Preventing Death from Exertional Heat Stroke—The Long Road from Evidence to Policy

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Abstract:

Exertional heat stroke (EHS) is among the leading causes of sudden death during sport and physical activity. However, previous research has shown that EHS is 100% survivable when rapidly recognized and appropriate treatment is provided. Establishing policies to address issues related to the prevention and treatment of EHS, including heat acclimatization, environment-based activity modification, body temperature assessment using rectal thermometry, and immediate, onsite treatment using cold-water immersion attenuates the risk of EHS mortality and morbidity. This article provides an overview of the current evidence regarding EHS prevention and management. The transfer of scientific knowledge to clinical practice has shown great success for saving EHS patients. Further efforts are needed to implement evidence-based policies to not only mitigate EHS fatality but also to reduce the overall incidence of EHS.

Keywords: rectal thermometry | cold-water immersion | tarp-assisted cooling | hydration | heat acclimatization

Article:

Exertional heat stroke (EHS) is among the leading causes of sudden death during sport and physical activity (Boden, Breit, Beachler, Williams, & Mueller, 2013; Mueller & Colgate, 2009). Various facets of EHS prevention, recognition, and treatment are supported in the scientific literature, allowing clinicians to develop and implement evidence-based practices to reduce the risk of EHS, or in the event of EHS, ensure 100% survival. This translation of scientific evidence into best practices and policies has allowed for transformational changes in the care we, as clinicians, provide to patients at all levels of sport and physical activity.

Establishing policies to address issues related to the prevention and treatment of EHS including heat acclimatization and environment-based activity modifications, body temperature assessment using rectal thermometry, and immediate, onsite treatment using cold-water immersion attenuates the risk of EHS mortality and morbidity. The purpose of this review is to provide the scientific research behind current evidence-based recommendations and policies related to EHS prevention and management.

Heat Acclimation/Acclimatization

It has been known since the early 1900s that heat acclimation plays a large part in the body's physiologic responses, adaptations, and overall ability to cope with heat exposure (Pandolf, 1998). *Heat acclimation* is a broad term loosely defined as a complex series of adaptations that occur in a controlled thermal environment over the course of 7–14 days, leading to reductions in heart rate, decreased core and skin temperature responses, decreased perceived exertion, increased sweat rate, hastened sweat onset, decreased sodium losses in sweat and urine, increased stroke volume, increased plasma volume, and an overall enhanced ability to perform in the heat (Armstrong & Maresh, 1991; Pawelczyk, 2001). Heat acclimatization results in the same physiologic changes; however, it is much more common as the term is used when these changes occur in a natural environment. Recent evidence has suggested that short-term heat exposure (5–7 days) is also effective for inducing heat acclimation (Chalmers, Esterman, Eston, Bowering, & Norton, 2014). However, not all physiological adaptations involved with heat acclimation, such as increased sweat rate, occur during this shortened period (Chalmers et al., 2014). To elicit all of the physiological benefits involved with heat acclimation, it requires 10–14 days of heat exposure (Armstrong & Maresh, 1991).

In addition, there are other factors that can determine the extent to which heat acclimation adaptations occur. For example, acclimation in hot and dry environments elicits a lower increase in sweat rate compared with heat acclimatization occurring in hot and humid environments (Armstrong & Maresh, 1991). Although the ideal intensity at which acclimation is elicited is diverse and still not completely clear, acclimation is known to depend on maintenance of an elevated body temperature during exercise (Armstrong & Maresh, 1991; Pandolf, 1979). Therefore, it is also important for athletes to exercise at an intensity great enough to elevate body temperature, which is the main stimulus behind heat acclimation.

