PRINCIPLES AND PRACTICES OF HEAT ADAPTATION

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ABSTRACT

During prolonged exercise or work in the heat, human thermal homeostasis is first challenged, and eventually lost, as one moves from a compensable state through to uncompensable heat stress. During the first week of such exposure, work and athletic performance is most affected, and the threat of heat illness is greatest. However, given adequate time, the body will undergo a three-phase adaptation to better tolerate the heat. In this review, the principles and practices of the six primary methods by which such heat adaptation may be achieved are evaluated. One technique involves repeated exposure to both heat and exercise, and is designed to elevate and maintain a target body temperature, by varying the intensity of the work rate during the acclimation period: the controlled-hyperthermia (isothermal) technique. It is recommended that this method provides the most dependable, and least hazardous, means of adapting workers and athletes for heat stress.

INTRODUCTION

Body tissues operate as thermal energy reservoirs, with local tissue temperatures varying as a function of the net heat exchange between the body and environment. Semi-clothed humans employ both autonomic and behavioural mechanisms by which to regulate the thermal status of the *miliue intérieur*. Heat dissipation is primarily mediated via its transportation to the skin surface within the blood. Since the specific heat of blood is relatively high, it is an ideal medium by which to transport heat to the skin surface. On reaching the skin, thermal energy is used to convert sweat into water vapour, thereby removing heat from the body.

Under hot conditions, particularly during prolonged exercise, human thermal homeostasis is first challenged, and may eventually be lost, as one moves from a compensable state through to uncompensable heat stress. This transition is dictated by the combined effects of air temperature and its water vapour pressure, exercise intensity, clothing and its permeability to water vapour, body composition, hydration status, long-term endurance fitness, and state of heat adaptation (Cheung *et al.*, 2000). During heat stress, the cardiovascular system must subserve both the

metabolic demands of active skeletal muscle, and the demand for blood flow at the skin, to dissipate metabolically-derived heat. In the short term, most people, particularly endurance-trained athletes, can satisfy this dual demand. Nevertheless, during prolonged exercise in the heat, thermal homeostasis is compromised, resulting in positive heat storage, and eventually uncompensable heat strain. If the heat loading is high enough, or if the exposure duration is long enough, cardiovascular function is compromised, and it can no longer serve both skin and muscle blood flow demands (Kenney and Johnson, 1992). In this situation, blood pressure declines, and cutaneous vasoconstriction ensues. While sweating can be still remain functional, continued exercise will rapidly elevate body core temperature, eventually leading to heat exhaustion and even heat illness. Regardless of whether such fatigue is associated with the attainment of a critical body temperature (Fuller *et al.*, 1998; González-Alonso *et al.*, 1999), reduced central drive (Brück and Olschewski, 1987), or reduced metabolic function triggered by oxidative stress (Mills *et al.*, 1996), the end result has the same practical outcome: impaired work performance. During the first week of an exercising heat ex-

posure, worker and athlete performance is most affected, and the threat of heat illness is greatest (Armstrong and Maresh, 1991). From a practical perspective, it is during these early days of repeated exposure that workers, and their supervisors, must exercise greatest caution. However, just as humans can adapt to increased physical work, so can they modify the function of both autonomic and behavioural mechanisms for heat dissipation and conservation, to overcome altered thermal stress. Herein, we shall briefly overview the principal physiological adaptations to heat stress, then emphasise how such modifications may best be achieved for military, industrial and sporting applications.

While transformations within the autonomic control of skin blood flow and sweating are perhaps most frequently associated with heat adaptation, a host of readily observed physiological changes are also apparent. For instance, there is an expansion of the plasma volume, associated with an elevation in, or a superior maintenance of, the osmotic potential of the blood, brought about by either a reduction in the heat-induced loss of plasma protein to the interstitial space (Senay, 1972; Harrison, 1985), or a greater retention of the extracellular electrolyte content (Patterson *et al.*, 1999). This plasma expansion typically wanes with progressive exposures, as adaptation to a constant exercise and thermal stress proceeds (Bass *et al.*, 1955; Wyndham *et al.*, 1968). However, when the physiological strain is maintained during adaptation, using small but progressive increments in exercise intensity, this expanded plasma volume is sustained, with elevations being reported for up to three weeks (Patterson *et al.*, 1998a). Indeed, the entire extracellular space may be significantly enlarged during this type of heat adaptation (Patterson *et al.*, 1998a).

