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Review

The importance of aerobic fitness in determining tolerance to uncompensable heat stress[☆]

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Abstract

When protective clothing is worn that restricts evaporative heat loss, it is not valid to assume that the higher sweat rates associated with improvements in aerobic fitness will increase heat tolerance. An initial study compared thermoregulatory and cardiovascular responses to both compensable and uncompensable heat stress before and after 8 weeks of endurance training in previously sedentary males. Despite a 15% improvement in $V\text{O}_{2\text{peak}}$, and lower heart rates and rectal temperature (T_{re}) responses while wearing combat clothing, no changes were noted when subjects wore a protective clothing ensemble. Tolerance times were unchanged at approximately 50 min. A subsequent short-term training model that used daily 1-h exercise sessions for 2 weeks also failed to show any benefit when the protective clothing was worn in the heat. Cross-sectional comparisons between groups of high and low aerobic fitness, however, have revealed that a high aerobic fitness is associated with extended tolerance time when the protective clothing is worn. The longer tolerance time is a function of both a lower starting T_{re} and a higher T_{re} tolerated at exhaustion. Improvements in cardiovascular function with long-term training may allow higher core temperatures to be reached prior to exhaustion. Conversely, elevations in core temperature that occur with normal training sessions may familiarize the more fit subjects to the discomforts of exercise in the heat. Other factors such as differences in body fatness may account for a faster increase in tissue temperature at a given metabolic rate for less fit individuals. Crown copyright © 2001 Published by Elsevier Science Inc. All rights reserved.

Keywords: Endurance training; Protective clothing; Body fatness; Heat storage; Core temperature

1. Introduction

Under certain conditions of high ambient temperature and/or relative humidity, or with the wearing of clothing ensembles that restrict evaporative heat loss, the evaporative heat loss required to maintain a thermal steady state (E_{req}) can exceed the maximal evaporative capacity of the environment (E_{max}) during light exercise or even at rest. In these conditions which define uncompensable heat stress (UHS) (Givoni and Goldman, 1972), the body constantly stores heat until dangerously high levels are reached leading to eventual collapse or death. When protective clothing is worn, it is not uncommon for condi-

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tions that would normally be defined as compensable to become uncompensable (Kraning and Gonzalez, 1991).

During UHS, tolerance time can be influenced by the initial and final core or rectal temperature (T_{re}), the heat capacity of the body ($C_{\mathrm{p,b}}$), and the rate of heat storage ($\dot{S}$) as shown in the following equation;

$$\text{Tolerance time} = (T_{\mathrm{re\ Final}} - T_{\mathrm{re,\ Initial}}) \times C_{p,b}\ \text{mass} \cdot \left(\dot{S} \cdot 60 \cdot A_{\mathrm{D}}\right)^{-1} \quad (1)$$

where tolerance time is expressed in minutes, $C_{\mathrm{p,b}}$ is in $\mathrm{J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$, $\dot{S}$ is in $\mathrm{W \cdot m^{-2}}$ and A_{D} represents the body surface area in m^2. One approach to the problem of UHS is to explore the physiology of the human inside the clothing ensemble and, by doing so, try to understand how the principal components defined in Eq. (1) are influenced by interventions that may lead to physiological adaptations.

2. Background

One such intervention that leads to adaptation is a regular involvement in aerobic activity. The purpose of this review, therefore, is to examine the impact of aerobic fitness on tolerance to uncompensable heat stress. A high level of cardiorespiratory fitness has been associated with an improved exercise-heat tolerance since the initial theoretical connection was made by Robinson et al. (1943) and Bean and Eichna (1943). These suggestions were based largely on anecdotal evidence, but have been supported by subsequent studies (Piwonka et al., 1965; Armstrong and Pandolf, 1988; Havenith and van Middendorp, 1990). For example Piwonka et al. (1965) reported that trained distance runners exhibited a decreased physiological strain compared to untrained individuals during exercise-heat stress. Gisolfi and Robinson (1969) were among the first to report a reduction in physiological strain and an improvement in exercise tolerance in compensable heat stress environments following a relatively long-term (6 weeks) interval training program. Four weeks of interval training also produced significant improvements in exercise-heat tolerance, with the improvement reaching a plateau after 8 or more weeks of training of approximately 50% of the adaptive responses brought about by heat acclimation (Gisolfi, 1973).