In 2003 the National Collegiate Athletic Association (NCAA) recommended that heat acclimatization be implemented during the preseason period (Casa, Anderson, et al., 2012). In 2009, similar recommendations were made for high school athletes (Casa et al., 2009). This has been highlighted in more recent years due to the number of athlete deaths that have occurred during the first few days when athletes return to activity (Bergeron et al., 2005; Casa et al., 2013; Grundstein et al., 2012; Kerr, Casa, Marshall, & Comstock, 2013). In support of this change and the dramatic results at the NCAA level, it is now recommended that all athletes, regardless of level of sport, follow a heat acclimatization program at the start of all preseason or return-to-activity periods (Casa, Anderson, et al., 2012; Casa et al., 2013; Casa, Guskiewicz, et al., 2012). When attempting to acclimatize to the heat, athletes should gain a base level of fitness in a cool environment before heat exposure. Highly fit individuals already have some of the physical advantages that are gained with acclimation, for example, an increased sweat rate. In addition, athletes should exercise at intensities greater than 50% of their maximal oxygen consumption (VO_{2max}), with intensity increasing throughout training to maximize adaptation (Armstrong & Maresh, 1991). After an athlete is acclimatized to the heat, he or she will lose less sodium and potassium during exercise, thereby retaining more water. The athlete will increase his or her sweat rate, which aids in cooling but also increases the demand for water consumption during exercise. This last point is extremely important to note because as athletes gain fitness and become acclimatized to the heat, their water needs increase. Guidelines have been introduced for the high school population to implement gradual heat acclimatization during the preseason period (Casa et al., 2009). The main recommendations can be seen in Table 1, starting with the first day of preseason practice. It should be noted that while these recommendations are specific to sports with equipment/helmets, it should not prohibit other sports from following the guidelines, as they apply, given their sport-specific equipment demands.

Table 1. Secondary School Preseason Heat Acclimatization Guidelines

	Practices 1–5		
Area of Practice Modification[1]	**Days 1–2**	**Days 3–5**	**Practices 6–14**
Number of practices permitted per day	1 session	1 session	2 sessions; only every other day
Equipment	Helmets only	Helmets and shoulder pads	Full equipment
Maximum duration of single practice session	3 hr	3 hr	3 hr; a total maximum of 5 hr on double session days
Permitted walk-through time[2]	1 hr; must be separated from practice for 3 continuous hours	1 hr; must be separated from practice for 3 continuous hours	1 hr; must be separated from practice for 3 continuous hours
Contact	No contact	Contact only with blocking sleds and dummies	Full, 100% live contact drills

[1] Warm up, stretching, cool-down, conditioning, and weight-room activities are included as part of practice time. [2] Walk-through is not included as practice time.
Adapted from Casa, D.J., & Csillan, D. (2009). Preseason heat-acclimatization guidelines for secondary school athletics. *Journal of Athletic Training, 44*, 332–333.

While the NCAA was the first to implement heat acclimatization policies in 2003 (National Collegiate Athletic Association [NCAA], 2012), the National Athletic Trainers' Association (NATA) released similar guidelines in 2009, with a consensus statement for high school students (Casa et al., 2009) followed by a 2012 interassociation task force document with expanded recommendations for college athletes during condition session periods (Casa, Anderson, et al., 2012). In 2011 the National Football League (NFL) followed suit and adopted heat guidelines for preseason practice that took it a step further by eliminating two-a-day practices (National Football League [NFL], 2010).

The most compelling result is that since the 2003 NCAA guidelines, there have only been two deaths from EHS during the preseason period (Kucera, Klossner, Colgate, & Cantu, 2015; Mueller & Colgate, 2009), when the NCAA was averaging ~one death every year before this, saving, at a minimum, over 15 athlete lives to this point, but potentially up to 30 athletes. (Stearns, O'Connor, Casa, & Kenny, 2017) This represents a sevenfold reduction in the rate of EHS deaths seen during the preseason. Similar success has been demonstrated within the high school model since its implementation. As of 2015, there were 14 states that adopted the NATA heat acclimatization guidelines (Attanasio, Adams, Stearns, Huggins, & Casa, 2016). Within these states, examining the period before the adoption of the guidelines from 1980 to 2015, there were a total of 22 EHS deaths; 50% of all EHS deaths were in high school football athletes during this time period. After the adoption of the heat acclimatization guidelines, no EHS deaths have occurred when the policies were followed. It is relevant to note that one death did occur within a state during this time, but the school was in violation of their state policy, further emphasizing the importance of these guidelines (Attanasio et al., 2016). See Figure 1 for heat acclimatization policy effectiveness.

