9

Heat

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Within the context of thermal physiology, the human body consists of a core that is maintained within a narrow temperature band and a periphery that varies in temperature depending on environmental influence. Body core temperature stability is sought to provide a constant physiological state by matching heat loss to metabolic heat production. Such thermoregulation requires a sophisticated set of homeostatic mechanisms and reflexes to enable physical activity in diverse environments, particularly for elite endurance athletes. The preoptic anterior hypothalamus houses the thermoregulatory control center that receives afferent impulses from thermoreceptors located in the core and periphery. Afferent input is referenced against a set point temperature that is subject to circadian rhythm with a nadir of early morning and peak in the late afternoon (Kräuchi and Wirz-Justice 1994). If the integrated body temperature is higher than the set point, effector heat loss mechanisms, such as sweating and increased blood flow to the cutaneous circuit, are initiated in an attempt to maintain thermal homeostasis (figure 9.1). Cutaneous blood flow enhances the potential for dry heat exchange, whereas increased sweating allows for heat loss through evaporation.

Physiological Responses to Hot Environmental Conditions

Endurance activities in the heat challenge human thermoregulation. For the purposes of this chapter, the terms *hot* and *humid* are used to describe environments that limit heat dissipation. Although it is acknowledged that the combination of heat and elevated environmental water vapor pressure pose a more severe thermoregulatory challenge than a hot but dry environment, the responses to physical activity and strategies to maximize performance contained within this chapter do not differentiate between environmental conditions. Rather, this chapter provides an overview of the physiological responses to exercise in the heat and provides strategies that can be tailored to meet the needs of the individual athlete.

Cardiovascular Responses

Skin temperature and cutaneous blood flow are higher for a given workload in hot environments (Patterson et al. 1994; Lee et al. 1995) because blood pools in the compliant cutaneous venous plexus at the expense of smooth muscle (Rowell, 1986) and possibly skeletal muscle (Gonzalez-Alonso et al. 1998). These responses displace central blood volume (Johnson and Rowell, 1975) and cause mean arterial pressure and venous return to decrease (Nybo and Nielsen, 2001a). A compensatory increase in heart rate eventuates in an effort to defend cardiac output (Gonzalez-Alonso et al. 1999) and meet demand from the contracting musculature and cutaneous circuit. A higher cardiac frequency for a given workload is therefore observed for physical activity in hot conditions.

High ambient temperatures limit endogenous heat transfer by convection, conduction, and radiation compared with a cool environment. A greater reliance is consequently placed on evaporative heat loss to achieve thermal equilibrium. The higher sweat rates observed in the heat (Galloway and Maughan 1997; Maxwell et al. 1996) contribute to cardiovascular

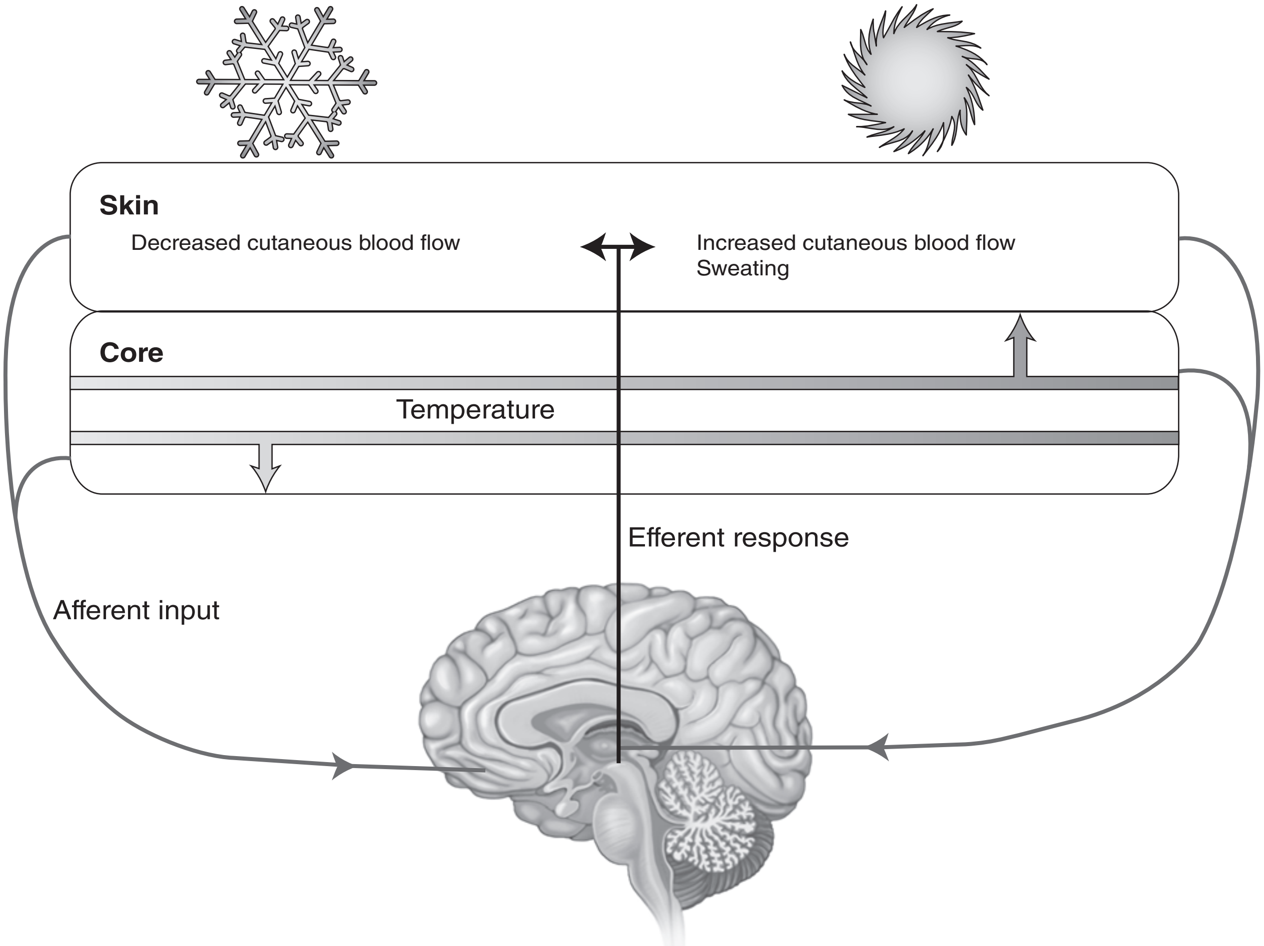

FIGURE 9.1 Schematic of effector responses to increased body temperature.

strain by lowering plasma volume (Singh et al. 1993). The concomitant loss of plasma volume and increase in plasma osmolality alter the body temperature to sweat production relationship, eventually causing sweat rate to plateau or decrease (Fortney et al. 1981; Sawka et al. 1989).