It has been most common for researchers to select environmental conditions that favour evaporative heat loss when work performance in the heat is examined before and after an endurance training program (Henane et al., 1977) or when comparisons are made among groups with different aerobic fitness levels (Piwonka et al., 1965). Whether the documented benefits of an increased aerobic fitness on work in the heat would be evident during UHS that restricts evaporative and dry heat loss is not as clear. It is possible that the increased sweat rate that accompanies an increase in aerobic fitness would have little impact on the rate of heat storage when the clothing is worn (Nunneley, 1989). The amount of insulation and the water vapour permeability of the protective clothing define the upper limit of evaporative heat loss for a variety of ambient temperatures and relative humidities (McLellan et al., 1996). Even with very hot and dry ambient conditions, evaporative heat loss through the clothing layers is less than 100 $\mathrm{W \cdot m^{-2}}$ (McLellan et al., 1996). Thus, by assuming a surface area of 2 m^2 and a latent heat of vaporization of $675 \cdot \mathrm{W \cdot h \cdot kg^{-1}}$, one can estimate that sweat rates in excess of 300 $\mathrm{g\ h^{-1}}$ will be ineffective in promoting further evaporative heat loss. These are low sweat rates that are reached even by sedentary subjects during heat stress exposure while wearing the protective clothing in hot and dry environments (Cheung and McLellan, 1998a,b). Since an increase in aerobic fitness would have little influence on the heat production associated with activities such as walking on a treadmill, its impact on tolerance during UHS would have to be through the other components, besides $\dot{S}$, that are described in Eq. (1). Because of their elevated sweat rates at a given core temperature (Nadel et al., 1974; Shvartz et al., 1974), it could be argued that individuals with an increased aerobic fitness would dehydrate faster and actually perform worse while wearing the protective clothing if fluid was not provided during the exercise. What evidence exists in the literature to support or refute the benefits of an increased aerobic fitness on tolerance to UHS?

3. Cross-sectional comparisons

Windle and Davies (1996) reported that subjects with a high $\dot{V}\text{O}_{2\max}$ relative to lean body mass (75 ml·kg^{-1}·min^{-1} LBM) had a lower heart rate, higher sweating rate and a trend towards longer tolerance times compared with subjects of moderate (60 ml·kg^{-1}·min^{-1} LBM) fitness while wearing a nuclear, biological and chemical protective ensemble and performing stepping exercise at 40°C and 50% relative humidity. Nine of the 10 subjects in this study ended the heat-stress exposure because core (aural) temperature reached an ethical ceiling of 38.5°C. There was no difference in the rate of increase in core temperature between fitness groups when the protective clothing was worn implying that $\dot{S}$ was similar between the groups that did not differ with respect to body fatness. Tolerance times were 54 and 45 min for the high and moderate fit subjects, respectively. The authors make no mention as to whether the lower starting core temperature of approximately 0.2°C for the high fit subjects was significant and whether this lower starting temperature, which was maintained throughout the heat-stress exposure, accounted for the apparent increase in tolerance time for these subjects. Due to the low ethical ceiling for core temperature of 38.5°C used to terminate the heat-stress exposure, this study could not address whether the differing fitness levels influenced the core temperature that could be tolerated at exhaustion.

