors coupled with thermistors. Final mean skin temperature ($\bar{T}_{sk}$) was higher for the humid trials and averaged 37.4 (0.3) °C, 38.9 (0.4) °C, 37.6 (0.5) °C and 38.5 (0.4) °C for LD, LH, HD and HH, respectively. Final rectal temperature (T_{re}) was higher for D with respective values for LD, LH, HD and HH of 39.0 (0.4) °C, 38.7 (0.4) °C, 38.8 (0.4) °C and 38.5 (0.4) °C. Tolerance time was significantly different among the trials and averaged 120.3 (19.3) min, 54.8 (7.3) min, 63.5 (6.9) min and 36. (3.1) min for LD, LH, HD and HH, respectively. $\dot{E}_{sk}$ was overestimated and, therefore, $\dot{S}$ was underestimated when the changes in dressed mass were used to determine evaporative heat loss. When skin vapour pressure determined from the humidity sensor data was used to calculate $\dot{E}_{sk}$, heat storage was significantly different among the trials and averaged 15.0 (3.0), 13. (1.8), 14.2 (2.6) and 12.2 (1.9) $\mathrm{kJ \cdot kg^{-1}}$ for LD, LH, HD and HH, respectively. It was concluded that while wearing the protective clothing all indices of heat strain, including tolerance time, were significantly affected by the change in ambient water vapour pressure from 1.1 to 4.8 kPa during both light and heavy exercise

Key words Rectal temperature · Mean skin temperature · Skin vapour pressure · Heat storage · Partitional calorimetry

Introduction

Clothing has been designed to protect personnel who must continue to operate in environments contaminated with biological or chemical agents. The low vapour permeability and overall thickness of the protective overgarment together with the respirator and impermeable rubber gloves and overboots have been designed to effectively eliminate the interaction of hazardous chemicals with the skin surface, and chemical and biological agents with the respiratory tract. However, the characteristics of the clothing also restrict the dry heat exchange, by radiation, conduction and convection, and wet heat flux, by evaporation, of metabolic heat from the body to the environment (Givoni and Goldman 1972). Thus body heat storage is increased and tolerance time is reduced while wearing the protective clothing compared with a clothing configuration that allows a more effective heat exchange with the environment (Carter and Cammermyer 1985

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Henane et al. 1979; McLellan 1993; McLellan et al. 1993; Montain et al. 1994).

Previously we reported that, while wearing a protective clothing ensemble, tolerance time appeared to be unaffected by variations in ambient vapour pressure (P_A) at metabolic rates that exceeded $15\,\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ (approximately 450 W) (McLellan 1993). Under the ambient vapour conditions studied, which varied from 2.1 to 3.7 kPa (or 16 to 28 mmHg), tolerance times of less than 50 min could be described solely by the rate of metabolic heat production or measured oxygen consumption ($\dot{V}O_2$). At metabolic rates below $15\,\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ the influence of P_A on evaporative heat loss, and thus the rate of heat storage, and resultant tolerance times became more evident (McLellan 1993). These findings suggest that the protective clothing markedly slows the development of steady-state evaporative heat loss kinetics governed principally by the vapour pressure gradient between the skin and the environment. Given this interpretation we hypothesized that even more extreme variations in P_A should have little impact on heat tolerance during heavy exercise but a very significant influence during light exercise while wearing the protective clothing. Furthermore, since the use of the dependent measure of time to exhaustion has been criticized as a means of characterizing heat strain (Montain et al. 1994) or submaximal exercise capability (McLellan et al. 1995), other indices of heat strain such as rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), heart rate and a calorimetric estimate of the rate of heat storage ($\dot{S}$) were used to examine the influence of P_A on thermoregulation during light and heavy exercise while wearing protective clothing.

Tolerance to hot environments can be predicted from $\dot{S}$ (Craig et al. 1954; Goldman et al. 1965; Shvartz and Benor 1972). It is most common to estimate changes in $\dot{S}$ by thermometry, a process which calculates the product of body mass, the specific heat of the tissue and the weighted sum of the change in T_{re} and $\bar{T}_{sk}$. In hot environments the ratio of the weighted coefficients for T_{re} and $\bar{T}_{sk}$ have varied from 2:1 (Craig et al. 1954; Goldman et al. 1965; Shvartz and Benor 1972) to 9:1 (Hardy and Stolwijk 1966; Shvartz et al. 1977). Alternatively, $\dot{S}$ can be calculated by indirect calorimetry, which entails calculating the various heat losses and gains from the individual components of the heat balance equation. For semi-nude resting subjects in a hot and dry environment, Vallerand et al. (1992) reported that thermometric estimates of $\dot{S}$ using weighted coefficients of 4:1 for T_{re} and $\bar{T}_{sk}$ could significantly underestimate heat storage determined by partitional calorimetry. When subjects are exercising, and especially if multiple clothing layers are worn, accurate calorimetric estimates of $\dot{S}$ become more difficult because of the assumptions involved in calculating the various components of the heat balance equation. In particular, the determination of evaporative heat loss from the skin ($\dot{E}_{sk}$) is complicated when clothing is worn. Estimates derived from changes in dressed mass before and after heat exposure may overestimate $\dot{E}_{sk}$ (Craig and Moffitt 1974). Since the heat transfer occurs at some distance removed from the skin surface and since some of the heat of vapourization may come from the ambient environment rather than entirely from the individual within the microenvironment of the clothing system, the efficiency of evaporative cooling from the clothed individual is reduced (Craig and Moffitt 1974; Nunneley 1989). To obtain a more direct estimate of $\dot{E}_{sk}$, vapour pressures at the skin surface and within the clothing microenvironment can be measured with dew-point or humidity sensors (Gonzalez and Cena 1985; Kakitsuba et al. 1988). The vapour pressure gradient from the skin to the ambient environment can then be determined and $\dot{E}_{sk}$ calculated if the resistance to water vapour transfer of the clothing ensemble is known. In the present study we compared calorimetric estimates of $\dot{S}$, with $\dot{E}_{sk}$ estimated from changes in dressed mass or from the calculation of skin vapour pressures obtained from humidity sensors positioned directly over the skin and between the clothing layers of the nuclear, biological and chemical (NBC) ensemble. It was hypothesized that the former procedure would overestimate $\dot{E}_{sk}$ and underestimate $\dot{S}$ and that the underestimation of $\dot{S}$ would be greater during exercise at the lower P_A.