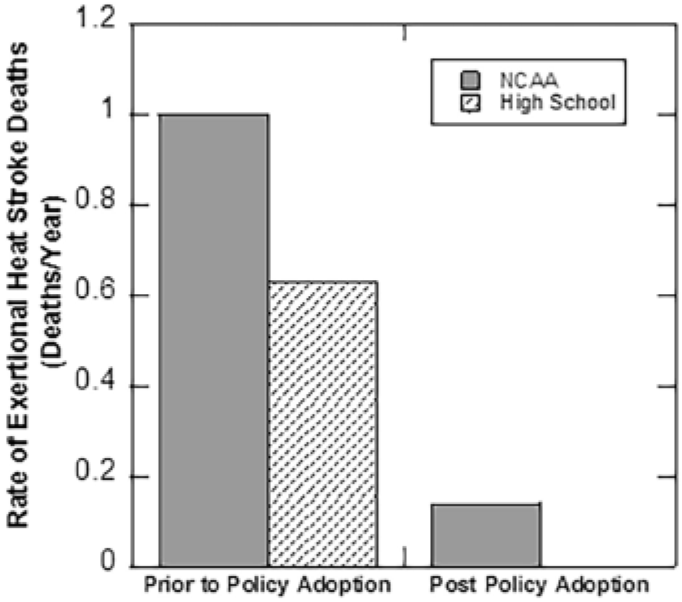

Figure 1. Heat acclimatization policy effectiveness at reducing heat stroke deaths during preseason practices within NCAA football and all high school sports within the 14 states that adopted the policy (as of 2015). Data compiled from Attanasio et al., 2016; Kucera et al., 2015; Mueller & Colgate, 2009; Stearns et al., 2017.

The authors strongly recommend that those with the responsibility for the health and safety of athletes within any organized sport program adopt and enforce these guidelines. The initial evidence for the effectiveness of these guidelines, the scientific basis for the advantages that accompany heat acclimatization, and the minimal to no cost associated with policy implementation makes these recommendations reasonable to implement and critical to enforce.

Environmental Conditions and Work-to-Rest Ratios

Maintenance of thermoregulatory balance between the amount of metabolic heat produced and dissipation of heat load is vital for safely sustaining prolonged periods of physical activity in the heat. During EHS, the metabolic heat generated by the body cannot be dissipated to the environment at an adequate amount, leading to dangerous rises in body temperature. This heat dissipation may be further inhibited by the environmental conditions. Environmental monitoring provides a unique chance for clinicians and organizers to detect potentially hazardous conditions on the day of an activity through a weather forecasting and live-monitoring system. This delivers an opportunity for universal precautions in modifying the time, duration, and intensity of physical activity (Table 2, Recommendation 1). When proper precautions, such as modifying the start of practice to cooler times of the day and adjusting the work-to-rest ratios according to environmental conditions are neglected, it may pose even greater risk for at-risk populations for exertional heat illness (Grundstein et al., 2012).

Numerous heat indices have been developed, but the two most commonly used indices in athletics are the Heat Index (HI) and wet bulb globe temperature (WBGT) (Budd, 2008; Epstein & Moran, 2006). HI is a model that utilizes ambient temperature (T_a) and relative humidity (RH) for the input values with an assumption that a person who is 5 ft. 7 in. and weight 147 lbs. is walking in light wind conditions while wearing a long sleeved shirt and pants (Steadman, 1979). On the other hand, WBGT was developed by the U.S. Navy as a solution to reduce the endemic episodes of exertional heat illness during military training (Yaglou & Minard, 1957). WBGT is derived from input values of wet bulb temperature (Tw), black globe temperature (T_g), and T_a (WBGT = $0.7T_w + 0.2T_g + 0.1T_a$); T_w is an indicator of maximal amount of evaporative cooling allowed in the air, T_g is an indicator of mean radiant temperature (i.e., combined influence from the solar radiation, air temperature, and air velocity), and T_a is the simple measure of the temperature of the air. Since WBGT takes into account the environmental factors that affect physical activity more than HI, sport organizations and clinical experts have recommended the use of WBGT over HI for activity modification measurements (Armstrong et al., 2007; Casa et al., 2015; NCAA, 2014) (Table 2, Recommendation 2). These recommendations include specific thresholds for allowing outdoor physical activities, as well as graded modifications for work-to-rest ratios, total practice time, and regulating the number and length of rest breaks for purposes of rehydration and body cooling (Table 2, Recommendation 4, 6–9). Recently, regionally-specific activity modifications were proposed to adjust for the different climate characteristics observed in the contiguous United States (Grundstein, Williams, Phan, & Cooper, 2015). This model will ensure that activity modifications are activated when the observed condition is above its regional standard (Table 2, Recommendation 3).