More recently Cheung and McLellan (1998b) performed a cross-sectional study comparing the responses of active endurance-trained ($\dot{V}\text{O}_{2\max}$ of 60 ml·kg^{-1}·min^{-1}) vs. inactive untrained individuals ($\dot{V}\text{O}_{2\max}$ of 43 ml·kg^{-1}·min^{-1}) during light exercise at 40°C and 30% relative humidity while wearing a protective clothing ensemble. The ethical limit for the increase in T_{re} was 39.3°C for this study. All subjects walked at the same speed of 3.5 km·h^{-1} so the more fit individuals were exercising at a lower % $\dot{V}\text{O}_{2\max}$. Nevertheless, individual differences in tolerance time are more closely related to an absolute rather than to a relative expression of metabolic rate because of the limits to evaporative heat loss created by the clothing layers (McLellan et al., 1996). Exercise-heat tolerance was greater in the fit compared with unfit individuals, with tolerance times averaging 110 and 88 min, respectively. As shown in Fig. 1, the rate of increase in T_{re} was similar during the heat-stress exposure between groups but significant differences were observed for both the initial T_{re} and the final T_{re} at which subjects terminated the experiment. The high fit subjects generally terminated the trials due to T_{re} reaching the ethical limit of 39.3°C and felt they could have continued. In contrast, the less fit inactive subjects predominantly ended the trial due to exhaustion, with an average final T_{re} of 38.6°C. Thus, these data indicate that differences in aerobic fitness have an impact on both the initial and final core temperatures and, therefore, would be expected to influence tolerance time as shown in Eq. (1).

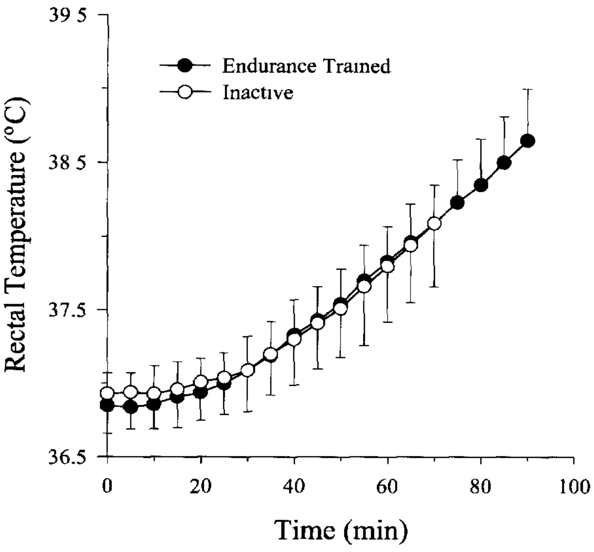

Fig 1 Rectal temperature responses for endurance trained and inactive subjects during heat stress exposure while wearing a protective clothing ensemble There was no difference between groups in the rate of increase in rectal temperature throughout the exposure (from Cheung and McLellan, 1998a,b,c)

In opposition to these findings by Cheung and McLellan (1998b), Sawka et al. (1992) found no relationship between the range in $\dot{V}\text{O}_{2\max}$ of 45–65 ml·kg^{-1}·min^{-1} and the core temperature that could be tolerated at exhaustion for 17 heat-acclimated subjects during uncompensable euhydrated and hypohydrated heat-stress trials. The ethical ceiling for the rise in T_{re} was 40°C in this study which involved subjects wearing shorts and exercising in a hot and dry environment (49°C and 20% relative humidity). Sawka et al. suggested that the 10-day heat acclimation period prior to the heat-stress trials masked the benefits that a high aerobic fitness would be expected to have on heat tolerance in this hot-dry environment that had an E_{max} close to 500 $W \cdot m^{-2}$. However, our findings of higher core temperatures tolerated at exhaustion for subjects of high aerobic fitness were consistent before and after a 10-day heat acclimation program that involved wearing the NBC clothing (Cheung and McLellan, 1998b). The reason for the discrepant findings is unclear but could reflect differences in the statistical approach used [i.e. group (Cheung and McLellan, 1998b) versus regression analyses (Sawka et al., 1992)], the severity of the heat stress index (i.e. the ratio of E_{req} to E_{max} was approximately 2.5 [Cheung and McLellan, 1998b) vs. 1.0 (Sawka et al., 1992)] or the presence (Cheung and McLellan, 1998b) or absence (Sawka et al., 1992) of protective clothing. Overall, our observations during uncompensable heat stress support the general consensus observed during compensable heat stress that an association exists between the level of cardiorespiratory fitness and improvements in physiological responses to exercise in a hot environment (Armstrong and Pandolf, 1988).