Methods

Subjects

Following approval from the Institute's human ethics committee, 12 non-heat-acclimated males volunteered to participate in the study. Mean values (SD) for age, mass, height, body surface area and $\dot{V}O_{2\,\mathrm{peak}}$ were 31.4 (4.5) years, 82.0 (11.1) kg, 1.77 (0.05) m, 1.98 (0.14) $\mathrm{m^2}$ and 48.5 (5.6) $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$, respectively. Subjects were informed of all details of the experimental procedures and the associated risks and discomforts. After an examination to ensure that there were no medical contraindications to their participation in the experiments, they gave their informed consent prior to the first day of data collection. Experiments were conducted from October to January, when outdoor temperatures varied from approximately +15° to −10°C.

Determination of peak aerobic power ($\dot{V}O_{2\,\mathrm{peak}}$)

$\dot{V}O_{2\,\mathrm{peak}}$ was determined using a motor-driven treadmill using open-circuit spirometry (McLellan 1993). $\dot{V}O_{2\,\mathrm{peak}}$ was defined as the highest $\dot{V}O_2$ observed during the incremental test. Heart rate was monitored throughout the incremental test from a transmitter/receiver telemetry unit (Polar Electro PE3000, Stamford, Conn., USA). The value recorded at the end of the exercise test was considered to be the individual's maximal heart rate.

Experimental design

Subjects initially performed a 60-min familiarization session wearing the protective clothing ensemble and performing light exercise at

40°C and 15% relative humidity. The protective ensemble consisted of underwear, a T-shirt, combat clothing, socks, jogging shoes, a semi-permeable one-piece overgarment and impermeable rubber boots, gloves and C4 respirator with cannister. The mass of the clothing ensemble and thermistor harness approximated 8 kg. The total thermal resistance of this ensemble, determined using a heated copper manikin, was 0.29 $m^2 \cdot °C \cdot W^{-1}$ (1.88 clo) and the Woodcock vapour permeability coefficient (i_m), determined with a completely wetted manikin, was 0.33 (Gonzalez et al. 1993). Subjects were evaluated at 40°C with a wind speed of less than 0.1 $m \cdot s^{-1}$ in a dry (15% relative humidity, 1.1 kPa) and humid (65% relative humidity, 4.8 kPa) condition, while wearing the protective clothing and performing light (continuous level treadmill walking at 0.97 $m \cdot s^{-1}$ or approximately 350 W) or heavy (continuous treadmill walking at 1.33 $m \cdot s^{-1}$ with a 3% grade or approximately 500 W) exercise. Since the subjects were not heat acclimated prior to the investigation, the order of the four experimental trials [light exercise with dry (LD) or humid (LH) conditions and heavy exercise with dry (HD) or humid (HH) conditions] was randomized to minimize any carry-over effects of partial heat acclimation during the protocol. All testing began between 8.30 and 9.30 a.m. A minimum of 2 days and a maximum of 5 days separated each trial for 11 of the subjects. One subject was tested in the dry conditions in December and in the wet conditions in January. No specific dietary restrictions were imposed. Subjects were asked to refrain from alcohol on the day before and caffeine on the morning of each session. Pre-trial nude mass varied by less than 1% for any given subject.

Tolerance time for all trials was defined as the time period until any of the following criteria first occurred: T_{re} reached 39.3°C; heart rate remained at or above 95% of maximum for 3 min; dizziness or nausea precluded further exercise; the subject asked to be removed or was removed from the chamber by one of the investigators or technicians; or 4 h had elapsed. Water was not allowed during these trials.

Dressing and weighing procedures

Subject preparation, insertion of the rectal thermistor and placement of skin thermistors have been detailed previously (Aoyagi et al. 1994, 1995a; McLellan et al. 1993). In addition, relative humidity capacitance sensors (Vaisala Sensor Systems, Wobum, Mass., USA) and thermistors were taped over the skin and combat clothing at the upper back, abdomen and upper thigh for eight of the subjects. With this configuration the sensors taped on the skin and combat clothing lay approximately 5 and 15 mm above the skin surface, respectively (as shown in Fig. 1). The same sensor and thermistor were used during each trial to measure humidity and temperature at a given site for a particular subject. These humidity sensors have an accuracy of ± 3% and the linearity of response was verified for each sensor with saturated salt solutions of lithium chloride, sodium chloride and potassium sulphate to provide relative humidity measurements of 12%, 75% and 97%, respectively. Both nude mass and dressed mass were recorded prior to entry into the chamber. Upon entering the chamber, the subject's humidity sensors and thermistors, and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the exercise began. Mean values over 1-min periods for T_{re}, a 12-point weighted mean skin temperature ($\bar{T}_{sk}$) (Hody 1973) and an unweighted average of skin and garment vapour pressure ($\overline{VP}_{sk}$ and $\overline{VP}_G$) was calculated, recorded and printed by the data acquisition system. Heart rate was recorded every 5 min from the display on the telemetry receiver. Subjects were not allowed water during the exposures. After the completion of each trial, dressed mass was recorded within 1 min after exit from the chamber and nude mass was recorded following a 5-min undressing procedure.

Differences in nude mass and dressed mass before and after each trial were corrected for respiratory and metabolic mass losses (see below). The amount of sweat produced was calculated as pre-trial minus post-trial nude mass (corrected). Evaporative sweat loss from the clothing was calculated as pre-trial minus post-trial dressed mass (corrected).

Gas exchange analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), $\dot{V}O_2$ and carbon dioxide production from a 2-min average obtained every 15 min. An adaptor was attached to the respirator, which allowed expired air to be collected. Respiratory water loss ($\dot{m}_e$ in $g \cdot min^{-1}$) was calculated from the measured $\dot{V}O_2$ ($l \cdot min^{-1}$), P_A and the respired mouth water vapour pressure (P_{resp}) in kPa as (Mitchell et al. 1972):

$$\dot{m}_e = 0.1425 \cdot \dot{V}O_2(P_{resp} - P_A) \tag{1}$$

Metabolic mass loss ($g \cdot min^{-1}$) was calculated from the $\dot{V}O_2$ ($l \cdot min^{-1}$) and the respiratory exchange ratio (R) as (Snellen 1966):

$$\text{mass change} = \dot{V}O_2(1.9769 \cdot R - 1.42904). \tag{2}$$

Heat balance calculations

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

$$\dot{S} = \dot{M} - \dot{W} + (\dot{R} + \dot{C}) - \dot{E}_{sk} - \dot{E}_{resp} + \dot{C}_{resp}. \tag{3}$$