Table 2. Heat Safety Policies Regarding Environmental Condition Monitoring

1. State requires all schools to have a heat modification policy for any sanctioned activity
2. The recommended heat policy is based off of WBGT (not heat index or any other methods); heat index is only acceptable for schools without funding for WBGT and where the state is actively petitioning for funding to supply WBGT
3. The WBGT temperature guidelines are based off of epidemiological data specific to that state/region (for bigger states, a more comprehensive analysis may be needed); state required to seek alternative ways to obtain WBGT for their area via weather station WBGT or other valid local sources
4. The heat policy has at least a four-step progression of modifications (does not include the limit that dictates normal practice)
5. Policy includes modification of equipment (if applicable to the sport)
6. Policy includes specific modification of work-to-rest ratios
7. Policy includes specific modification of total practice time
8. Policy includes specific modification of water breaks
9. Policy mentions the use of a shaded area for rest breaks

WBGT = wet bulb globe temperature.

Protective equipment and clothing worn during athletic activities also play a significant role in determining the thermal load experienced by the exercising individual. The extra layer introduced by the garments creates a microenvironment that hinders the ability of the body to dissipate heat (Armstrong et al., 2010; Kulka & Kenney, 2002). For example, with environmental conditions of 85 °F and 60% humidity, it would be too oppressive for a person to exercise with full football gear (e.g., helmet, undershirt, shoulder pads, jersey, shorts, and game pants with thigh, hip and knee pads), but would be tolerable if he is in a practice ensemble (i.e., no game pants with thigh and knee pads) (Kulka & Kenney, 2002). Therefore, in high thermal conditions, modifying the attire worn is warranted in addition to modifying the activity itself (i.e., duration, time of day, intensity) (Table 2, Recommendation 5). Taken together, the use of activity modifications according to environmental conditions allows for greater opportunities to limit excess heat gain and promote adequate heat dissipation through appropriate rest breaks and exercise attire.

Rectal Temperature

The emergent nature of EHS is likely due to the duration of time that an individual is hyperthermic, rather than the maximal body temperature attained. Therefore, it has been suggested that the "Golden Hour" for EHS treatment is well within 1 hr to optimize outcomes from the life-threatening event (Heled, Rav-Acha, Shani, Epstein, & Moran, 2004). In fact, Adams et al. identified that the timing for a clinician to recognize EHS may actually begin well in advance of the athlete's collapse (Adams, Hosokawa, & Casa, 2015). It is for this reason, to maximize the likelihood of survival, EHS needs to be identified rapidly.

One of the greatest obstacles faced by clinicians is the large amount of misinformation that exists regarding EHS diagnosis. EHS is not a condition that only occurs in warm environments. EHS has been documented in individuals performing intense exercise in temperate and cool environments (Shapiro & Seidman, 1990). Furthermore, many texts perpetuate signs and symptoms associated with classical heat stroke as applying equally to EHS. The EHS patient is typically sweating profusely and may not be hypohydrated in contrast to classical heat stroke, which may present with these signs.