Typically, during an exercise-heat stress, the interstitial and plasma volumes contract, as fluid is drawn to fuel sweating. In the unadapted state, this can result in a reduced stroke volume and elevated heart rate, to preserve cardiac output and systemic blood pressure. However, an expanded plasma volume is better able to withstand this fluid loss without compromising stroke volume. Therefore, it is often seen that, following heat adaptation, and when working at a given intensity, the stroke volume is larger and the cardiac frequency lower (Mitchell *et al.*, 1976; Shapiro *et al.*, 1981; Cadarette *et al.*, 1984). The combined effects of these changes permit an eleva-

tion in skin blood flow during heat exposure, and a lowering of the vasodilatory threshold (Fox *et al.*, 1963). Both these mechanisms facilitate a more rapid transference of heat to the periphery for dissipation. Accordingly, people report being less stressed, via thermal and effort sensations, and are better able to tolerate the exercise-heat stress.

Sweating provides our most effective means of heat dissipation within hot environments. This heat dissipation is a form of mass transfer, because fluid is lost from the body, down the water vapour pressure gradient, and with it, heat is transferred up the thermal energy gradient. That is, heat moves from the cooler skin to the warmer air. Therefore, it is not surprising to observe an enhancement of the sweating response accompanying heat adaptation. In fact, the sudomotor modifications potentially represent our most potent adaptive responses.

Specifically, there is an increased steady-state sweat rate (Libert *et al.*, 1983; Sato *et al.*, 1990; Patterson *et al.*, 1998b), an increased sweat gland sensitivity relative to body temperature changes, and a reduced body temperature threshold for sweating onset (Nadel *et al.*, 1974; Patterson *et al.*, 1998b). These adaptations can produce a two-fold increase in sweat rate, increasing from 1.5 to 3 l h⁻¹. The eccrine sweat glands appear to reabsorb more sodium and chloride from the primary sweat, leading to a better conservation of the extracellular electrolyte content (Allan and Wilson, 1971). These changes may also be induced by endurance training, even when conducted in cool-temperate environments (Nadel *et al.*, 1974; Avellini *et al.*, 1982; Henane *et al.*, 1977). Nevertheless, such changes are universally found to be less than elicited through similar training in the heat.

Unfortunately, a more robust, heat-adapted sudomotor system, while advantageous to the semi-clothed endurance athlete, does not implicitly bestow a physiological benefit upon the clothed worker. Consider the worker wearing chemical protective clothing. Typically, this clothing is impermeable to water molecules. Thus, the microclimate will rapidly attain a water vapour pressure which will prevent the evaporation of sweat. Under such conditions, the continued secretion of sweat will not facilitate cooling, but will instead elevate thermal discomfort (Hensel, 1981), and lead to a more rapid dehydration and work performance decrement (McLellan *et al.*, 1993). While it is beyond this review to fully address

the interaction of heat adaptation and clothing (see: Cheung *et al.*, 2000; Goldman, 1994), readers should consider these implications with some circumspection.

When combined with the above cardiovascular changes, sudomotor adaptations act to minimise the affects of exercise and heat stress upon thermal homeostasis, permitting reduced physiological strain and elevated heat tolerance. Collectively, these transformations permit a greater potential for heat flow from the core and active muscles to the skin, a greater potential for dissipation of this heat via the evaporation of sweat, and result in a reduction in both the average skin temperature and core temperature for a given combination of exercise and heat stress (Mitchell *et al.*, 1976; Pandolf *et al.*, 1977; Houmard *et al.*, 1990). Thus, in the semi-clothed state, and following heat adaptation, one may move from an exercising state which may be deemed to be physiologically uncompensable, and into a state in which compensation is physiologically attainable.