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

$$\dot{M} = 352(0.23 \cdot R + 0.77)(\dot{V}O_2 \cdot A_D^{-1}). \tag{4}$$

The external power, $\dot{W}$, was calculated for the heavy exercise condition using the treadmill speed, V in $m \cdot s^{-1}$, the grade fraction (0.03), and the dressed mass, m in kg, as:

$$\dot{W} = 9.8 \cdot 0.03 \cdot V \cdot m \cdot A_D^{-1}. \tag{5}$$

The radiative and convective heat exchange, $\dot{R}$ and $\dot{C}$, contributed to a positive heat storage since the chamber temperature exceeded skin temperature. Its value was estimated using the total insulative value of the NBC clothing ensemble, I_T, of 0.291 $m^2 \cdot °C \cdot W^{-1}$ (or 1.88 clo) determined using a heated and dry 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. 1993):

$$\dot{R} + \dot{C} = (40 - \bar{T}_{sk})/0.291. \tag{6}$$

Respiratory evaporative heat loss, $\dot{E}_{resp}$, and convective heat gain, $\dot{C}_{resp}$, were calculated for chamber vapour pressures, P_A, of 1.11 and 4.79 kPa for 40°C and 15% and 65% relative humidity, respectively, respired vapour pressures, P_{resp}, of 5.32 and 6.27 kPa assuming 100% saturation of expired air at mouth temperatures, T_{resp}, of 34 and 37°C for the dry and humid conditions, respectively (Livingstone et al. 1994), the density of air, ρ, of 0.001293 $kg \cdot l^{-1}$, the specific heat of dry air, c_{pa}, of 0.28 $W \cdot h \cdot kg^{-1} \cdot °C^{-1}$, the specific heat of water vapour, c_{pwv}, of 0.52 $W \cdot h \cdot kg^{-1} \cdot °C^{-1}$, the measured $\dot{V}_E$ in $l \cdot h^{-1}$ (STPD), the latent heat of vapourization, λ, of 675 $W \cdot h \cdot kg^{-1}$, and the difference in the humidity ratio,

$$W_{resp} - W_A \text{ of } 0.622 \cdot [P_{resp}/(101 - P_{resp}) - P_A/(101 - P_A)], \text{ as} \tag{7}$$

$$\dot{E}_{resp} = \rho \cdot \lambda \cdot V_E \cdot (W_{resp} - W_A) \cdot A_D^{-1} \text{ and} \tag{8}$$

$$\dot{C}_{resp} = \rho \cdot V_E \cdot (T_{resp} - 40) \cdot A_D^{-1} \cdot (c_{pa} + c_{pwv} \cdot W_A). \tag{9}$$

Evaporative heat loss from the skin, $\dot{E}_{sk}$, was determined using the following three methods. First, $\dot{E}_{sk}$ was determined from the rate of sweat loss from the clothing, SE in kg·h^{-1}, as

$$\dot{E}_{sk} = SE \cdot \lambda \cdot A_D^{-1}. \tag{10}$$

This procedure is referred to as Method A.

Second, an unweighted average of T_{sk} was calculated from the skin thermistor readings on the upper back, abdomen and front thigh. Assuming 100% saturation at the skin, a skin vapour pressure, P_{sk}, was calculated for each 5-min interval and $\dot{E}_{sk}$ was determined using the Woodcock vapour permeability coefficient, i_m, of 0.33, I_T, the Lewis relation of 16.5 °C·kPa^{-1} and P_A, as (Gonzalez et al. 1993):

$$\dot{E}_{sk} = 16.5 \cdot (0.33,\ 0.291) \cdot (P_{sk} - P_A). \tag{11}$$

This estimated value of $\dot{E}_{sk}$ represents the maximum evaporative potential between the clothing system and the environment and was defined $\dot{E}_{max}$ and referred to as Method B.

Third, vapour pressure at the skin was also estimated from a model which used the vapour pressure readings obtained with the humidity sensors positioned 5 and 15 mm above the skin surface, as shown in Fig. 1. The objective of this analysis was to predict the water vapour pressure at the skin as a function of time given measurements of the water vapour pressure in the clothing throughout the exercise trials. The problem was approximated as a one-dimensional flow of water vapour through a number of layers that produced resistance to the flow. Convection and condensation were not considered in this analysis. The relative humidity sensors had a cylindrical protective cage around them that resulted in a 5-mm air gap on either side of the sensor. For this analysis, it was assumed that the sensors (small flat plates) were parallel to the body surface. The water vapour resistance of the combat clothing and T-shirt were both estimated as $5.0 \cdot 10^3$ Pa·m^2·s·g^{-1} (1 mm still air) from measurements derived from a water vapour permeability apparatus (Van Beest and Wittgen 1986). The water vapour resistance due to the air gap on either side of each sensor was calculated as the diffusion resistance of the 5 mm of still air ($2.5 \cdot 10^4$ Pa·m^2·s·g^{-1}) for sedentary conditions. The thermal resistance of the clothing and air layers were then adjusted for the effects of walking (Danielsson 1993). $\dot{E}_{sk}$ was calculated using Eq. 11 using P_{sk} generated from the model. This procedure is referred to as Method C and defined as $\dot{E}_{model}$.

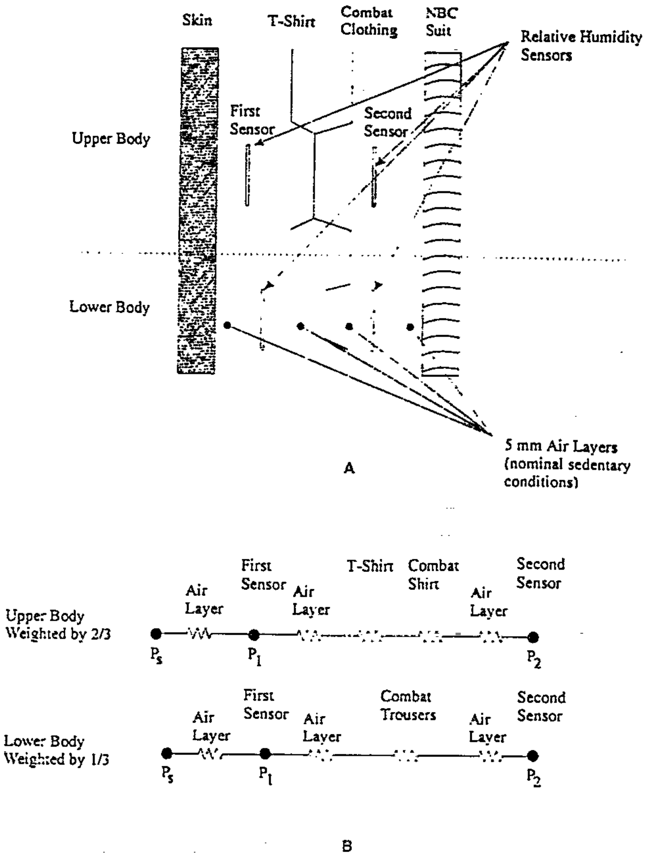

Fig. 1 A schematic representation showing A the placement of the humidity sensors and thermistors in relation to the skin and clothing layers and B the model geometry used to calculate skin vapour pressure (P_{sk}) from the vapour pressures recorded from the first (P_1) and second (P_2) humidity sensors coupled with a thermistor. The model assumed that the air layer between the T-shirt and the combat clothing was compressed with the placement of the second sensor in close proximity to the first sensor