Thermal Responses

The combination of physical activity and restricted dry and evaporative heat exchange in a hot and humid environment elevates peripheral and core tissue temperatures compared with cooler conditions. For example, 25 min of moderate cycling in 40 °C resulted in a core body temperature of 38.9 °C, whereas the same exercise bout in a thermoneutral 20 °C produced approximately 37.9 °C (Parkin et al. 1999). A similar experimental design extended to 40 min of cycling resulted in core body temperatures of 38.7 and 39.7 °C for temperate and hot conditions, respectively (Febbraio et al. 1994). Similar findings are reported for less intense exercise. Jentjens and colleagues (2002) reported a core body temperature of 39.1 °C following 90 min of 55% $\dot{V}O_2$max cycling in 35 °C compared with a core body temperature of 38.3 °C cycling in 16 °C. Time trial performances permit self-selection of pace (power output) based on physiological and perceptual cues. Such performances also result in higher (Tucker et al. 2004) or similar core body temperature (Tatterson et al. 2000) responses despite lower power outputs and heat production in hot conditions. Peripheral temperatures are also higher during exercise in the heat as demonstrated by the 3 to 5 °C skin temperature discrepancy between hot and thermoneutral environments (Adams et al. 1975; Jentjens et al. 2002).

Higher rates of body heat storage in hot conditions coupled with the maintenance of moderate metabolic rates ensure the onset of hyperthermia, a condition observed to occur at an esophageal temperature of approximately 40 °C during fixed workload cycling for well-trained subjects (Gonzalez-Alonso et al. 1998, 1999; Nybo and Nielsen 2001b). These findings purport high internal temperatures (~40 °C) as an independent cause of exhaustion during prolonged exercise in the heat. Although evidence of a set point temperature for fatigue is persuasive, observations of substantially cooler internal temperatures at exhaustion following fixed workload exercise (Cheung and McLellan 1998; Mitchell et al. 2003; Saboisky et al. 2003) signify that other factors contribute to fatigue in the heat. Furthermore, when athletes are free to select their workload, exercise intensity appears to be regulated prior to the failure of the thermoregulatory system that manifests as heat stroke. The integration of afferent feedback from the body's physiological systems combined with motivation, experience, and expected distance or duration therefore determines pace selection (Noakes 2011; Noakes et al. 2005). The aforementioned observations of fatigue that coincides with core body temperatures of ~40 °C (Gonzalez-Alonso et al. 1998, 1999; Nybo and Nielsen 2001b) precedes the development of heat stroke support such a protective mechanism (Noakes 2011). Hence the physiological responses observed during athletic competition in the heat contribute to the selection of a pace that allows physical activity to be completed within the physiological limits of the body, ultimately serving the preservation of life.

Metabolic Responses

Evidence exists for an alteration in metabolism with physical activity in a hot environment. Some (Dimri et al. 1980; Febbraio et al. 1994; Young et al. 1985) but not all investigators (Maxwell et al. 1996; Snow et al. 1993) have concluded that exercise in a hot environment relies more on anaerobic processes than does exercise in a cool environment based on observations of elevated blood and plasma lactate concentrations during submaximal exercise in the heat. Because blood lactate concentration is the net product of lactate production and removal, blunted lactate clearance may account for the observed differences, rather than a greater reliance on anaerobic processes per se. Exercise-induced heat stress results in redistribution of blood flow to the periphery to permit heat exchange, which causes vasoconstriction of renal and splanchnic vascular beds (Rowell 1986), thereby mobilizing vascular reserves to defend central blood volume such that splanchnic vasoconstriction may reduce the rate of hepatic lactate removal. However, observations of slower rates of adenosine diphosphate rephosphorylation (Willis and Jackman 1994), elevated respiratory exchange ratio, and reduced muscle blood flow in the heat support the concept of anaerobic processes (Febbraio et al. 1994; Gonzalez-Alonso and Calbet 2003), particularly during intense exercise.

Diversion of blood flow to the cutaneous circuit lowers cardiac output (Gonzalez-Alonso et al. 1999; Nadel et al. 1979), thus decreasing maximal aerobic power in the heat (Gonzalez-Alonso and Calbet 2003), whereas hot conditions increase the aerobic energy cost of submaximal physical activity (MacDougall et al. 1974) that might be related to additional cost of sweating, circulatory, and respiratory mechanisms. Exercise in the heat also increases glycogen usage (Febbraio et al. 1994) and accelerates adenosine triphosphate degradation and muscle glycolysis (Kozlowski et al. 1985). Overall, the metabolic response to exercise in the heat is characterized by increased aerobic and anaerobic energy cost during submaximal exercise and reduced maximal aerobic power.

Hematological Responses

Expansion of plasma volume has been commonly reported after heat adaptation and leads to an increase in stroke volume (Nielsen et al. 1993; Patterson et al. 2004). The increase in plasma volume associated with training in the heat may be a result of an influx of protein from the cutaneous interstitial space to the vascular compartments or perhaps from sodium and water retention that results in an isosmotic plasma volume expansion (Nielsen et al. 1993). Patterson and colleagues (2004) demonstrated that exercise in the heat induced a volume expansion that was present across the entire extracellular compartment and not restricted to just plasma volume. The expansion of extracellular fluid and plasma volume is a factor of water movement between the body fluid compartments and is driven by the balance of osmotic and hydrostatic forces acting across the capillary beds. This can result from reduced capillary hydrostatic pressure, elevated interstitial hydrostatic pressure, or an elevated intravascular osmotic pressure due to an increased plasma protein content (Patterson et al. 2004).

Performance in the Heat

In addressing physical performance in hot conditions, most investigators have used continuous exercise modes to show that sustained exercise performance is compromised in the heat. Time to exhaustion at a constant workload is lower when conducted in hot conditions across a variety of research designs (Febbraio et al. 1994; Galloway and Maughan 1997; Parkin et al. 1999). Figure 9.2 demonstrates the relationship between time to exhaustion and environmental temperature.