Classically, the above physiological modifications have been shown to be elicited in response to naturally-occurring climatic changes (acclimatisation: Hellon *et al.*, 1956; Wells *et al.*, 1980), artificial heat exposure (acclimation: Nadel *et al.*, 1974; Patterson *et al.*, 1998a, 1998b, 1999), or endurance training which produces significant elevations in body temperatures (Gisolfi and Robinson, 1969; Pandolf *et al.*, 1977). In addition, a number of techniques have arisen from which thermal adaptation may also be derived. These methods may confer various levels of pre-exposure heat adaptation, and will be reviewed herein, along with a critical assessment of their relative merits.

HEAT ADAPTATION PROCEDURES

Natural acclimatisation

It is generally recognised that natural heat acclimatisation forms the most effective means by which to increase heat tolerance (Edholm *et al.*, 1963). In climates which undergo considerable seasonal change in air temperature, physiological adaptation occurs via a gradual transition, as air temperatures climb from the cooler to the hotter months (Shapiro *et al.*, 1981; Inoue *et al.*, 1995). In this situation, the simple completion of daily physically-demanding tasks confers some degree of thermal adaptation. Indeed, from an occupational perspective, these subtle changes allow the thermal tolerance of workers and ath-

letes to gradually develop. Thus, long-term residents, and some indigenous groups, appear to be better adapted to the heat than do transient visitors (Hellon *et al.*, 1956; Duncan and Horvath, 1988). Nevertheless, such an extended adaptation procedure is not always possible. For instance, military personnel, athletes and some workers are constrained by the need to rapidly move from one environment to another, and must do so without compromising either their physical performance or their health. Thus, while natural adaptation is the most effective technique, its practical limitations minimise its relevance to many occupational and sporting groups.

Passive heat acclimation

This method represents an extension of natural acclimatisation. Since external (exogenous) heat sources can invoke physiological adaptation (Hensel, 1981; Wells *et al.*, 1980), one may achieve some degree of heat adaptation by passively raising body tissue temperatures, at rest, via the external application of heat. Various means have been employed by which to apply heat: water baths, saunas, climate chambers and vapour-barrier suits (Fox *et al.*, 1963, 1964, 1967; Fox, 1968; Sugeno *et al.*, 1986; Ogawa *et al.*, 1988; Inoue *et al.*, 1995). Fox and colleagues extensively explored the use of vapour-barrier suits to maintain an elevated body temperature. With this controlled, passive hyperthermia technique, body temperature was rapidly increased using exercise in the heat, then held stable (2 h) by dressing subjects in vapour-barrier suits, placing them within a heated chamber, and controlling the rate of heat loss. The authors reported this technique to be very effective in achieving an acclimation effect. Notwithstanding, passive acclimation is less effective than methods which incorporate an active, exercise stress into the acclimation procedure (Shapiro *et al.*, 1981; Wyndham, 1973), and might generally be considered to be a technique of last resort.

Exercise-induced heat adaptation in temperate climates

Exercise elevates muscle and deep tissue temperatures in proportion to the intensity of the exercise stress (Nielsen, 1938; Saltin and Hermansen, 1966). In addition, once an exercise steady state is achieved, and sustained, the body may be placed under a significant thermal load, which very slowly decays when exercise is terminated. If this exercise-induced thermal load is applied on a regular basis, then exercise can in-

duce heat adaptation responses. This association was first recognised by Bean and Eichna (1943), Robinson *et al.* (1943), and Bass *et al.* (1955). Greenleaf (1964) and Piwonka *et al.* (1965) described their endurance-trained subjects as behaving as if they were already heat acclimatised. An elevated aerobic power, which typically accompanies endurance training in more sedentary people, permits a greater cardiovascular stability (Gisolfi and Robinson, 1969; Wells *et al.*, 1980), and more favourable body-fluid dynamics when exposed to the heat (Senay, 1979). In addition, improved heat tolerance is ascribed to the results of repeated simultaneous activation of cutaneous blood vessels and sweat glands to dissipate metabolic (endogenous) heat (Piwonka *et al.*, 1965). Indeed, endurance-trained subjects display an earlier sweat onset (Nadel, 1979) and a greater sweat sensitivity to increments in body temperature (Wells *et al.*, 1980).