Statistics

Data are presented as mean values and standard deviation of the mean. A one-factor (trial) repeated measures ANOVA was performed to compare tolerance time, sweat rates and the components of the heat balance equation during the four conditions. A two-factor (trial and time) repeated measures ANOVA was used also to analyse changes in gas exchange, heart rate, $\dot{V}P_{sk}$, T_{re} and $\bar{T}_{sk}$. When a significant F-ratio was obtained, a Newman-Keuls post-hoc analysis was performed to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

Results

Indices of heat strain

Tolerance times were significantly different among the trials (Table 1). However, the decrease in P_A from 4.8 to 1.1 kPa had a significantly greater impact on the relative change in tolerance time during light exercise conditions. This change in tolerance time represented 121.4 (36.6)% for light exercise compared with 74.1 (26.6)% for the heavy exercise. The dry condition also significantly prolonged the time required for an increase in T_{re} of 1.0°C at both metabolic rates (Table 1). The relative difference between the dry and humid conditions for this measure was significantly greater for the light exercise [84.3 (35.9)%] compared with the heavy exercise [48.8 (14.9)%].

Sweat rates were significantly elevated during the humid trials and during the heavy exercise conditions (Table 1). Mean values reached 1.5 kg·h^{-1} during the heavy exercise in the humid condition. The ambient vapour pressure had a significant impact on the rate of sweat evaporation calculated from the changes in dressed mass (Table 1). Mean values approached 0.4 kg·h^{-1} during the dry trials and were less than 0.1 kg·h^{-1} for the humid test conditions.

For both the light or heavy exercise in the humid condition heart rates were significantly elevated after 10 min compared with the dry trials. As would be expected during either the humid or dry conditions, heart rates were higher during the heavy exercise. Final

Table 1 The rate of sweat loss, the rate of sweat evaporation (calculated from changes in dressed mass) tolerance time and the time required for a 1.0 °C increase in rectal temperature (T_{re}) for the light and heavy exercise at 40 °C in dry (15% relative humidity) or humid (65% relative humidity) conditions. Values are mean (SD) for $n = 12$

	Light exercise		Heavy exercise	
	Dry	Humid	Dry	Humid
Sweat rate ($kg \cdot h^{-1}$)	0.87^{a,b} (0.17)	1.23^{a} (0.22)	1.21^{b} (0.29)	1.49 (0.27)
Evaporation rate ($kg \cdot h^{-1}$)	0.35^{b} (0.03)	0.09 (0.02)	0.38^{b} (0.03)	0.09 (0.03)
Tolerance time (min)	120.3* (19.3)	54.8* (7.3)	63.5* (6.9)	36.8* (3.1)
Time (min) for 1.0°C increase in T_{re} ($n = 9$)	73.7* (16.0)	40.1 (5.4)	45.4 (7.2)	30.6* (3.9)

[a] The light exercise conditions combined are significantly different from the heavy exercise conditions

[b] The dry conditions combined are significantly different from the humid conditions

* Significantly different from the other conditions

heart rates were significantly affected by the different P_A during the light exercise only and averaged 157.4 (12.9), 164.0 (16.8), 169.4 (12.1) and 168.9 (14.1) beats·min^{-1} for LD, LH, HD and HH, respectively.

The changes in $\bar{T}_{sk}$ are shown in Fig. 2. After 5 min of either light or heavy exercise, $\bar{T}_{sk}$ was significantly elevated during the humid condition. For the dry trials, the intensity of exercise did not influence the change in $\bar{T}_{sk}$ until after 30 min. In contrast, during the humid condition higher $\bar{T}_{sk}$ values were observed during the heavy exercise at 10 min. Final $\bar{T}_{sk}$ was significantly higher during the humid trials and averaged 37.36 (0.25)°C, 38.89 (0.28)°C, 37.63 (0.48)°C and 38.64 (0.42)°C for LD, LH, HD and HH, respectively.

Figure 3 depicts the increase in T_{re} for the different conditions. The increase in T_{re} was significantly greater during the humid trials following 20 and 15 min for the light and heavy exercise, respectively. The increase in T_{re} was similar during the first 30 min of exercise for conditions LH and HD. Final T_{re} was significantly higher for the dry conditions combined or for the light exercise trials and averaged 38.97 (0.31)°C, 38.71 (0.40)°C, 38.80 (0.36)°C and 38.48 (0.43)°C for LD, LH, HD and HH, respectively.

Vapour pressure increased more rapidly and reached higher values during the humid trials at both the skin and combat clothing layers. Average values were higher also during the heavy exercise trials compared with the light exercise conditions for both the skin and combat layers. After 30 min of exercise, the vapour pressure gradient from the skin to the combat clothing layer was significantly less for the humid trials.