4. Longitudinal comparisons

Few studies have compared the heat tolerance response of unfit subjects during uncompensable heat stress before and after a controlled endurance training program designed to improve aerobic fitness. We have examined this response with the use of two different training models. Our first attempt used the more classical endurance training model that involved typical progressions in intensity, frequency and duration such that by the end of 8 weeks subjects were training 4 days $\cdot$ week^{-1}, 45 min $\cdot$ session^{-1} at 80% $\dot{V}O_{2max}$ (Aoyagi et al., 1994). This training stimulus increased $\dot{V}O_{2max}$ approximately 15% from 40 to 46 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}, increased blood volume 5% as calculated from changes in hematocrit and hemoglobin, and produced significant decreases in heart rate (Fig. 2) and T_{rc} (Fig. 3) responses during 2 h of compensable heat stress exposure at 40°C and 30% relative humidity. In addition, control subjects showed no change in $\dot{V}O_{2max}$ over the 8-week period and no change in their thermoregulatory or cardiovascular response during the 2 h of compensable heat stress. However, the endurance training program offered no benefit to the subjects during UHS which involved wearing a protective clothing ensemble. Tolerance times remained unchanged at 50 min during metabolic rates that approximated 275 $W \cdot m^{-2}$ and heart rate and T_{rc} responses also were unaffected by

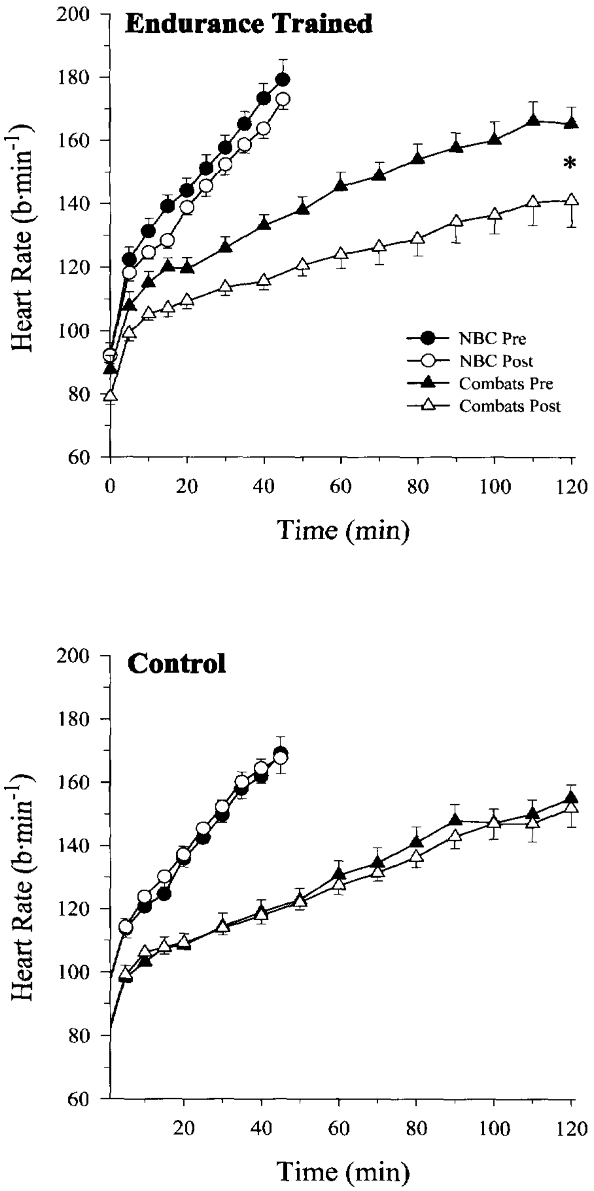

Fig 2 Heart rate responses pre- and post-8 weeks of endurance training (top) or no training (bottom) for men during heat stress exposure while wearing either combat clothing or a protective clothing ensemble. There was a significant decrease in heart rate throughout the heat stress exposure for the endurance trained subjects only while wearing combat clothing (from Aoyagi et al., 1994).