Table 3. Differential Diagnosis of a Collapsed Athlete

Sign and Symptoms	Heat Exhaustion	Exertional Heat Stroke	Exertional Sickling	Hyponatremia	Cardiac Conditions
Body temperature < 40.5 °C	X		X	X	X
Body temperature ≥ 40.5 °C		X			
Blood sodium < 130 mEq/L				X	
Blood sodium ≥ 130 mEq/L	X	X	X		X
CNS dysfunction	X	X		X	
Loss of consciousness		X	X	X	X
Diarrhea	X	X		X	
Vomiting	X	X		X	
Nausea	X	X		X	
Peripheral swelling			X	X	
Seizures		X		X	X
Muscle cramping	X		X	X	X
Fatigue	X		X		
Inability to catch one's breath			X		

CNS = central nervous system.
Adapted from Casa, D.J., & Stearns, R.L. (Eds.). (2017). *Preventing Sudden Death in Sport and Physical Activity* (2nd ed.). Burlington, MA: Jones and Bartlett Learning.

The two accepted criteria for the diagnosis of EHS are the presence of (a) end-organ dysfunction, typically central nervous system (CNS); and (b) a body temperature greater than 40.5 °C (Casa et al., 2015). CNS dysfunction in EHS typically manifests as mood changes, confusion, irritability, or aggressive behavior culminating in collapse or loss of consciousness (Casa et al., 2015). However, in the context of exercise in warm environments there are myriad conditions that could present with CNS dysfunction, ranging from hypoglycemia to hyponatremia, making diagnosis based on patient observation alone very difficult (see Table 3). In addition, a lucid interval may persist, further complicating identification. Therefore, to definitively rule-in EHS the clinician must obtain an accurate body temperature to determine the extent of hyperthermia (Casa, Armstrong, Kenny, O'Connor, & Huggins, 2012).

One of the prevailing reasons why athletes continue to die of EHS is the lack of an accurate body temperature measurement delaying appropriate treatment (Casa, Armstrong, et al., 2012). While there are many devices designed to measure body temperature, very few have been shown to be valid for hyperthermic individuals performing exercise. Esophageal, pulmonary artery, and bladder temperature are all commonly used in hospitals to accurately measure internal body temperature (Moran & Mendal, 2002). However, the logistics of obtaining these temperature measures on a comatose or combative patient limit their effectiveness in the field. Similarly, although gastrointestinal temperature via ingestible thermistor has been shown to be accurate, the logistics of the method preclude its use in an EHS emergency situation (Hosokawa, Adams, & Casa, 2016; Hosokawa, Adams, Stearns, & Casa, 2016).

Aural, oral, tympanic, temporal, and axillary temperature are all commonly proposed as methods for body temperature measurement. However, the multiple influences of the external environment and the body's physiology impede these devices from being accurate under exercising conditions (Casa et al., 2007; Ganio et al., 2009). For example, oral temperature can be affected by the fluid an individual drinks (Mazerolle, Ganio, Casa, Vingren, & Klau, 2011) and aural temperature is influenced by the external environment (Huggins, Glaviano, Negishi, Casa, & Hertel, 2012). Further complicating matters, these external measurements show a nonuniformity in their bias, making mathematical corrections impossible (Casa et al., 2007; Ganio et al., 2009).

With the above-mentioned methods to assess body temperature excluded, the only acceptable field-expedient method remaining is rectal temperature. Rectal temperature has been shown to reflect internal body temperature during exercise and is an acceptable reference (Moran & Mendal, 2002). Furthermore, the logistical issues associated with other internal methods are easy to overcome with rectal temperature. Finally, when using an indwelling thermistor, temperature monitoring during treatment is easily facilitated.

The prompt recognition of EHS is a key component of management and treatment of the condition. Even a few minutes that are wasted because of the lack of an accurate body temperature can quickly degrade the window in which the clinician may still save a life. Once a clinician knows that an individual is acutely hyperthermic via a rectal temperature measurement, the decision to continue EHS treatment and potentially save a life is very easy. For these reasons, NATA, the American College of Sports Medicine, and the U.S. Air Force and Army indicate the use of rectal thermometry for EHS recognition (Armstrong et al., 2007; Casa et al., 2015; Headquarters, Departments of the Army and Air Force, 2003).