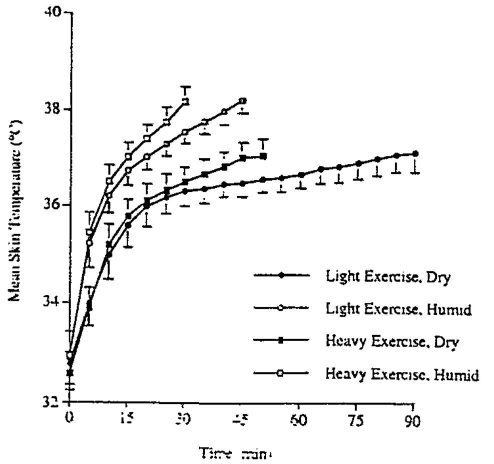

Fig. 2 Changes in mean skin temperature while wearing the protective clothing during light or heavy exercise at 40°C with 15% (*Dry*) or 65% (*Humid*) relative humidity

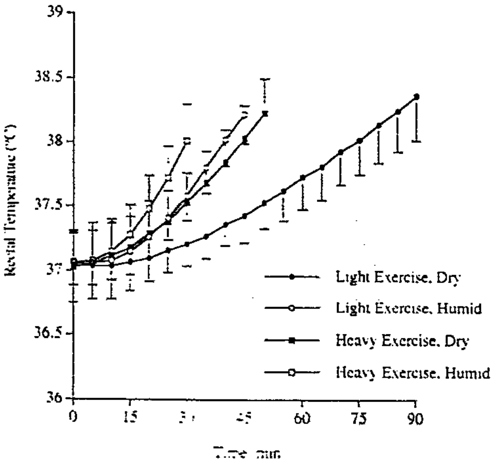

Fig. 3 Changes in rectal temperature while wearing the protective clothing during light or heavy exercise at 40°C with 15% (*Dry*) or 65% (*Humid*) relative humidity

Calculation of heat storage

The various components of the heat balance equation are shown in Table 2. The calculation of $\dot{E}_{max}$ (Method B) produced a significantly lower estimate of evaporative heat loss compared with the estimate obtained from dressed mass changes for all trials except the heavy exercise in the humid condition. The calculation of evaporative heat loss using $\dot{E}_{model}$ (Method C) was significantly lower than the $\dot{E}_{max}$ calculation for all trials. A graphical representation of the model's prediction of skin vapour pressure and the assumed skin vapour pressure used in the $\dot{E}_{max}$ determination is shown in Fig. 4A and B for the light exercise in the dry and humid environments, respectively. Similar differences between the model's prediction of skin vapour

Table 2 The rate of metabolic heat production ($\dot{M}$), radiative and convective heat gain ($\dot{R} + \dot{C}$), heat loss through the production of external power ($\dot{W}$), net heat loss through respiration ($\dot{C}_{resp} - \dot{E}_{resp}$) and evaporative heat loss from the skin calculated by weight loss (Method A), the maximum evaporative potential of the clothing system and the environment (Method B) and the calculated evaporative heat loss using the vapour pressures determined with the humidity sensors (Method C) during light or heavy exercise at 40 C and dry (15% relative humidity) or humid (65% relative humidity) conditions. The resultant rate of heat storage ($W \cdot m^{-2}$) would be calculated as $\dot{M} + (\dot{R} + \dot{C}) - \dot{W} - \dot{E}_{resp} + \dot{C}_{resp}$ - Method A, B or C. Values are mean (SD) in $W \cdot m^{-2}$ for $n = 8$

Condition					Evaporative heat loss		
	$\dot{M}$	$\dot{R} - \dot{C}$	$\dot{W}$	$\dot{C}_{resp} - \dot{E}_{resp}$	Method A	Method B	Method C
Light,	173.1^{a}	12.7^{a,b}	0	14.4*	121.1*	91.2**^{b}	81.6**^{b}
dry	(8.6)	(0.5)		(0.9)	(5.1)	(1.6)	(4.6)
Light,	172.9^{a}	10.5^{a}	0	5.2*	31.9	28.6	19.5**
humid	(10.7)	(0.7)		(0.4)	(4.2)	(2.2)	(2.8)
Heavy,	256.0	14.1^{b}	17.7	20.4*	130.2*	90.0**^{b}	79.7**^{b}
dry	(19.0)	(2.1)	(1.2)	(1.6)	(9.2)	(2.3)	(4.2)
Heavy,	249.9	10.8	17.7	7.1*	28.7	28.2	17.3**
humid	(22.0)	(1.2)	(1.2)	(0.9)	(3.5)	(2.5)	(4.3)

[a] The light exercise conditions combined are significantly different from the heavy exercise conditions

[b] The dry conditions are significantly different from the humid trials

* Significantly different from the other trials

** Significantly different from the other methods

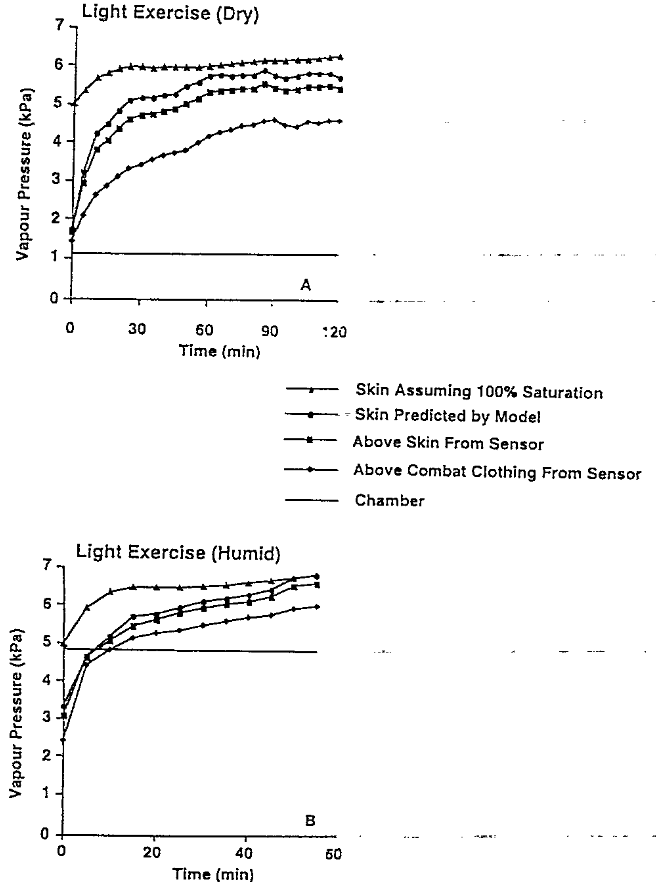

Fig. 4 An example, during the light exercise trials in the A dry and B humid condition of the vapour pressures recorded over the combat clothing and the skin, and the resultant vapour pressures predicted for the skin from our model versus values determined with the assumption of 100% saturation at skin temperature. The *shaded area* represents the potential overestimation of skin vapour pressure with the assumption of 100% skin wettedness from the beginning of the experiment. During the early stages in the humid condition (B) our model predicts the vapour pressure gradient between the skin and the chamber (*straight line*) to be negative

pressure and the value associated with 100% saturation at skin temperature were evident during the heavy exercise trials.

The rate of heat storage was significantly different among the trials regardless of which method was used to estimate evaporative heat loss (Table 3). Furthermore, the calorimetric estimate of the rate of heat storage was significantly different for the dry conditions with each method used to determine $\dot{E}_{sk}$.