Pandolf *et al.* (1977) and Cohen and Gisolfi (1982) reported that, not only does temperate exercise induce heat adaptation, but it also facilitates a more rapid response to the traditional heat acclimation protocols (combined exercise and heat stress; $r=-0.68$). Pandolf *et al.* (1977) found that subjects with an aerobic power $>65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ could be acclimated within about four days, to achieve more stable cardiac frequency and body temperatures during a subsequent heat stress. Moreover, subjects who display an insufficient acclimation response during heat adaptation, have been found to have a low basal fitness level (Kok, 1973). Consequently, the early part of the traditional acclimation regimen might be considered to act more to elevate fitness than acclimation state, with less trained subjects requiring a longer acclimation regimen to achieve a comparable acclimation status.

It is important to note that it is not the aerobic power *per se* which enhances the heat acclimation response, but the method in which aerobic power was elevated, and in particular, the endogenous thermal load accompanying that elevation. This relationship is perhaps best exemplified within the experiments conducted on trained swimmers (Hennane *et al.*, 1977), and the sweatless training work of Hessemer *et al.* (1986). These projects have shown that exercise *per se* is not a sufficient stimulus for heat adaptation. Instead, exercise must induce, and hold, an elevated body temperature to elicit thermal adaptation.

Over the past 50 years, many research groups

have endeavoured to determine which method of exercise-induced heat adaptation best facilitates improved heat tolerance. With hind sight, it is apparent that one cannot make such an assessment without simultaneously quantifying the thermal loading imposed by the exercise. For example, Edholm *et al.* (1963) and Turk and Worsley (1974) relied upon traditional military training regimens to evaluate the efficacy of exercise-induced heat adaptation, finding minimal benefit. Similarly, Cohen and Gisolfi (1982) appraised the impact of differing endurance training intensities upon subsequent heat tolerance, but again without monitoring thermal strain. While such reports are often cited, it is impossible to draw firm conclusions from these investigations, as between-trial differences in thermal strain will result in differences in the stimulus for adaptation. Notable exceptions include studies conducted by Shvartz *et al.* (1973) and Regan *et al.* (1996), wherein exercise-induced adaptation was found to be less effective than traditional heat acclimation. Nevertheless, exercise under temperate conditions can foster heat adaptation, and the following conclusions would appear valid: (a) exercise-induced heat adaptation depends upon the capacity of the exercise to elevate body temperatures, and hold that elevation for an extended duration; (b) body heat storage is proportional to the intensity of the exercise; (c) the total endurance-training volume appears to be more critical than the intensity, once an adequate intensity threshold has been obtained; (d) continuous exercise will more reliably hold an elevated body temperature than will intermittent exercise; (e) heat tolerance is best improved by more prolonged endurance training.

In spite of the benefits of endurance training, it only appears to provide a thermoregulatory benefit during heat exposures of $\sim 2 \text{ h}$ (Wyndham, 1973). Once an adequate basal endurance fitness has been attained, there appears to be little additional thermoregulatory advantage that may accrue from continued endurance training (Bean and Eichna, 1943; Eichna *et al.*, 1945). In addition, on its own, it appears that endurance exercise is an inadequate substitute for heat acclimation (Armstrong and Pandolf, 1988; Gisolfi, 1973; Lind and Bass, 1963; Pandolf, 1979; Regan *et al.*, 1996). It may not be sufficient to simply elevate deep tissue temperatures. Instead, the elevation of peripheral tissue temperatures may be needed to provide a critical thermal

stimulus for complete heat adaptation (Regan *et al.*, 1996). Finally, one must note that endurance training and heat adaptation subserve vastly different physiological and psychological outcomes, and require quite different exercise programmes. While endurance exercise may improve heat tolerance, exercise-induced heat adaptation may have minimal beneficial impact upon the endurance fitness of some trained people, particularly the endurance athlete, and may even be detrimental, due to the reduced work load which may be tolerated in the heat. Thus, it must be remembered that heat acclimation training merely acts to enhance heat tolerance, and should not be used as a substitute for endurance training. For these athletes, heat acclimation is a form of supplementary training.