Cold-Water Immersion

The process of treating a patient with EHS is not overly complicated, but it requires the completion of a few vital elements to assure a successful outcome (see Table 4). The first step is immediate recognition of the condition from both physical signs and symptoms as well as the assessment of internal body temperature with a valid device. Once EHS is suspected, survival is contingent on time; the evidence in the EHS treatment literature has shown that the number of minutes above the threshold for cell damage (estimated to be approximately 40.8 °C) will determine the outcome of the patient (Hubbard et al., 1977). Hubbard et al. (1977) first demonstrated the inverse relationship of duration of extreme hyperthermia and the decreased likelihood of survival in a rat model. These data were redrawn by Casa, Stearns, et al. (2010) to present the data in a format that showed the percent of rats that survived for a range of degree-minutes over 40.8 °C. While the rats did not have 100% survival with less than 30 min above 40.8 °C in the Hubbard study, a clear linear relationship was identified. Furthermore, Costrini (1990) described the success of rapid cooling for EHS treatment in a U.S. military cohort with EHS. However, this account did not include any detail related to the parameters present for EHS victims. The data simply reported that they all survived. Specific information related to cooling rates, starting temperatures, and lasting consequences were not reported. Demartini et al. (2015) published the largest known data set of EHS patients and established the notion that EHS can be completely survivable when the duration of rectal temperature over 40.8 °C is minimized. This evidence was further expanded by Adams et al. (2015) with a theoretical framework emphasizing that the number of minutes of extreme hyperthermia really begins at some point before the collapse when the 40.8 threshold is crossed. This theoretical postulation, if proven correct in the future, narrows the window for optimal treatment outcome from EHS.

Table 4. 10-Point Checklist to Assure Proper Implementation of Cold-Water Immersion

☐ Cool first, transport second is included as part of the emergency action plan
☐ Cold-water immersion tub setup (e.g., ice, water, tub) is located near venue
☐ Flexible rectal thermistor is used to continuously monitor rectal temperature while cooling to identify when to remove the patient from tub
☐ Torso is fully submerged under water; head, face, neck, and limbs that are not immersed are covered in ice wet rotating towel
☐ Water temperature under 18 °C; under 10 °C for most optimal care
☐ Aggressive and continuous circulation of water during cold-water immersion to optimize cooling rates
☐ Adequate number of staff is available to manage combative patients
☐ Adequate number of staff is available to transport patient in and out of tub and restrain, if necessary, during rectal temperature assessment
☐ A watch to track the length of cooling to calculate cooling rates and estimate the length of cooling while the treatment is being provided
☐ Ability to rewarm patient that becomes hypothermic after cooling (e.g., blankets, sun exposure, dry clothes)

Emergency action planning for EHS must encompass the time sensitiveness of both recognition and treatment, which is similar to how cardiac emergencies are handled. The current EHS treatment gold-standard is to implement the concept of “cool-first, transport second”. EHS has the best chance for survival if cooling begins immediately upon recognition of the condition. Medical providers should not delay cooling until arrival to a medical facility as this greatly prolongs the time in which an individual is severely hyperthermic. Therefore, the following items need to be considered in the emergency action plan: time to contact emergency medical services (EMS), time for EMS to arrive to the site of the incident, time for on-site evaluation, transport time to the emergency room (ER), wait-time at ER before assessment is complete, and time at ER before cooling modality is implemented. When taken collectively, these barriers may expose the patient to hyperthermia for longer than the critical threshold of 30 min. Just as you would not delay the application of an automated external defibrillator (AED) for a patient with sudden cardiac arrest to maximize the survival rate, one should not delay the cooling of an EHS patient.