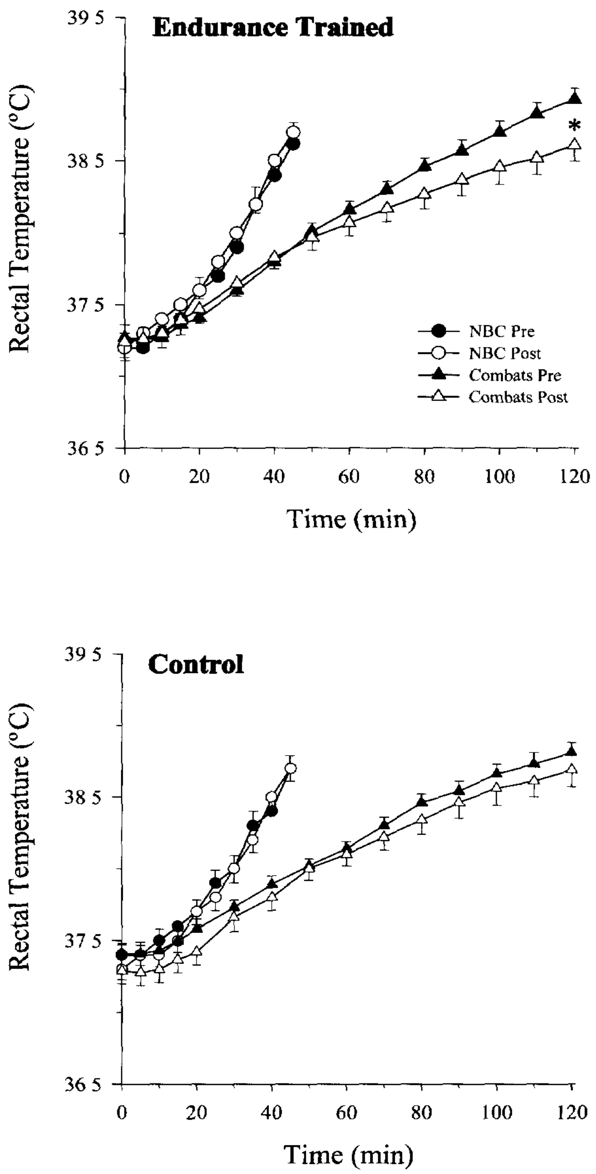

Fig 3 Rectal temperature responses pre- and post-8 weeks of endurance training (top) or no training (bottom) for men during heat stress exposure while wearing either combat clothing or a protective clothing ensemble There was a significant decrease in rectal temperature after 60 min of heat stress exposure for the endurance trained subjects only while wearing combat clothing (from Aoyagi et al., 1994)

the training program (see Figs. 2 and 3). Sweat rates increased significantly from 1.2 to 1.4 kg·h^{-1} after the training but evaporative heat loss was unchanged at 0.3 kg·h^{-1} when the protective clothing was worn indicating that the characteristics of the clothing determined the amount of evaporative heat loss to the environment. These findings, therefore, would suggest that an increase in aerobic fitness offers no advantage while wearing protective clothing and exercising in a hot environment.