Exercise-induced heat adaptation in hot climates with solar radiation

While some degree of heat adaptation may be derived from training in temperate conditions, one might expect these adaptations to be less effective than those which might be induced by short-term training in hotter conditions, in which solar radiation constitutes a significant part of the thermal load. Very few studies have addressed this issue, and such studies are very hard to interpret, due to the inability of the researchers to control environmental conditions. Nevertheless, since this type of exposure most closely approximates the conditions that would obtain during natural acclimatisation, it would seem reasonable to suggest that this method would be superior to temperate endurance training. Furthermore, direct solar radiation more readily elevates skin temperature, than does an equivalent increase in air temperature, and Jessen (1990), using the goat model, has shown that the thermoregulatory responses, at a given air temperature, are markedly different when solar radiation forms part of the thermal stimulus. Earlier, Chen and Elizondo (1974), investigating differences between the impact of changes in body and local skin temperature upon heat acclimation, determined that an increased central thermal stimulus, in conjunction with elevated skin temperatures, was necessary for heat acclimation. Since physiological systems adapt to stress, with some degree of adaptation specificity, then it is reasonable to suggest that endurance training, with a solar loading, would elicit a more specific heat adaptation. This premise was first supported by Edholm *et al.* (1963), who compared the thermal tolerance of soldiers living in two vastly different environ-

ments: the Aden (6 weeks) and Scotland. The naturally-acclimatised soldiers displayed superior heat tolerance, and had fewer field-related heat casualties. Similarly, Wells *et al.* (1980) found their endurance-trained males, who regularly exercised under sunny desert conditions, were better adapted than were their acclimatised counterparts. The investigators interpreted this observation to indicate that both endogenous and exogenous heat loads were required for optimal heat adaptation (Wells *et al.*, 1980), a proposition also advanced by Regan *et al.* (1996).

Armstrong *et al.* (1987) investigated highly-trained distance runners during both spring and summer training. They observed equivalent heat tolerance both before and after summer training. Thus, the additional summer training, and its concomitant solar loading, did not elevate heat tolerance above that which existed at the end of spring. Therefore, the state of heat adaptation of the athletes did not improve over summer. This does not mean these athletes were optimally heat adapted, just that summer training did not provide an adequate additional stimulus for heat adaptation. There are two practical implications from this work. First, highly-trained endurance athletes or workers, do not need special thermal preparation to facilitate heat tolerance during seasonal climatic changes. Second, when athletes or workers are required to travel from their winter to compete or work in the summer months of the other hemisphere, additional heat exposure may be required, due to the inadequacy of the solar load during winter exposures.

Combined exercise and heat stress acclimation

We have established that, prior to artificial heat adaptation (acclimation), endurance-trained people will have a thermal tolerance advantage over the untrained. However, Cadarette *et al.* (1984) has shown that this advantage subsides after both trained and untrained subjects undergo heat acclimation, and their thermal tolerance is more homogenous. It is widely acknowledged that, for practical objectives, heat acclimation produces a reasonable and close approximation of the physiological benefits which accompany natural acclimatisation.

One of the paramount advantages of heat acclimation is that one may choose a combination of air temperature and relative humidity which most closely matches the environmen-