Heat storage per unit of mass was significantly lower for the dry trials when loss of mass was used to estimate $\dot{E}_{sk}$ (Table 3). In contrast, heat storage per unit of mass was significantly greater for the dry trials when $\dot{E}_{max}$ or $\dot{E}_{model}$ was used for the estimate of evaporative heat loss. Heat storage per unit of mass was not different between Methods A and B for the humid trials (Table 3).

Discussion

The results from the present investigation have revealed that tolerance time while wearing the protective clothing was affected significantly by the different P_A for both the light and heavy exercise conditions. These data stand in contrast to previous findings, which implied that tolerance time was affected by variations in P_A only during light exercise corresponding to rates of heat production below 400 W or about 200 to 220 $W \cdot m^{-2}$ (McLellan 1993). In these other studies P_A varied from 2.1 to 3.7 kPa (16 to 28 mmHg). In the present investigation a greater dispersion from 1.1 to 4.8 kPa was set for the independent variable to test the hypothesis that variations in P_A would have little or no impact on tolerance time and other indices of heat strain at heavier metabolic rates while wearing the protective clothing. Clearly this hypothesis must be rejected as all indices of heat strain were affected by the

Table 3 The rate of heat storage ($W \cdot m^{-2}$) and the total heat storage per unit of mass ($kJ \cdot kg^{-1}$) calculated from the heat balance equation assuming evaporative heat loss from the skin was represented by weight loss (Method A), the maximum evaporative potential of the clothing system and the environment (Method B) and the calculated evaporative heat loss using the vapour pressures determined with the humidity sensors (Method C) during light or heavy exercise at 40°C in dry (15% relative humidity) or humid (65% relative humidity) conditions. Values are mean (SD) for $n = 8$

	Heat storage ($W \cdot m^{-2}$)		
	Method A	Method B	Method C
Light exercise, dry	50.5*	80.2*·**	89.8*·**
	(9.9)	(8.2)	(11.3)
Light exercise, humid	146.5*	149.6*	158.7*·**
	(12.8)	(10.2)	(9.6)
Heavy exercise, dry	102.0*	142.0*·**	152.4*·**
	(22.6)	(19.2)	(19.4)
Heavy exercise, humid	207.4*	207.7*	218.6*·**
	(22.0)	(20.7)	(20.6)
		Heat storage ($kJ \cdot kg^{-1}$)	
Light exercise, dry	8.5*	13.5**	15.2*·**
	(2.0)	(2.3)	(3.1)
Light exercise, humid	12.0	12.3*	13.0*·**
	(1.8)	(1.8)	(1.8)
Heavy exercise, dry	9.5*	13.3**	14.3*·**
	(2.3)	(2.5)	(2.7)
Heavy exercise, humid	11.6	11.6*	12.2*·**
	(2.0)	(1.8)	(1.9)

* Significantly different from the other trials
** Significantly different from the other Methods

variations in P_A at both the light and heavy metabolic rates. There was some evidence, however, to suggest that variations in P_A could have a greater impact on the heat strain associated with wearing protective clothing at lighter metabolic rates. For example, decreasing the P_A from the humid to the dry condition had a greater effect on the change in the time required for a 1.0°C increase in T_{re} and in tolerance time for the light exercise. In addition, final heart rates were affected by the change in P_A only during the light exercise trials. The decreasing curvilinear relationships between tolerance time and average metabolic rate for the different P_A used in this study and previous investigations (McLellan 1993; McLellan et al. 1992, 1993) are depicted in Fig. 5. For all of the different ambient conditions, a hyperbolic function was used to describe this relationship. At least for the dependent measure of time, the impact of a changing P_A on evaporative heat loss and heat tolerance becomes more evident at lower metabolic rates.

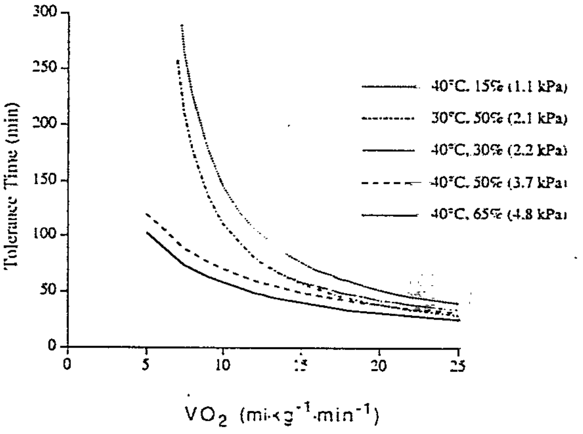

Fig. 5 The relationship between tolerance time and metabolic rate (expressed in units of oxygen uptake) while wearing the protective clothing at a series of different ambient vapour pressures. The curves relating to 1.1 and 4.8 kPa were generated from the present investigation whereas data from McLellan et al. (1993), McLellan et al. (1992) and McLellan (1993) produced the curves relating to 2.1, 2.2 and 3.7 kPa, respectively

Recently, Montain et al. (1994) reported that exhaustion from heat strain while wearing protective clothing occurred at the same T_{re} regardless of variations in P_A between 1.7 and 2.8 kPa (13 and 21 mmHg) and metabolic rates between 425 and 600 W. The present study was not designed to challenge these findings as ethical constraints imposed several end-point criteria which could cloud the association between final T_{re} and exhaustion from the heat strain of wearing protective clothing. Nevertheless, final T_{re} was significantly higher for the dry trials or for the light exercise conditions. Similarly, heat storage expressed per kilogram of mass was significantly greater for the light exercise and for the dry conditions when $\dot{E}_{model}$ was used to estimate evaporative heat loss from the skin. The interpretation of these analyses is influenced by the fact that mean tolerance time was only 37 min for trial HH and that the rate of response for T_{re} is known to be slower than at other sites of measurement of core temperature such as the oesophagus (Nielsen and Nielsen 1962). However, if condition HH was not included in the analyses final T_{re} and heat storage were still significantly higher for LD compared with LH. Thus, at metabolic rates below 400 W, hot and humid ambient conditions appear to lower the T_{re} and total heat storage associated with the intolerance of wearing protective clothing. A greater cardiovascular instability under these hot and humid environmental conditions may account for these findings just as was proposed by Montain et al. (1994) to account for the decreased tolerance associated with wearing a full rather than a partial protective clothing ensemble. The higher final $\bar{T}_{sk}$, during the LH trial of over 1.5°C compared with LD should reflect a greater cutaneous vasodilation, a decreased central blood volume and cardiac filling, and a lower total peripheral resistance and mean arterial pressure. The higher heart rates throughout and at the end of the LH condition compared with LD support the suggestion of a reduced cardiac filling and a lower arterial pressure. However, without measurements of cardiac output and or arterial pressure (which are difficult to obtain while wearing the protective clothing ensembles), the suggestion of a greater cardiovascular instability during the LH condition is only speculative.