One issue of concern evolved from this study by Aoyagi et al. (1994) that may have limited the possibility of observing a positive effect for aerobic fitness. We have shown that the curvilinear relationship between tolerance time and metabolic rate for different ambient temperatures and water vapour pressures while wearing biological and chemical protective clothing is accurately defined by a hyperbolic function where the vertical asymptote of the equation defines the metabolic rate that delineates compensable and uncompensable heat stress (McLellan et al., 1992, 1993, 1996; McLellan, 1993). At work intensities above 250 W·m^{-2}, tolerance times converge at approximately 50 min indicating that variations in the ambient conditions have very little impact on tolerance time. This is because any change in E_{max} due to a change in the ambient vapour pressure represents a smaller percentage of E_{req} at higher metabolic rates. For example in hot and dry environments, E_{max} would be estimated at approximately 100 W·m^{-2} for the NBC protective ensemble but this value would decrease to 30 W·m^{-2} in more humid conditions (McLellan et al., 1996). This decrease in E_{max} of 70 W·m^{-2} between the dry and humid environments represents approximately 25–30% of the heat produced during heavy exercise but 45–50% of the heat produced during light exercise. It has also been shown that 20–40 min of exercise are required before the vapour pressure gradients at the skin surface are similar to those defined by E_{max} (McLellan et al., 1996; Cain and McLellan, 1998). Thus, some time is required to establish maximal vapour pressure gradients and evaporative heat loss to the environment through the clothing layers. As a result, our data and those of others, have shown differential effects of rehydration (Cheung and McLellan, 1998a), heat acclimation (Aoyagi et al., 1994, 1995; McLellan and Aoyagi, 1996), the menstrual cycle (Kolka and Stephenson, 1997; Tenaglia et al., 1999) and ambient vapour pressure (McLellan et al., 1996) on tolerance time while wearing protective clothing and performing light and heavy exercise in a hot environment. In addition, differential effects of heat acclimation and endurance training on the psychological strain of wearing protective clothing has been documented during light and heavy exercise (Aoyagi et al., 1998). It is possible, therefore, that the metabolic rate chosen to evaluate the training program used by Aoyagi et al. (1994) was too high and that a different conclusion would have been reached with the use of a lighter metabolic rate.

Our next approach (Cheung and McLellan, 1998c) was to use a short-term aerobic training model that had been reported to induce rapid cardiovascular and thermoregulatory changes during submaximal exercise following three to 14 daily aerobic training sessions at 60–80% $\dot{V}\text{O}_{2\max}$ for 1–3 h (Green et al., 1991). We rationalized that in a military environment there may be little time available prior to deployment to increase aerobic fitness and also that many military personnel may be unwilling to commit to the long-term training required to achieve aerobic fitness levels equivalent to a $\dot{V}\text{O}_{2\max}$ of 60 $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. As a result, unfit subjects with a $\dot{V}\text{O}_{2\max}$ below 45 $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ were evaluated before and after 12 days of treadmill walking at 65% $\dot{V}\text{O}_{2\max}$ for 1 h each day (Cheung and McLellan, 1998c). The 12 days of training led to significant decreases in the rise in T_{re} and heart rate at the end of the 1 hour of walking in a thermoneutral environment. The heat-stress test involved wearing the protective clothing and performing light exercise because of our concern that heavy exercise may have masked the beneficial effects of aerobic fitness on tolerance time in the study by Aoyagi et al. (1994). Sweat rate was increased significantly with the training from 0.9 to 1.0 $\text{kg} \cdot \text{h}^{-1}$ but evaporative heat loss from the clothing ensemble was again unchanged at 0.3 $\text{kg} \cdot \text{h}^{-1}$. In addition, there were no changes in the heart rate or T_{re} responses (Fig. 4) and tolerance times approximated 90 min regardless of the state of training.