tal conditions which might reasonably be expected to be encountered. While the experimental evidence is somewhat sparse, it does appear that some degree of specificity exists relating to the transference of acclimation benefits between hot-dry and hot-humid conditions (Goldman *et al.*, 1965). Humid heat acclimation generally results in a greater elevation in sweating than does dry heat acclimation (Henane, 1980; Shvartz *et al.*, 1973), and dry adaptation does not provide optimal protection for humid exposures (Armstrong *et al.*, 1987). However, Shvartz *et al.*, (1973) found, when subjects were exposed to hot-dry conditions (50°C) following either hot-humid or hot-dry heat acclimation, that the hot-dry acclimation regimen resulted in less thermal strain (see also: Eichna *et al.*, 1950; Gisolfi and Robinson, 1969; Piwonka and Robinson, 1967). Therefore, careful consideration of the projected environment is critical to successful heat acclimation. The conventional heat acclimation regimen involves moderate-to-heavy exercise (e.g. walking, running, cycling, bench stepping) within a temperature- and humidity-controlled chamber. These methods may be grouped into one of three general modes: (a) constant work-rate methods; (b) self-regulated exercise methods; and (c) controlled-hyperthermia methods.

Constant work-rate methods

For this heat-acclimation procedure, subjects exercise at a fixed rate, with body temperatures tracking nett heat storage. This is the most common heat-acclimation method (see: Greenleaf and Greenleaf, 1970 and Sciaraffa *et al.*, 1980), and is the typical model used by military-based researchers, who are tasked with evaluating performance at various fixed work rates, such as the standard marching rate of soldiers (Pandolf *et al.*, 1977, 1988). While this method has wide-ranging application, the observations from this work must be applied with caution. First, since all subjects are forced to exercise at the same absolute intensity, there may be considerable variability in the relative load imposed upon various subjects, thus physiological strain may vary widely between subjects. Such variance within pre-adaptation data will inherently drive these experiments towards the more conservative statistical outcomes. Second, since the work rate is held constant throughout adaptation, the strain during subsequent heat exposure will decline progressively. Thus, the physiological adaptations which derive from this type of regimen may not be identical to those which obtain from ei-

ther of the two methods described below, and the universal application of these observations must be treated with caution.

Self-regulated exercise methods

This method allows subjects to select their own work rates, during prescribed work:rest intervals, on the basis of their endurance fitness or perceived exertion, during heat acclimation exposures (see: Miller, 1984; Armstrong *et al.*, 1986). The between-subject variability is minimised with this approach, but the technique suffers in that it can become quite difficult to control the endogenous thermal load. Accordingly, this method has greater practical utility than is does research application.

Controlled-hyperthermia methods

In this isothermal model, exercise in the heat is used to elevate and maintain a steady-state body temperature above the sweating threshold. Most previous research, which has evaluated the efficacy of exercise-heat exposure regimens, has simply compared heat adaptation responses elicited by those methods, and not the differential thermal forcing functions applied via each method. Since we have herein established that exercise, in the absence of an elevation in body temperature, is an inadequate stimulus for heat adaptation (Hennane *et al.*, 1977; Hessemer *et al.*, 1986), then it follows that, to compare various heat-acclimation methods, one must control and equate the thermal strain imposed upon subjects. Therefore, it is considered more germane to compare experimental conditions on the basis of the thermal potency of the methods, rather than on the basis of their secondary impact upon physiological function. This fundamental methodological limitation has prevented the unequivocal interpretation of most experimental observations, and has made verification of the physiological mechanisms which drive heat adaptation hard to discriminate. Indeed, one may argue that both the constant work-rate and controlled-hypothermia models invoke qualitatively similar, yet quantitatively different physiological outcomes. Fox *et al.* (1961) first utilised the isothermal approach, controlling a constant and elevated body temperature by regulating air and microclimate temperatures, using vapour-barrier suits. Subsequently, Turk (1974), and Turk and Worsley (1974), employed the method to acclimate soldiers, exercising them in the heat whilst monitoring body temperatures, and adjusting the work rate to maintain a predetermined thermal strain. Havenith and van Middendorp (1986) revised this

procedure, adapting it to a work-rest protocol. More recently, we have further developed this technique, using it to explore acclimation-induced changes sweating and body-fluid balance (Regan *et al.*, 1996; Cotter *et al.*, 1997; Patterson *et al.*, 1998a, 1998b, 1999). Two key observations from these studies are applicable to the current discussion.