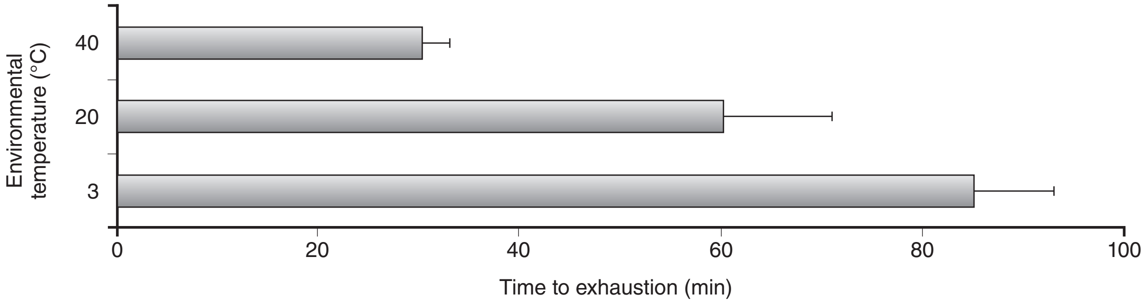

FIGURE 9.2 Time to exhaustion at 70% $\dot{V}O_2max$ in 3, 20, and 40 °C (<50% relative humidity). Data given as mean with error bars representing standard deviation.

Adapted from J.M. Parkin et al., 1999, "Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise," *Journal of Applied Physiology* 86(3):902-908. Used with permission.

Time trial performance is also detrimentally influenced by high environmental temperatures. Thirty minutes of high-intensity cycling in the heat (32 °C) reduces self-selected power output by 6.5% compared with cycling in temperate (23 °C) conditions (Tatterson et al. 2000). Similar findings have been reported for 20 km time trial performances in 15 and 35 °C respectively, where power output significantly decreased toward the end of the cycling bout (Tucker et al. 2004). Hence, continuous exercise performance in the heat consistently demonstrates an adverse influence for high environmental temperatures.

Although the magnitudes of effect comparisons between continuous and intermittent tests are problematic given the diversity of experimental designs, prolonged intermittent exercise also demonstrates an adverse effect for hot conditions. This point has been supported by studies showing shorter time to exhaustion during (Kraning and Gonzalez 1991; Maxwell et al. 1996; Morris et al. 1998) and following intermittent activity (Finn et al. 2001). The detrimental effect of heat on prolonged intermittent exercise should be delineated from the performance benefits of brief supramaximal exercise in the heat (Ball et al. 1999; Falk et al. 1998). Although high muscle temperatures are conducive to increasing power output (Sargeant 1987), prolonging the duration of activity induces rapid heat storage that becomes detrimental for endurance.

Hot conditions exert a profound effect on physiological, perceptual, and performance responses to continuous and intermittent exercise. Higher core and peripheral temperatures, cardiac frequencies, sweat rates, cutaneous blood flow, and thermal sensation eventuate during physical activity in the heat. While all physiological responses may contribute to the curtailment of endurance performance, core body temperature is recognized as the key physiological variable for athletes competing in hot conditions (Sawka et al. 1992). Core body temperature measurement and analysis are therefore priorities in efforts to maximize performance.

Thermal Assessment of Athletes

Responses to physical activity in the heat are highly individual, the product of heat generation and dissipation. Heat production is dependent upon muscle mass and work rate, whereas heat dissipation relies on sweat rate, skin blood flow, morphology, and the environment. Although work rate, sweat rate, and skin blood flow can be routinely measured, the impact of athlete morphology is difficult to model yet extremely important, with in excess of half an individual's body tissue located within 2.5 cm of the heat dissipation site, the skin (DuBois 1951).

Advancements in technology for measuring core body temperature have permitted the monitoring of athletes in the field via an ingestible thermometer (Mittal et al. 1991). Assessing an individual's core body temperature response to training sessions or, preferably, competitions allows sport scientists to analyze the net result of the interactions among the environment, heat production, and heat loss, negating the need for complex modeling. Ideally, the thermal assessment takes place in a hot environment with enough lead time to allow athletes to adjust to and become accustomed to heat management strategies prior to their key competition. Such analysis can predict which athletes require individualized heat management strategies, a process deemed critical to the performance of team sports in hot conditions given that it may not be practical to provide cooling for the entire team.

The data need to be analyzed in conjunction with additional physiological observations such as cardiac frequency and sweat rate; perceptual data including rate of perceived exertion, thermal sensation, and thermal discomfort; and performance data inclusive of movement (global positioning system) and coaches' feedback.

Checklist for Thermal Assessment Using Core Body Temperature Pills

1. Administer core body temperature pill with meal a minimum of 4 h prior to assessment.
2. Immediately prior to the assessment session, measure core body temperature before and following consumption of cool fluid. A rapid reduction in temperature indicates that the pill is located within the stomach and is susceptible to underestimating core body temperature following fluid consumption.
3. Assess core body temperature throughout the session or during breaks. Collect as many data points as possible.
4. Measure core body temperature at end of session.

Such analysis will identify athletes who consistently achieve high core body temperatures (>39.5 °C) in conjunction with the aforementioned factors. Figure 9.3 summarizes the core body temperature response of three international field hockey athletes to a test match played in hot and humid conditions. The analysis and the coaches' feedback indicated that athlete 3 had a high workload that manifested in the core body temperature response displayed. This athlete was prioritized as the most likely to benefit from heat management strategies that include acclimatization or acclimation, hydration, and cooling.

Acclimatization

Heat acclimatization is the process of adaptation to sustained thermal stress in the natural environment. Although acute heat storage causes increased cutaneous blood flow and sweating, repeated bouts of thermal stress lead to physiological and perceptual adaptation thereby improving tolerance of hot and humid conditions. Heat acclimation refers to the same process achieved through simulated conditions and is addressed in a subsequent section.

Heat acclimatization can be achieved passively or actively. Substantial heat storage in the absence of physical activity is rare, requiring extremely hot conditions. Heat acclimatization can be supplemented by sustained passive heat exposure; however, this is not recommended because of limited advantages observed during physical activity, this method's poor time efficiency, high levels of perceptual strain, and impact on recovery from training. Active heat acclimatization uses physical training as an endogenous heat source in warm to hot conditions to limit heat dissipation and promote heat storage.