The calorimetric estimate of heat storage was affected significantly by the different methods used to determine evaporative heat loss from the skin. The differences among the methods became less as the impact of total $\dot{E}_{sk}$ on $\dot{S}$ decreased with the increase in P_A. The data from the present study would support the earlier findings by Craig and Moffitt (1974) that revealed that $\dot{E}_{sk}$ was overestimated if the term was calculated from changes in dressed mass for a clothed individual. As explained by Nunneley (1989), sweat evaporated from the clothing surface is less effective at removing heat from the body than sweat evaporated at the skin surface. The decreased efficiency in body cooling occurs because the phase change occurs at a distance removed from the skin and a significant proportion of the energy required for vapourization comes from the environment rather than from the individual. Certainly when protective clothing is worn we would not recommend the use of changes in dressed mass to estimate $\dot{E}_{sk}$. This recommendation reflects the acceptance that the other methods used to determine evaporative heat loss, $\dot{E}_{max}$ and $\dot{E}_{model}$, provided a more accurate representation of $\dot{E}_{sk}$. Evaporative heat loss from the skin should not exceed $\dot{E}_{max}$, which represents the maximum evaporative potential of the clothing system and the environment. $\dot{E}_{sk}$ calculated from changes in dressed mass was significantly greater than $\dot{E}_{max}$ for both exercise trials in the dry environment (see Table 2). It could be argued that $\dot{E}_{max}$ was underestimated. The water vapour permeability coefficient (i_m) and total clothing insulation values of the NBC ensemble were determined at a wind speed of 1.12 $m \cdot s^{-1}$ using a wetted and heated manikin articulated to simulate leg motion (Gonzalez et al. 1993). These simulations are comparable with, but not identical to, the conditions in the present study, in which subjects walked on a treadmill at speeds between 1 and 1.3 $m \cdot s^{-1}$ but with no wind. If the type of exercise used in the present study more accurately reflects evaluations made with the articulated manikin at a lower wind speed, the i_m is unchanged but the total clothing insulation is greater (Gonzalez et al. 1993). The ratio of i_m to I_T, therefore, would be smaller and the resultant $\dot{E}_{max}$ would be even less than the values reported in Table 2.

It is also possible that the ratio of i_m to I_T does not accurately reflect the movement of water vapour through the clothing layers. The equation used to calculate $\dot{E}_{max}$ was proposed by Givoni and Goldman (1972) to predict core temperature responses under different environmental conditions. The equation also has been incorporated into a mathematical heat stress model used to predict tolerance times, work and rest schedules and water requirements (Pandolf et al. 1986). Thus the equation used to calculate $\dot{E}_{max}$ was developed previously and has been applied by others under environmental conditions similar to those used in the present study.

The calculation of $\dot{E}_{max}$ assumes 100% saturation of water vapour at skin temperature. A more accurate determination of $\dot{E}_{sk}$ should account for skin wettedness (Nishi 1981). In the present study the evaporative cooling required to maintain thermal balance exceeded $\dot{E}_{max}$ for all of the trials. Thus skin wettedness should approach 100% during the course of each experiment. However, it would be an incorrect assumption to accept 100% relative humidity at skin temperature from the beginning of each trial. The use of $\dot{E}_{max}$, therefore, would overestimate the "true" evaporative heat loss from the skin with the extent of the overestimation being dependent on the time required to reach complete saturation of water vapour at $\bar{T}_{sk}$. An example of this overestimation with the use of $\dot{E}_{max}$ was shown in Fig. 4A, B. The model used in the present study to calculate $\dot{E}_{sk}$ predicted, on average, that greater than 95% saturation at skin temperature was achieved by 20 min during the heavy exercise trials and by 30 and 40 min for conditions LH and LD, respectively. Individual values varied from as short as 10 min for condition HH to greater than 60 min during trial LD. These individual variations would reflect differences in core temperature thresholds for the onset of sweating, total sweat rates and patterns of sweating (Cotter et al. 1995) since only three measurement sites (upper back, abdomen and front thigh) were used for the model predictions. $\dot{E}_{model}$ represented 89.4 (5.5)%, 68.3 (8.4)%, 88.5 (3.8)% and 61.7 (17.0)% of $\dot{E}_{max}$ for condition LD, LH, HD and HH, respectively.

The variations in heat storage expressed per kilogram of mass also reflected the potential problem with the use of mass changes to estimate $\dot{E}_{sk}$ (see Table 3). When this method was used to represent $\dot{E}_{sk}$, heat storage approximated 9 $kJ \cdot kg^{-1}$ during exercise in the dry conditions. This amount of heat storage while wearing protective clothing is comparable to values reported previously from this laboratory using similar calorimetric methods (Aoyagi et al. 1995b) and with thermometric estimates of heat storage generated from weighted coefficients of 2:1 (Craig et al. 1954; Shvartz and Benor 1972) or 4:1 (Henane et al. 1979) for the respective changes in T_{re} and $\overline{T}_{sk}$. If a value of 3.47 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ is used for the specific heat of the tissue (Burton 1935), 9 $kJ \cdot kg^{-1}$ represents a change in mean body temperature of approximately 2.5°C, a value comparable to an accepted upper limit of body heat storage (Henane et al. 1979; Kaufmann 1963). If one accepts that $\dot{E}_{sk}$ is overestimated from changes in dressed mass then one must also accept that heat storage is significantly greater than the value of 9 $kJ \cdot kg^{-1}$. As shown in Table 3 our estimates of heat storage approached 14–15 $kJ \cdot kg^{-1}$ when our model was used to calculate $\dot{E}_{sk}$. These heat storage values translate into a change in mean body temperature of about 4°C, a value which far exceeds expected changes due to thermometric (Craig et al. 1954; Henane et al. 1979) or calorimetric (Aoyagi et al. 1995b) estimates of heat storage in hot environments while wearing protective clothing. The discrepancy with the latter investigation reflects the different methods used to estimate $\dot{E}_{sk}$ in the calorimetric calculation of heat storage. The magnitude of the discrepancy with the other investigations (Craig et al. 1954; Henane et al. 1979) would depend on the weighting of the coefficients used for the changes in T_{re} and $\overline{T}_{sk}$ for the thermometric estimate of heat storage. Given the magnitude of change in $\overline{T}_{sk}$ of 5–6°C in the present series of exposures and the fact that this change in $\overline{T}_{sk}$ was anywhere from 2.5 to 4 times greater than the change in T_{re}, our data would suggest that the thermometric determination of heat storage while wearing protective clothing should place more emphasis on the change in $\overline{T}_{sk}$ than the change in T_{re}. Traditional concepts of thermometry partition the body into a core and shell, represented by T_{re} and $\overline{T}_{sk}$, respectively (Burton 1935). When protective clothing is worn in hot environments more uniform temperatures are observed throughout the body as $\overline{T}_{sk}$ approaches or even exceeds T_{re} (Nunneley et al. 1992; Pandolf and Goldman 1978). Thus the separation of the body into core and shell components may not be appropriate in hot environments when protective clothing is worn, and the weighted coefficients used to obtain a thermometric estimate of heat storage from the change in T_{re} and $\overline{T}_{sk}$ should be re-evaluated.