First, based on significant post-acclimation reductions in core temperature, forehead skin blood flow and perceived exertion, and elevated forehead sweating, Regan *et al.* (1996) concluded that, when a controlled-hyperthermia regimen is performed in the heat, it will invoke a more complete heat acclimation than when controlled-hyperthermia is used under temperate conditions, even when both elicit equivalent core temperature changes during adaptation. Second, we have shown that the plasma volume expansion, previously considered to be only a transitory outcome of short-term heat acclimation, is preserved, with such elevations lasting as long as 21 days (Patterson *et al.*, 1998a). It is concluded that the controlled-hyperthermia model induces a more complete heat adaptation than either the constant or the self-regulated work rate techniques.

Exercise-induced heat adaptation in combination with sweat clothing

An overview of this topic would be incomplete without noting the use of insulated clothing and vapour-barrier clothing to help induce heat adaptation. Interest in this procedure may be traced back to the work of Bass (1963) and Gisolfi and Robinson (1969). Clearly, if this technique was successful, it would have a great practical advantage over the more traditional heat acclimation methods. Unfortunately, there is little empirical evidence to indicate that this procedure is any more beneficial than is endurance training (Allan *et al.*, 1965; Crowdy and Haisman, 1965; Marcus, 1972; Dawson, 1994). Furthermore, it is evident that researchers have generally failed to use appropriate experimental controls or to equate the dependent variables between experimental conditions. For instance, if one treatment elevates body temperatures more than another, then between-condition differences could be predicted *a priori*. In the absence of adequate research, one must conclude at this time, that minimal physiological benefit can arise from the use of sweat clothing during physical training.

RECOMMENDED HEAT ACCLIMATION PROCEDURES

Before discussing the practical recommendations for heat acclimation, it is important for the scientist, supervisor or coach to consider matters related to the acclimation specifications, subject safety and efficiency. These points are listed within Table 1, and will serve to help better decisions to be made concerning the principles and practices of the chosen heat acclimation regimen.

It is the author's view that heat acclimation which employs exercise in the heat, in combination with the controlled-hyperthermia (isothermal) technique, provides the most dependable, and least hazardous, means of heat acclimation. That is, this method permits one to prescribe the thermal load, in terms of the magnitude of the core temperature elevation, and the duration for which the elevation is sustained. However, the technique also produces more uniform body temperature elevations across subjects, which are supervised by both the subjects and trained observers. The following points are noted for careful consideration by the experimenters.

- (i) Select an air temperature which is at least equivalent to that which is anticipated.
- (ii) The upper temperature limit should be ~40 °C for humid exposures, and ~50 °C for dry exposures.
- (iii) Choose the relative humidity based upon the highest anticipated within the target environment.
- (iv) The core temperature elevation should be ~1 °C, but core temperatures should not exceed 39.5 °C. Within these constraints, the magnitude of the core temperature elevation during acclimation should be determined by the following factors: the other duties that the subjects are required to perform between acclimation sessions; the extent of medical coverage available; the ratio of the acclimation subjects to supervisors.
- (v) The mode of exercise used is only an important consideration for athletic groups. For all other groups, one should consider: cost, subject monotony, and the number of people to be simultaneously heat acclimated.
- (vi) The controlled-hyperthermia technique permits the supervisor to focus upon exposure duration, while the subjects themselves modify their work intensity to hold the target core temperature. While there is little empirical data available, the literature indicates that a minimal heat

Table 1 Operational considerations for determining methods of heat adaptation

<i>Acclimation specifications</i>	
	Operational definition of heat acclimation
	Basal acclimation state of workers
	Anticipated worst case thermal stress
	Level of heat acclimation required
	Specificity of the exposure: dry versus humid conditions
	Critical heat exposure work durations
	Test for attainment of heat acclimation
<i>Safety</i>	
	Monitor body temperature and cardiac frequency
	Establish criteria for exposure termination
	Identify subjects most likely to experience dysthermia
	Establish adequate emergency procedures
<i>Efficiency</i>	
	Efficiency of technical personnel
	Individual variations in pre-exposure heat adaptation
	Throughput of subjects
	Acclimation duration required
	Acclimation decay and its minimisation
	Availability of heat acclimation facility