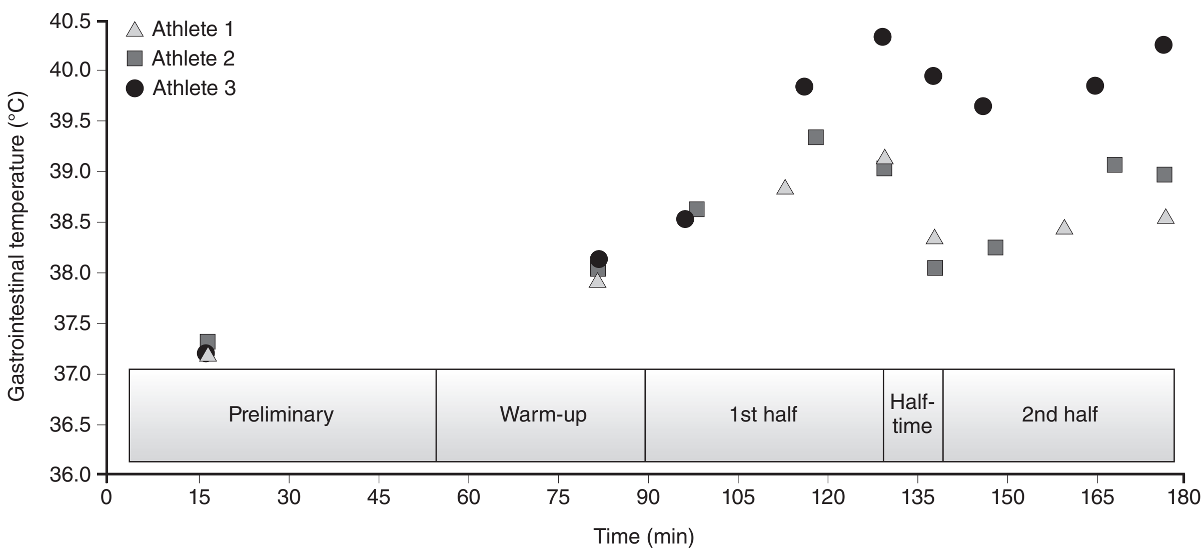

FIGURE 9.3 Gastrointestinal temperature responses of three international field hockey athletes to a test match played in hot and humid conditions.

For acclimatization to be beneficial in maintaining thermal homeostasis in hot conditions, metabolic heat production or heat dissipation pathways must be modulated. Body heat loss pathways at rest and during physical activity are augmented by acclimatization, such that a lower resting metabolic rate and improved capacity for evaporative heat exchange are observed. Heat acclimatization promotes a series of adaptations as summarized in the sidebar, including lower resting core body temperature (Kampmann et al. 2008), an earlier onset of sweating (Shido et al. 1999), and an increased capacity to sweat (Armstrong and Kenney 1993).

Augmentation of cutaneous blood flow following heat acclimatization allows for greater dry heat exchange, and although cutaneous blood flow has been observed to increase following acclimatization (Armstrong and Kenney 1993), this may be principally a result of training (Aoyagi et al. 1994). Collectively, these adaptations provide a greater window for heat storage prior to attainment of an abnormally high core body temperature.

The classic view of heat acclimatization dictates that individuals require up to 14 days of daily heat storage to confer full acclimatization (Armstrong and Maresh 1991). Such observations have come from a small field of research examining trained but not elite athletes. Adaptations to chronic endurance training mimic those of heat acclimatization; therefore, elite endurance athletes are considered to be partially heat acclimatized (Pandolf et al. 1977), especially those who train and compete in temperate climates. Elite athletes who predominantly train and compete in warm to hot environments can be classified as heat acclimatized. For these athletes, the primary goal of undertaking sessions in hot conditions in the lead-up to an event or competition in the heat is to practice pacing and heat management strategies rather than to promote physiological adaptation per se.

The time required to maximize performance in hot conditions requires individual consideration of the following factors:

- Training status
- History of training and competing in hot conditions
- Climate of key event or competition
- Familiarity with pacing strategies in the heat

Elite endurance athletes are unlikely to require 2 weeks to induce heat acclimatization. They may, however, require a similar amount of time to practice pacing and to become accustomed to pacing and heat management strategies. Training should be specific and should induce elevations of core body temperature beyond 38.5 °C with a concomitant thermal sensation of warm to hot, some thermal discomfort, and a high sweat rate. Self-pacing requires a delicate balance between enduring a level of physiological stress to promote adaptation and preventing the development of excessive heat storage, particularly during the early stages of a heat acclimatization program. Therefore, the initial sessions upon visiting a hot climate should account for the additional effect of the new climate.

If the heat acclimatization or pacing period occurs immediately prior to key competition, planning is required to ensure that tapering doesn't limit opportunities to adapt and sustain efforts similar to those of the competition. This potentially results in the earlier commencement of heat acclimatization and maintenance throughout the latter stages of the taper. Again, this will be an individual consideration.

Other factors to take into account for heat acclimatization planning are seasonal influence, age, and gender. It's intuitive to expect that daily activity during the summer months would contribute to heat acclimatization. Behaviors such as avoiding the hottest part of the day and using air conditioning limit physiological strain and the associated stimulus for adaptation. Unless specific sessions that induce substantial heat storage are undertaken during the summer months, minimal benefit is anticipated (Bain and Jay 2011). Heat acclimatization appears to

Adaptations Observed During Heat Acclimatization

Initial

- Expanded plasma volume
- Increased cutaneous blood flow
- Decreased heart rate
- Decreased perception of effort

Subsequent

- Decreased resting core body temperature
- Decreased exercise core body temperature
- Increased sweat secretion

be equally effective for individuals irrespective of age or gender when matched for fitness and morphological variables (Avellini et al. 1980).

Acclimation

As previously mentioned, the negative effects of exercising in heat and humidity can be attenuated to a large degree by a period of heat acclimatization, a process that involves training under similar conditions to allow the body to adapt and to perform better. Heat acclimation is another method of preparing for competition in the heat, making use of heat rooms or climate chambers during winter months or when in a location where conditions are much cooler than the competition. Acclimation can be used for longer periods, because there is constant respite from the heat and athletes are not consequently exposed to oppressive conditions. It is recommended that heat acclimation be supplemented with a shorter session (1-2 weeks) of acclimatization in a climate similar to that of competition to allow the body full adaptation for competing in the heat. The type of training done should be specific to the sport as long as the particular ergometer (treadmill, cycle, rowing) can be sourced. Nonspecific exercise can be used (e.g., cycling for a runner) if this is the only option and will still drive adaptations from exercising in the heat. Initially, low-intensity exercise should be performed, with duration and intensity added during the acclimation process.