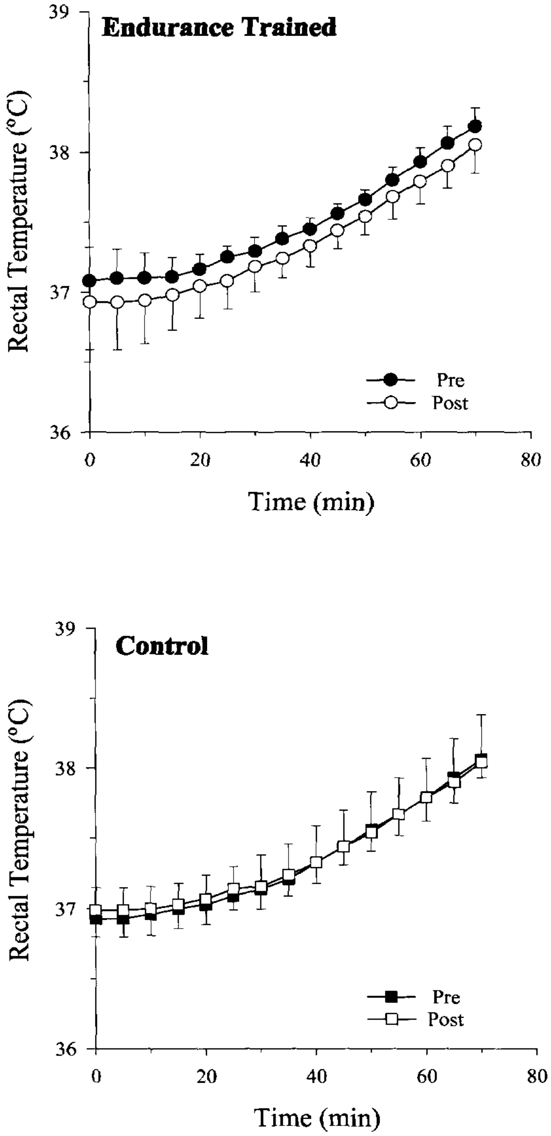

Fig. 4. Rectal temperature responses pre- and post-2 weeks of endurance training (top) or no training (bottom) during heat stress exposure while wearing a protective clothing ensemble. There was no effect of training on the rectal temperature response (from Cheung and McLellan, 1998c).

The ability of short-term aerobic training of unfit individuals to replicate the decreased physiological strain and elevated exercise-heat tolerance observed in individuals with a high level of aerobic fitness is of direct occupational interest. In many occupational settings, workers may be required to work in hot environments with minimal preparation time to significantly increase aerobic fitness or facilities to perform heat acclimation through heat exposures. However, our cross-sectional analyses suggests that, when wearing protective clothing, short-term aerobic training is not an adequate substitute for a high level of aerobic fitness resulting from habitual exercise and training (Cheung and McLellan, 1999). We observed that, following 2 weeks of aerobic training, cardiovascular and thermoregulatory strain during uncompensable heat stress were similar in individuals of low to moderate fitness compared with those of high fitness. However, the range of core temperature that could be tolerated during the heat exposure remained significantly lower in the less fit individuals, as did the final T_{re} before the onset of voluntary exhaustion and overall tolerance time.

Based on the findings from these studies (Cheung and McLellan, 1998b,c, 1999) we would have to conclude that aerobic training programs lasting from 2 to 8 weeks offer little benefit to work performance in the heat for previously unfit subjects when protective clothing is worn. However, the cross-sectional analyses presented above support the importance of aerobic fitness to improve work performance when a very hot and humid microenvironment is created with the wearing of protective clothing. Clearly the longitudinal studies by Aoyagi et al. (1994) and Cheung and McLellan (1998c) were not able to increase aerobic fitness to the level of the high fit subjects involved in the cross-sectional comparison by Cheung and McLellan (1998b). Thus, additional longitudinal studies that involve longer periods of aerobic training with greater changes in aerobic fitness are necessary to relate the magnitude and time course of change in fitness to the changes observed in tolerance time during UHS.

5. Other factors

Other factors, besides elevations in sweat rates that accompany improvements in aerobic fitness, must be involved in explaining the differences in heat tolerance between aerobically fit and unfit subjects. Both the lower resting core temperature and the higher core temperature tolerated at exhaustion for subjects with higher aerobic fitness levels are factors that will increase the work time when the protective clothing is worn (Cheung and McLellan, 1998b). However, sex-related comparisons have shown that the lower heat capacity of adipose tissue can account for the different heat-stress response of men and women when a protective clothing ensemble was worn (McLellan, 1998). Thus, it is unclear whether the greater heat tolerance noted by Cheung and McLellan (1998b) for their high fit subjects was due to their higher aerobic fitness, lower body fatness or some combination of these factors.