acclimation to expected heat exposure ratio would be 1:2 (Wyndham, 1973; Avellini *et al.*; 1980). When it is anticipated that heat exposures will be relatively short (<2 h), and separated by full recovery periods, then it is recommended that acclimation exposures be of at least equal duration to the anticipated heat exposures. For exposures >3 h, also separated by a full recovery, acclimation exposures should be at least 2 h, or 50% of the anticipated duration, whichever is longer. If consecutive exposures are not planned to provide full recovery periods, then recovery should be considered incomplete, and successive durations should be summed to determine the duration of the acclimation exposure.

(vii) It appears that the length of discrete acclimation exposures is a more important consideration than is the cumulative exposure duration within a day. For instance, Lind and Bass (1963) found that a single 100-min exposure was superior to two 50-min exposures (morning and afternoon). The critical consideration is the time spent at the target body temperature. Therefore, since each exposure has an inherent warm period during which tissue temperatures rise towards the target temperature, then longer exposures permit greater time at, or above, the critical temperature.

(viii) Given enough time, heat acclimation will

progress through three distinct phases (Candas, 1987): the acute phase elevates body temperature; short-term acclimation enhances the sweat response; and long-term acclimation results in sudomotor habituation and improved sweat efficiency, with a reduction in sweat secretion and drip rate. The aim of heat acclimation is to drive the subject into the short-term phase. This cannot occur when exposures are at one-week intervals (Barnett and Maughan, 1993). Furthermore, since not all physiological variables respond at identical rates (Armstrong and Maresh, 1991), it may take up to fourteen days for all systems to enter the short-term heat adaptation phase. However, since there are decreasing returns with each additional day of exposure, once the first week has elapsed, then one must often consider financial factors when determining the duration of the acclimation regimen. For instance, while heat acclimation may not be complete, and will vary between subjects, Turk and Worsley (1974) found that 86% of their subjects could be acclimated within four days, using a one-hour controlled-hyperthermia procedure.

(ix) Finally, we must consider acclimation decay. Williams *et al.* (1967) reported that about 25% of the thermoregulatory adaptation was lost after 6-7 days without heat exposure. As a general guide, it is considered that one loses the

equivalent of one days acclimation every two days (Givoni and Goldman, 1973). Nevertheless, Pandolf *et al.* (1977, 1998) found that subjects with greater endurance fitness, or some degree of pre-existing acclimation state, lost acclimation effects more slowly. Retention seems to last longer following dry acclimation than humid heat acclimation (Pandolf, 1998). While yet awaiting definitive research, it is recommended that one additional heat exposure be used for each five days away from significant heat exposures.

CONCLUSION

It is well established that humans can adapt to many forms of physical stress, including altered thermal environments. While it is generally recognised that natural heat acclimatisation forms the most effective means by which to increase heat tolerance, its practical limitations minimise its relevance to many occupational and sporting groups. The passive exposure to external heat, while mimicking natural thermal exposures, is less effective than are methods which incorporate an active, exercise stress, and might generally be considered to be a technique of last resort. Unquestionably, endurance-trained subjects behave physiologically as if they were already heat acclimatised, but endurance training only appears to provide a thermoregulatory benefit for short-duration heat exposures. Once an adequate basal endurance fitness has been established, there appears to be little additional thermoregulatory advantage from such training.

However, when training is combined with a solar load, one can more closely approximate natural acclimatisation, and such conditions may elicit superior heat adaptation, though the evidence for this is not unequivocal. Therefore, it has become widely acknowledged that heat acclimation produces a close approximation of the physiological benefits which usher natural acclimatisation. Of the conventional heat acclimation methods, it may be concluded that the constant work-rate and controlled-hypothermia models invoke qualitatively similar, yet quantitatively different physiological outcomes. Indeed, the technique which elicits the more complete adaptation, and which provides the more dependable, and less hazardous, means of heat acclimation is the controlled-hyperthermia (isothermal) technique.

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