Work done at the Australian Institute of Sport (AIS) found good performance benefits for race walkers who were preparing for competitions in the heat at the Osaka World Championships 2007 and Beijing Olympic Games 2008. The athletes undertook 7 to 8 weeks of 60 to 90 min of exercise in a heat tent once per week prior to departure and a further 10 days of acclimatization in the race venue prior to competition. This strategy provided good preparation for the athletes by exposing them to the heat once per week but allowed adequate respite and recovery between these sessions. In this particular heat acclimation, the 60 to 90 min exercise sessions were conducted at easy intensity at the start of the 8 weeks and then increased in intensity, with the last 2 weeks including intervals at race pace. This strategy can be used in preparation for summer competition; during the spring, athletes undertake 1 or 2 sessions per week outdoors in the middle of the day, or in a heated gym or a hot room on a treadmill or stationary bike to start the acclimatization process.

Hydration

In the absence of fluid replenishment during prolonged physical activity in the heat, the production of sweat results in dehydration. Sweating can reduce plasma volume (Maw et al. 1998) and diminish extracellular fluid reserves during high-intensity exercise of prolonged duration. This decreases the volume of blood that can be distributed between the active muscles and the cutaneous circuit. Dehydration-induced decreases in blood volume have the primary effects of decreasing venous return, decreasing cardiac output (Nadel et al. 1980), and increasing plasma osmolality (Kamijo et al. 2005). Such responses have led sport scientists to use hydration strategies to maximize performance in the heat. In this regard, hydration may have been overemphasized as a quick-fix for athletes competing in hot conditions. In terms of heat management strategies, hydration appears to be more familiar to athletes than the alternative or complementary strategies of heat acclimatization and cooling. Furthermore, this awareness exists despite the lack of consensus in the published literature regarding optimal athlete hydration practices. Athletes and coaches should understand that hydration is one factor that can contribute to performance in the heat and that consideration of all strategies is a prerequisite for best results. So how do athletes ensure that their hydration practices are helping them maximize their performance in the heat?

One viewpoint is to ensure that fluid losses are limited to less than 2% of body mass to prevent performance decrement (Cheuvront et al. 2003). To satisfy this criterion, athletes need to assess sweat rates and dehydration levels across a variety of sessions and climatic conditions. Hence, the relatively simple procedures of monitoring athlete fluid balance are now common in elite sport. Dehydration can be assessed by monitoring pre- and postcompetition seminude body mass on calibrated scales. Postcompetition body mass is measured following the removal of sweat from the skin surface and hair by toweling down, and dehydration is estimated by the following equation:

$$\text{Dehydration (\% body mass)} = (\text{Precompetition Body Mass} - \text{Postcompetition Body Mass}) / (\text{Postcompetition Body Mass} \times 100).$$

In addition to body mass, fluid consumption, urine or fecal output, and analysis time can be monitored to permit estimation of sweat rate (see following equation). Athletes can be allocated individual drink bottles from which they exclusively consume fluids. Fluid consumption is calculated by measuring bottle mass prior to and following the analysis period. Bottles can be weighed empty and again following refilling when multiple bottles were required. Urine and fecal output can be accounted for by measuring body mass prior to and following toilet breaks without the need to remove training attire. Respiratory and metabolic fluid losses are generally not accounted for in field settings, and it is assumed that 1 kg is equivalent to 1 L of sweat.

$$\text{Sweat Rate } (\text{L} \cdot \text{h}^{-1}) = (\text{Precompetition Body Mass} - \text{Postcompetition Body Mass} + \text{Fluid Consumption} - \text{Urine and Fecal Output}) \,/\, \text{Analysis Time (hours)}.$$

To complement sweat rate and dehydration, hydration status is routinely assessed through a variety of urinary indices (Kavouras 2002). The accuracy of urine hydration status diminishes during periods of rapid fluid turnover (Kovacs et al. 1999). Because athletes typically hydrate prior to competition and training, which generally requires the consumption of large volumes of fluid in hot climates, the validity of urine hydration indices could be jeopardized. Despite this limitation, urine specific gravity is a common measurement that can be compared with published standards (table 9.1) to permit interpretation of results and provide feedback to athletes and coaches.

Intense exercise in the heat can lead to high sweat rates (Brearley and Watkins 2007). Factors including gastrointestinal distress and limited access to fluids can reduce opportunities to match such sweat rates with fluid consumption. Hence, athletes generally develop a degree of dehydration during training or competition in the heat. Approximately 2% body mass is thought to be a criterion for dehydration-induced performance decrement (Below et al. 1995; Walsh et al. 1994), reflected in the consensus statement of the American College of Sports Medicine Roundtable on Hydration and Physical Activity (Casa et al. 2005). Through the estimation of sweat rates and dehydration, athletes can develop a schedule of fluid consumption to maintain their fluid balance within the 2% body mass window.

An alternative recommendation is for athletes to consume fluids ad libitum, thereby drinking to the dictates of thirst (Noakes 2007). Thirst sensation maintains serum osmolality and sodium concentration, increasing the drive to drink and reducing the intensity of exercise (Sawka and Noakes 2007). Hence, avoiding a reduction in power output can be achieved by avoiding thirst.

TABLE 9.1 Urine Specific Gravity and Equivalent Level of Hydration

Condition	Urine specific gravity value
Well hydrated	<1.010
Minimal dehydration	1.010-1.020
Significant dehydration	1.021-1.030
Serious dehydration	>1.030

Adapted, by permission, from D.J. Casa et al., 2000, "National Athletic Trainers' Association position statement: Fluid replacement for athletes," *Journal of Athletic Training* 35(2): 212-224.

Despite the obvious differences between strategies, the common feature is that athletes require fluid during prolonged activity in the heat. Whether to consume fluid to nearly match sweat losses or to drink ad libitum is an individual consideration. Ad libitum consumption is an appropriate starting point for athletes. For short- to moderate-duration events, ad libitum fluid consumption may limit dehydration to less than 2% body mass because drinking to one's pleasure accounts for 50% to 70% of sweat losses during exercise (Cheuvront and Haymes 2001). As discussed for heat acclimatization and pacing, testing the fluid consumption strategy is required to optimize strategies for individual athletes. Fluid volume is only one drinking variable: beverage temperature, availability to fluids, scheduled breaks, and hydration beliefs are other factors to consider.

Acclimatization and fluid consumption are two strategies that potentially augment body heat loss in the heat. An alternative strategy is cooling, a method that demonstrates potential for increasing the ability to store heat.

Cooling

Precooling entails a range of methods that decrease skin and possibly core body temperature by the individual or combined application of ice, cold air, and cold or temperate water prior to competition. Specific precooling methods used to date include ice jackets, water immersion, crushed ice ingestion, ice towels, forearm immersion, fans, and cold air.