In summary, the present study has examined the heat strain associated with wearing a protective clothing ensemble during light or heavy exercise in a hot and dry or humid environment. The variations in ambient vapour pressure from 1.1 to 4.8 kPa had a significant impact on all indices of heat strain, including tolerance time, during both the light and heavy metabolic rates. These findings stand in contrast to previous data that implied that variations in ambient vapour pressure had little or no effect on tolerance time at metabolic rates above 450 W. In addition the present investigation has developed a model to generate skin vapour pressure from humidity sensors and thermistors taped on the skin and over the combat clothing layer of the protective ensemble. The information generated from the model allowed evaporative heat loss from the skin to be calculated. The findings from the model revealed that evaporative heat loss from the skin was overestimated from changes in dressed mass and that tolerable limits of heat storage per unit of mass are much greater than previously stated.

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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 (1995a) Effects of 6 versus 12 days of heat acclimation on heat tolerance in lightly exercising men wearing protective clothing. Eur J Appl Physiol 71:187–196

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

Burton AC (1935) Human calorimetry J Nutr 9:261–280

Carter BJ, Cammermyer M (1985) Emergence of real casualties during simulated chemical warfare training under high heat conditions. Mil Med 150:657–665

Cotter JD, Patterson MJ, Taylor NAS (1995) The topography of eccrine sweating in humans during exercise. Eur J Appl Physiol 71:549–554

Craig FN, Moffitt JT (1974) Efficiency of evaporative cooling from wet clothing. J Appl Physiol 36:313–316

Craig FN, Garren HW, Frankel H, Blevins WV (1954) Heat load and voluntary tolerance time. J Appl Physiol 6:634–644

Danielsson U (1993) Convection coefficients in clothing air layers. Doctoral Thesis, The Royal Institute of Technology, Stockholm

Givoni B, Goldman RF (1972) Predicting rectal temperature response to work, environment, and clothing. J Appl Physiol 32:812–822

Goldman RF, Green EB, Iampietro PF (1965) Tolerance of hot, wet environments by resting men. J Appl Physiol 20:271–277

Gonzalez RR, Cena K (1985) Evaluation of vapor permeation through garments during exercise. J Appl Physiol 58:928–935

Gonzalez RR, Levell CA, Stroschein LA, Gonzalez JA, Pandolf KB (1993) Copper manikin and heat strain model evaluations of chemical protective ensembles for the technical cooperation program (TTCP). US Army Research Institute of Environmental Medicine, Technical Report no. T94-4

Hardy JD, Stolwijk JAJ (1966) Partitional calorimetry studies of man during exposures to thermal transients. J Appl Physiol 21:1799–1806

Henane RJ, Bittel J, Viret R, Morino S (1979) Thermal strain resulting from protective clothing of an armored vehicle crew in warm conditions. Aviat Space Environ Med 50:599–603

Hody GL (1973) The field measurement of cold stress in the marine environment. Defence and Civil Institute of Environmental Medicine Consultant Report, North York, Canada

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

Kaufmann WC (1963) Human tolerance limits for some thermal environments of Aerospace. Aerosp Med 34:889–896

Livingstone SD, Nolan RW, Cain JB, Keefe AA (1994) Effect of working in hot environments on respiratory air temperatures. Eur J Appl Physiol 69:98–101

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, Meunier P, Livingstone SD (1992) Influence of a new vapour protective clothing layer on physical work tolerance times at 40 °C. Aviat Space Environ Med 63:107–113

McLellan TM, Jacobs I, Bain JB (1993) Influence of temperature and metabolic rate on work performance in Canadian Forces NBC clothing. Aviat Space Environ Med 64:587–594

McLellan TM, Cheung SS, Jacobs I (1995) Variability of time to exhaustion during submaximal exercise. Can J Appl Physiol 20:39–51

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

Montain SJ, Sawka MN, Cadarette BS, Quigley MD, McKay JM (1994) Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. J Appl Physiol 77:216–222

Neilsen B, Neilsen M (1962) Body temperatures during work at different environmental temperatures. Acta Physiol Scand 56:120–129

Nishi Y (1981) Measurement of thermal balance of man. In: Cena K, Clark JA (eds) Bioengineering, thermal physiology and comfort. Elsevier, New York, pp 29–39

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

Nunneley SA, Antunano MJ, Bomalaski SH (1992) Thermal convergence fails to predict heat tolerance limits. Aviat Space Environ Med 63:886–890

Pandolf KB, Goldman RF (1978) Convergence of skin and rectal temperature as a criterion for heat tolerance. Aviat Space Environ Med 49:1095–1101

Pandolf KB, Stroschein LA, Drolet LL, Gonzalez RR, Sawka MN (1986) Prediction modeling of physiological responses and human performance in the heat. Comput Biol Med 16:319–329

Shvartz E, Benor D (1972) Heat strain in hot and humid environments. Aerosp Med. 43:852–855

Shvartz E, Glick Z, Magazanik A (1977) Responses to temperate, cold and hot environments and the effect of physical training. Aviat Space Environ Med 48:254–260

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

Vallerand AL, Savourey G, Hanniquet A-M, Bittel JHM (1992) How should body heat storage be determined in humans: by thermometry or calorimetry? Eur J Appl Physiol 65:286–294

Van Beest CA, Wittgen PPMM (1986) A simple apparatus to measure water vapour resistance of textiles. Text Res J 57:566–568

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