We have recently completed data collection from a study that matched subjects for $\dot{V}O_{2max}$ expressed relative to lean body mass and body fatness (Selkirk, 2000). Four groups (six subjects in each group) with either a high ($\dot{V}O_{2max}$ of 65 $ml \cdot kg^{-1} LBM \cdot min^{-1}$) or low (53 $ml \cdot kg^{-1} LBM$ min^{-1}) aerobic fitness and either a high (20%) or low (12%) body fatness were matched and the thermoregulatory and cardiovascular responses were compared during light exercise at 40°C and 30% relative humidity while wearing protective clothing. Tolerance times were significantly greater for subjects with a high aerobic fitness and low body fatness (116 min) compared with the other groups that were similar (70–80 min). Fifty percent of the difference in the rate of increase in T_{re} among groups could be attributed to differences in body fatness with the remainder being due to differences in rates of heat production. Consistent with our previous observations (Cheung and McLellan, 1998b; McLellan, 1998), this study also revealed that subjects with a higher aerobic fitness could tolerate a higher core temperature at exhaustion and that more fit individuals could store more heat per unit of total mass than their less fit counterparts.

Recent evidence has documented that fatigue during heat stress is associated with the attainment of a critically high core temperature approaching 40°C for endurance trained subjects (González-Alonso et al., 1999a,b; Nielsen et al., 1993, 1997). By far, the greatest effect of aerobic fitness on tolerance time during UHS is mediated through the core temperature tolerated at exhaustion. Differences were as great as 0.9°C in our recent study (Selkirk, 2000) between subjects with differing fitness levels matched for a low body fatness and this difference accounted for approximately 70% of the difference in tolerance time between these matched groups. All subjects in the high fit and low body fatness group attained our ethical ceiling of 39.5°C and felt that they could have continued. Thus, differences in tolerance time between these groups were underestimated.

It is unclear why the core temperature that can be tolerated at exhaustion during UHS is considerably less for sedentary subjects. The classical description of the cardiovascular response to heat stress involves a progressive increase in the redistribution of the central blood volume to the cutaneous circulation to increase convective and evaporative heat loss resulting in a lowered venous return, stroke volume, central venous pressure and mean arterial pressure (Rowell, 1986). If the rise in body temperature is sufficiently high, the pooling of blood in the cutaneous circulation may lead to circulatory collapse and a state of unconsciousness. It is tempting to suggest that the untrained compared with the endurance trained may experience greater circulatory strain at any given core temperature during heat stress because of their lower blood volume and stroke volume (Hopper et al., 1988) and that these differences may account for the lower core temperature tolerated at exhaustion. Yet, to our knowledge, there has not been a systematic comparison of the cardiovascular responses during exhaustive exercise in UHS conditions between endurance trained and untrained subjects that might explain the reason for the differing core temperatures that can be tolerated. Recently, Coyle and colleagues have challenged the classical explanation of the cardiovascular response to heat stress in endurance trained subjects. They have shown conclusively with the use of a low dose β-blocker (Fritzsche et al., 1999), supine exercise (González-Alonso et al., 1999c) or prior dehydration and exposure to hot and cold environments (González-Alonso et al. 2000) that the fall in stroke volume during exercise in the heat is not related to peripheral blood flow but instead is the result of the increase in heart rate and decrease in central blood volume. Approximately one-half of the fall in stroke volume during exercise in the heat can be attributed to changes in central blood volume with dehydration (González-Alonso et al., 2000) or change in posture (González-Alonso et al., 1999c). It is interesting that approximately one-half of the difference in the exercise stroke volume between trained and untrained subjects can be attributed to their differences in blood volume (Hopper et al., 1988). Thus, some of the differences in the cardiovascular strain during exercise in the heat between trained and untrained subjects could reflect their differences in central blood volume and this could have an impact on the core temperature that could be tolerated at exhaustion. It is also clear that other factors, in addition to differences in blood volume, may be involved in explaining the differences in the core temperature tolerated at exhaustion. It is likely that well trained subjects are more accustomed through their regular training to the psychological discomforts of exercising at high body temperatures and are willing to endure greater discomfort before they say they are exhausted.

6. Summary

In summary, a high level of aerobic fitness confers an advantage while exercising in the heat and wearing protective clothing that does not involve a greater evaporative heat loss due to elevated sweat rates. Instead, the ability to tolerate higher core temperatures at exhaustion together with typically lower levels of body fatness appear to be the primary factors involved in explaining the longer tolerance times and slower rates of increase in body temperature.

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