Ice Jackets

The cooling mode most widely used in sport science entails compressing ice against the skin in jackets or vests. Prior to the 1996 Atlanta Olympics, AIS scientists developed ice jackets that slightly blunted the core body temperature increase when worn during warm-up periods. Others have cooled athletes during warm-up periods to achieve cooler core and peripheral temperatures prior to performance. Arngrimsson and colleagues (2004) applied the AIS-designed ice jacket during a 38 min warm-up in tropical conditions to lower core body temperature by 0.2 °C. Using a cooling jacket during moderate cycling in hot conditions resulted in a lower rectal temperature (0.2 °C) following 45 min (Hasegawa et al. 2005). The limited cooling power of ice jackets probably explains the failure to lower core body temperature with a 5 min application before and during scheduled breaks of a simulated hockey protocol (Duffield et al. 2003). However, ice jackets have the potential to maintain a lower core body temperature achieved through other cooling methods (Quod et al. 2008).

The primary advantage of using garments containing ice for cooling is their practicality; however, this advantage is diminished for repeated bouts of use, because the garment requires recooling. Overall, commercially available ice jackets demonstrate a limited potential to curb heat storage and are only recommended for short warm-up periods. Combining the use of ice jackets with additional cooling modalities is required to achieve and maintain substantial decreases in core body temperature, because ice jackets are ineffective for precooling when used in isolation.

Water Immersion

There are two primary options for water immersion precooling: a relatively short immersion (<10 min) at cold water temperatures (<15 °C) or a longer immersion protocol of 20 to 30 min in temperate water (25-28 °C). The limited data available for short-duration immersions show that 5 min of exposure to 14 °C water is not effective for resting subjects (Peiffer et al. 2010a), which is not surprising given that short bouts of cooling are most effective for individuals following heat storage, as high internal temperatures limit the effect of local skin cooling on vasoconstriction, allowing greater contact time for blood with the cooled periphery (Casa et al. 2007). The same protocol can lower core body temperature by approximately 0.5 °C for warm or hot subjects (Peiffer et al. 2009a); however, there is minimal core body temperature difference when immersion in 14 °C is sustained for 5, 10, or 20 min (Peiffer et al 2009b) and minimal differences for 5 °C versus 14 °C cooling for 12 min (Clements et al. 2002). Although short-duration cold water protocols are effective in rapidly reducing core body temperature during hyperthermia, practicality issues arise when operating in tropical field conditions. The availability of the required volumes of ice to initially lower and subsequently maintain water temperature limits the utility of this method. For example, lowering the temperature of a 600 L water bath from 25 °C to 14 °C would require approximately 83 kg of ice (table 9.2).

In the absence of an appropriate mechanical cooling apparatus, immersion protocols that use temperate water are most likely to be of use in the field. Temperate water immersion is a popular means of cooling prior to competition, as athletes seek to lower their core body temperature without inducing shivering. To achieve this, athletes undergo approximately 30 min of 25 to 28 °C immersion, which can lower core body temperature by approximately 0.5 °C (Brearley and Finn 2006; Marino et al. 1998). Gradually lowering water temperature limits "cold shock" and allows transmission of body heat to the water over an extended period. Despite the logistical benefits of using temperate water as a cooling modality following heat storage, it has been the topic of less research than other cooling methods.

TABLE 9.2 Volume of Ice Required to Lower Water Temperature of a 600 L Bath From 25 °C to Desired Temperature

Desired water temperature	20 °C	14 °C	8 °C
Ice requirement, kg	37.5	82.5	127.5

Water immersion shouldn't be limited to precooling. Immersion during scheduled breaks of competition can be achieved, even for sports that have short half-time periods (10 min), such as field hockey (figure 9.4).

Crushed Ice Ingestion

Consumption of cold fluid can modestly decrease core body temperature prior to performance and improve submaximal time to exhaustion in the heat (Lee et al. 2008), demonstrating some potential as an alternative to water immersion. Preliminary research suggests that the ingestion of crushed ice may be both effective and practical. Commonly referred to as a *slurpee* or *slushie*, crushed ice was identified as a possible cooling method for athletes prior to the 2004 Athens Olympics (Brearley and Finn 2003), because the mechanical cooling properties of ice are far greater than an equivalent volume of cold fluid. The Northern Territory Institute of Sport (NTIS) physiologists subsequently experimented with ice ingestion for athletes in the field, who provided positive feedback in terms of thermal comfort and performance. Preliminary research supports the feedback from field trials. For example, consuming 7.5 mL · kg^{-1} of crushed ice (−1 °C) lowered core body temperature by approximately 0.7 °C and improved submaximal running performance, whereas an equivalent volume of cold fluids (4 °C) reduced core body temperature by approximately 0.3 °C (Siegel et al. 2010). Ihsan and colleagues (2010) demonstrated that crushed ice ingestion lowers core body temperature prior to exercise and translates to improved time to complete a given volume of cycling compared with temperate fluid ingestion. The combination of a large bolus of crushed ice (14 mL · kg^{-1}) with the application of iced towels also improved physiological and performance responses to a simulated time trial based on characteristics of the 2008 Beijing Olympic time trial course (Ross et al. 2011).

Although crushed ice has been the subject of less research than have alternative modes of cooling, its

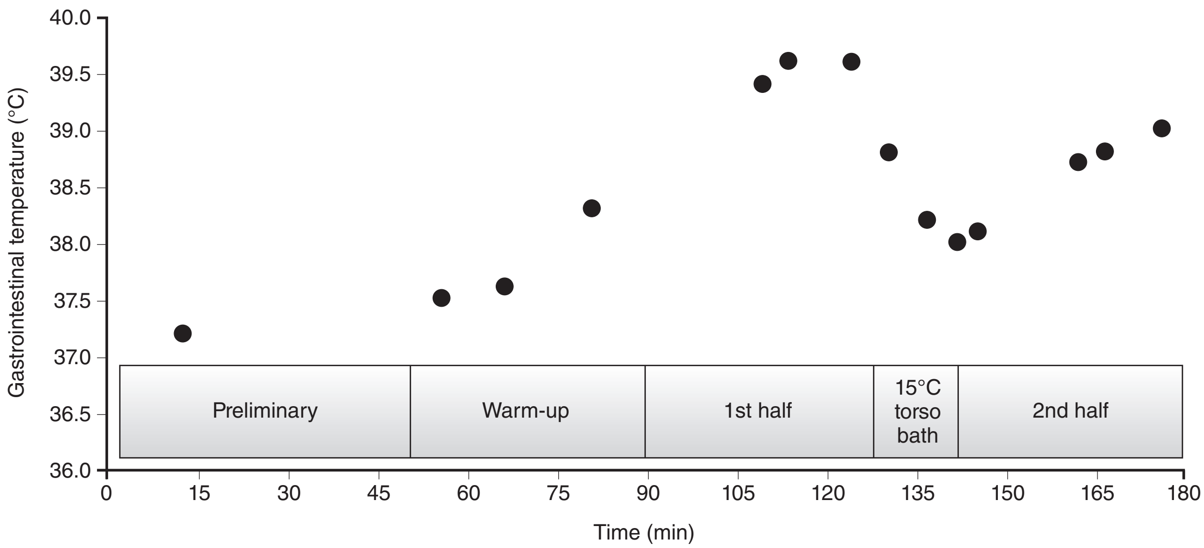

FIGURE 9.4 Gastrointestinal temperature response of an international field hockey athlete to 8 min of 15 °C torso immersion at half-time during a test match played in hot and humid conditions.

practicality and preliminary physiological and performance benefits warrant strong consideration for cooling in athletic settings. The potential for cooling at half-time and during breaks in competition ought to be explored in a research setting. Given the tropical field experiences of the NTIS, research is likely to support the use of crushed ice as a viable alternative to water immersion prior to and during endurance events in the heat (Siegel et al. 2012). This method requires refinement for each individual in terms of timing of ingestion and required volume. Making a slurpee or a slushie can involve elaborate, commercially available machines or simply cubed ice, a powered sports drink, and a blender.

Ice Towels

Ice towels have not been stringently researched but are nonetheless recognized as a treatment for hyperthermia (Roberts, 2007), best suited to field settings where core body temperature cooling rates for hyperthermic runners approximate half the rate observed for cold water immersion (Armstrong et al. 1996). In terms of precooling, ice towels have been tested as part of broader precooling strategies for athletes (Duffield et al. 2009; Myler et al. 1989; Ross et al. 2011). Based on the limited data available, alternative cooling techniques possess greater potential to achieve a substantial reduction of core body temperature, leading sport scientists to use ice towels in conjunction with other precooling methods (Duffield et al. 2009; Ross et al. 2011). Having limited cooling power, ice towels appear best suited to scheduled breaks in competition, and their use is frequently observed in elite team sports played in hot conditions.

Forearm and Hand Immersion

Another practical cooling method is immersion of the forearm and hand or of the hand alone in cold water, typically set at 10 °C. Forearm immersion relies on lowering core body temperature through convective heat transfer between the blood and forearm tissue (Ducharme and Tikuisis 1991) and can be effective for repeated work and cooling bouts. Giesbrecht and colleagues (2007) used three bouts of working for 20 min followed by 20 min of 10 °C forearm immersion, which lowered core body temperature by 0.6 °C more than control and 0.3 °C more than 20 °C forearm immersion. Hand immersion at 10 °C has also provided small physiological benefits when used for only 10 min following 50 min of work (Khomenok et al. 2008). Forearm immersion has been observed in some athletic settings despite the small physiological benefits observed to date. This method is much simpler to implement by using custom-made chairs with forearm cooling reservoirs and is useful in events where more powerful cooling modalities are not feasible. Using hand cooling may influence manual dexterity (Cheung et al. 2003), so testing this method in the training environment is recommended prior to implementation for competition.

Fans

Evaporative cooling is a simple method that can be effective and is often bypassed in favor of more technically demanding cooling modes. Evaporative cooling needs to be maximized as part of any heat management strategy. Movement of air should be the initial consideration for athlete management in the heat, with additional cooling strategies used to supplement the convection achieved by fans.

Cold Air

Cold air cooling is primarily reliant on convective heat loss for reductions in body temperature given the lack of mechanical cooling power exerted by air. Application of cold air to the skin causes vasoconstriction of the cutaneous circuit (Makinen et al. 2000), which limits the blood supply available to be cooled, negating convective heat transfer. This factor appears responsible for the inability of cold air (5-10 °C) cooling protocols to lower deep tissue temperature during precooling of moderately trained athletes (Lee and Haymes 1995; Oksa et al. 1993; Olschewski and Bruck 1988). However, 30 min of air cooling (5 °C) for lean, highly trained athletes can decrease core body temperature by approximately 0.5 °C (Kruk et al. 1990), suggesting that the lack of mechanical cooling power can be partially diminished by low subcutaneous fat levels. Overall, cold air precooling is unlikely to be an option for elite athletes because access to commercial portable "cold rooms" may be limited in hot conditions. Rooms that are cooled simply by standard air-conditioning are warmer (minimum temperature ~16 °C) than cold rooms and thus are unlikely to provide a substantial benefit during precooling; however, their use during scheduled breaks in competition is an option worth pursuing.

The different physiological responses between air precooling and the provision of air cooling during physical activity to alter body heat storage appear related to the temperature gradient between the air and skin and the evaporative potential of sweat. Maintenance of skin temperature above approximately 32 °C will minimize cutaneous vasoconstriction and maximize blood volume available to be cooled at the skin's surface (Veicsteinas et al. 1982). At higher metabolic rates that induce sweating, the provision of conditioned air augments sweat efficiency (Shapiro et al. 1982), thereby limiting body heat storage (Vallerand et al. 1991). Air conditioning also provides perceptual relief from the heat and is a preferred option for scheduled breaks in play, particularly for team sports in which many athletes potentially require cooling and other methods are deemed impractical.

Other Factors

Spending time between training sessions in cool conditions is considered important for acclimatizing athletes who are unused to the hotter conditions and assists in the adaptation process by allowing optimal recovery following training. Should the coach and athlete detect symptoms of unusual tiredness or problems associated with insufficient recovery between quality sessions or extended-duration sessions, the athlete should train during the coolest part of the day before resuming more stressful training in expected race conditions. This becomes increasingly important the closer it gets to the final taper period. Access to air-conditioned living quarters is essential between training to obtain respite from the heat and facilitate recovery. However, it is advisable to assist acclimatization by spending a certain amount of time in the natural environment. It is a good idea, perhaps for psychological as well as physical reasons, to train, at least on some occasions, at the same time of day as the competition. Of course, coaches and athletes must be very careful to avoid overexposure to any harsh conditions.

Athletes should avoid direct solar radiation where possible by using head protection as well as appropriate clothing and sunscreen. Clothing provides a barrier to heat dissipation during exercise and can interfere with evaporation of sweat and impair the cooling effect of sweating (Wendt et al. 2007). However, clothing provides protection from the radiant heat from the sun. Therefore, when exercising in the heat, athletes should wear minimal clothing if there is not a large degree of radiant heat from the sun (early morning, evening, or overcast) but should wear loose-fitting, light-colored clothing as well as a hat and sunglasses if exercising in the middle of the day to protect against the radiant heat from the sun. Sunscreen is recommended in summer to avoid sunburn.

Carbohydrate requirements for exercise are increased in the heat because of a shift in substrate utilization toward carbohydrate oxidation (Febbraio et al. 2001). The daily diet should focus on replacing glycogen stores after exercise. Competition strategies should include activities to enhance carbohydrate availability, such as building up glycogen stores in preparation for endurance events; pre-event carbohydrate intake; and intake of glucose or electrolytes in events lasting longer than 60 min. This can be done using water and carbohydrate gel preparations or using sports drinks. It has been reported that intake of carbohydrates prior to and during prolonged exercise in the heat enhances exercise performance (Burke et al. 2005).

Use of Heat and Humidity as a Training Intervention

Lower core body temperatures resulting from training in the heat as well as an increase in plasma volume resulting from both acute and chronic bouts of exercise in the heat may attenuate the magnitude of the thermoregulatory response (increased ventilation, circulation, and sweating) and reduce the increased energy requirements associated with heat stress (Svedenhag 2000). It follows that whole blood viscosity would be reduced from training in the heat, and a decreased viscosity has been shown to have positive effects on endurance performance (Telford et al. 1994). Adaptations from training in warm to hot conditions may also allow athletes to train at any given speed with a lower heart rate and core body temperature, both of which are associated with improved exercise economy (Thomas et al. 1995). These findings support the premise that training in moderate heat may improve economy and performance at normal temperatures. Training in the heat can be used as an additional stress, similar to altitude training, because the training load is higher at any given speed when training in the heat. A recent study demonstrated that 10 days of 90 min submaximal exercise training in a hot environment (40 °C and 30% humidity) improved cycling time trial performance in a cool environment (13 °C and 30% humidity) compared with a matched control group who did the same training in the cool environment (Lorenzo et al. 2010). The authors of this study suggested the increased performance was due to an ability to exercise at a higher power for reduced relative intensity (improved economy), an improved lactate threshold, and an improved cardiac performance, all a result of using heat as training intervention.

Core Body Temperature Measurement Site

No single internal temperature site represents core body temperature (Sawka and Wenger 1988); however, multisite internal temperature measurement is difficult in controlled settings and not possible during athletic training and competition. Given the proximity of the esophagus to the aorta, esophageal temperature is considered to represent the temperature of the blood perfusing the heart (Shiraki et al. 1986). Rectal temperature transition is more reliant on conduction of heat and therefore reacts more slowly to variations in temperature because of its deep position and lower blood flow (Mairiaux et al. 1983), whereas the gastrointestinal tract is not as well insulated as the rectum and receives higher blood flow (Mortensen et al. 1998). Direct comparisons between core body temperature measurement sites validated the use of gastrointestinal temperature as a core body temperature index, as it corresponds to increased heat storage in an intermediate manner to esophageal and rectal temperature (O'Brien et al. 1998). The valid measurement of core body temperature from the gastrointestinal tract has provided sport scientists access to data that were previously collected from the tympanic membrane. The cost-effectiveness, ease of measurement, and relatively noninvasive nature of tympanic temperature measurement still promote the tympanum as a core body temperature measurement site. Although agreement between tympanic and other core body temperatures has been reported (Amoateng-Adjepong et al. 1999; Christensen and Boysen 2002), the data from athletes competing in the heat do not support such a claim. The NTIS has vast experience measuring athlete core body temperature. Several trials have analyzed tympanic temperature in the field referenced against gastrointestinal temperature. One such study examined the physiological responses of cricketers during competition in the tropics, where tympanic temperature averaged approximately 1.3 to 1.6 °C lower than gastrointestinal temperature, confirming that large discrepancies occur between tympanic and deep tissue temperature (Armstrong et al. 1994). It is reasonable to expect greater variation for tympanic temperature and gastrointestinal temperature in the field compared with the laboratory, because fluctuating environmental conditions would influence tympanic temperature (Fraden and Lackey 1991).

Improved results are likely through the use of tympanic probes (Sato et al. 1996) and insulation of the ear (Muir et al. 2001), but these are not practical in sporting settings given the requirement for exact positioning, irritability of placement proximal to tympanic membrane, and a decreased ability to detect aural cues. Additionally, the use of tympanic temperature is limited by the ability to straighten the auditory canal via the "ear tug" maneuver and permit access to the tympanic membrane. Therefore, it is strongly recommended that sport scientists refrain from interpreting tympanic temperature data of athletes in the field. If core body temperature is to be measured in field settings, gastrointestinal temperature is recommended due to its validity and practicality.

Heat-Associated Illness

The combination of physical activity and hot environments has produced observations of heat syncope, heat exhaustion, and general heat illness with collapse and a loss of consciousness a common feature. As Noakes (2008) describes, postexercise postural hypotension is the primary cause of heat illness, not heat storage per se. Although the hypotension is multifactoral, environmental conditions are not the primary cause. The term *heat illness* should be used to describe the excessive retention of body heat during exercise via abnormal heat production or failure to dissipate an adequate amount of body heat with a resultant severe elevation of core body temperature beyond 41 °C.

Normally, human behavior will modulate exercise intensity (and therefore metabolic heat production) in response to efferent feedback, including that from the central and peripheral thermoreceptors. The development of core body temperatures in excess of 41 °C is relatively rare, generally being observed in athletes treated by medical staff following mass participation events such as fun runs and marathons (Richards et al. 1979). Observations of athletes achieving core body temperatures of 38.5 to 40.5 °C in hot conditions are common, as these measurements can be considered operating temperature for athletes in such conditions. A more common symptom observed for those requiring medical attention is hypotension (Noakes 2008), most frequently observed immediately following exercise. Cessation of exercise removes the lower-limb muscle pump, instantly displacing central blood volume and rapidly reducing right atrial pressure (Noakes 2003). This in turn evokes the Barcroft-Edholm reflex, which results in paradoxical vasodilation and resultant hypotension. Sport scientists should be aware of this "finish line syncope" and understand that attaining a severely high core body temperature is extremely unlikely for healthy individuals who pace their effort according to physiological cues and have sufficient time in hot conditions to practice such pacing.

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