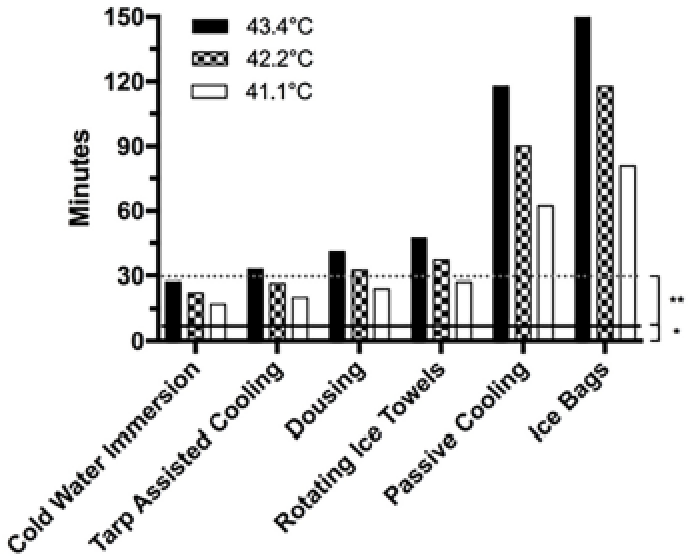

Figure 2. Number of minutes to treat an exertional heat stroke patient based on time to diagnose, cooling modality utilized, and patient's starting temperature. Treatment time (**) is based on time to cool patient to 38.9 °C, accounting for 7 min of delay (*) for assessment and initiation of treatment.

The modality of choice to cool an EHS patient must meet three critical criteria: (a) it must be practical for set-up at the particular event/venue where it is being used, (b) it must provide effective cooling rates (at least 0.11 $°C \cdot min^{-1}$, but optimally above 0.15 $°C \cdot min^{-1}$), and (c) it must be cost effective to be used across a wide swath of military, labor, and sport settings. The evidence indicates that immersion of the body in cold water has the most effective cooling rates. Research from the University of Ottawa has shown that immersion of the whole body (except the head) in vigorously circulated and extremely cold water could theoretically lower an EHS patient to under 40.8 °C in less than 10 min (Proulx, Ducharme, & Kenny, 2003). This is a staggering testament to the cooling potential of cold water on human skin. Even the cooling rates of more moderate water temperature (8–20 °C) have been shown to exhibit cooling rates of 0.2–0.3 $°C \cdot min^{-1}$ (Proulx et al., 2003). These cooling rates could lower body temperature of 41.1, 42.2, and 43.3 °C to 38.9 °C in 10, 15, and 20 min, respectively (see Figure 2). These optimal cooling rates allow some flexibility for clinicians to take time to assess the patient and prepare the cooling modality as depicted in the theoretical framework proposed by Adams et al. (2015). These are optimal results given they keep the patient on the preferred side of the 30-min window, and even offer a little wiggle room to account for the extra period of hyperthermia that Adams et al. (2015) speculated about and the amount of time to get the patient to the nearby cooling tub. In certain circumstances, cold-water immersion (CWI) might not be possible due to venue-specific limitations (i.e., remote location) or lack of preparation. As alternative methods, less stationary cooling modalities have shown comparable cooling rates as CWI (Figure 2). Recent work by Hosokawa, Adams, Belval, Vandermark, and Casa (2016) demonstrated that a tarp-assisted cooling method was 75% as effective as CWI while offering unique portability advantages for remote settings. The cold-water dousing method used by the marines at Quantico and at the

Marine Corps Marathon and described by McDermott et al. (2009) has shown effective cooling rates of about .14 °C/min or about 65% as effective as CWI (Figure 2). Rotating cold wet towels is another viable option that only requires towels, ice, and water. (Armstrong, Crago, Adams, Roberts, & Maresh, 1996) This method has an advantage for application during transport.

Hydration

The average human body is composed of 50–70% water, with body water being compartmentalized within both the intracellular and extracellular (plasma and interstitial) spaces (Sawka & Pandolf, 1990). During exercise, particularly in the heat, dissipation of metabolically produced body heat is needed to avoid a rise in body temperature, which increases the risk of EHS. As environmental temperatures exceed skin temperature, evaporation of sweat from the skin is the only effective means in which body heat can be dissipated; the evaporation of 1 L of sweat from the skin will remove 2.4 MJ (580 kcal) of heat from the body (Maughan, 1997).

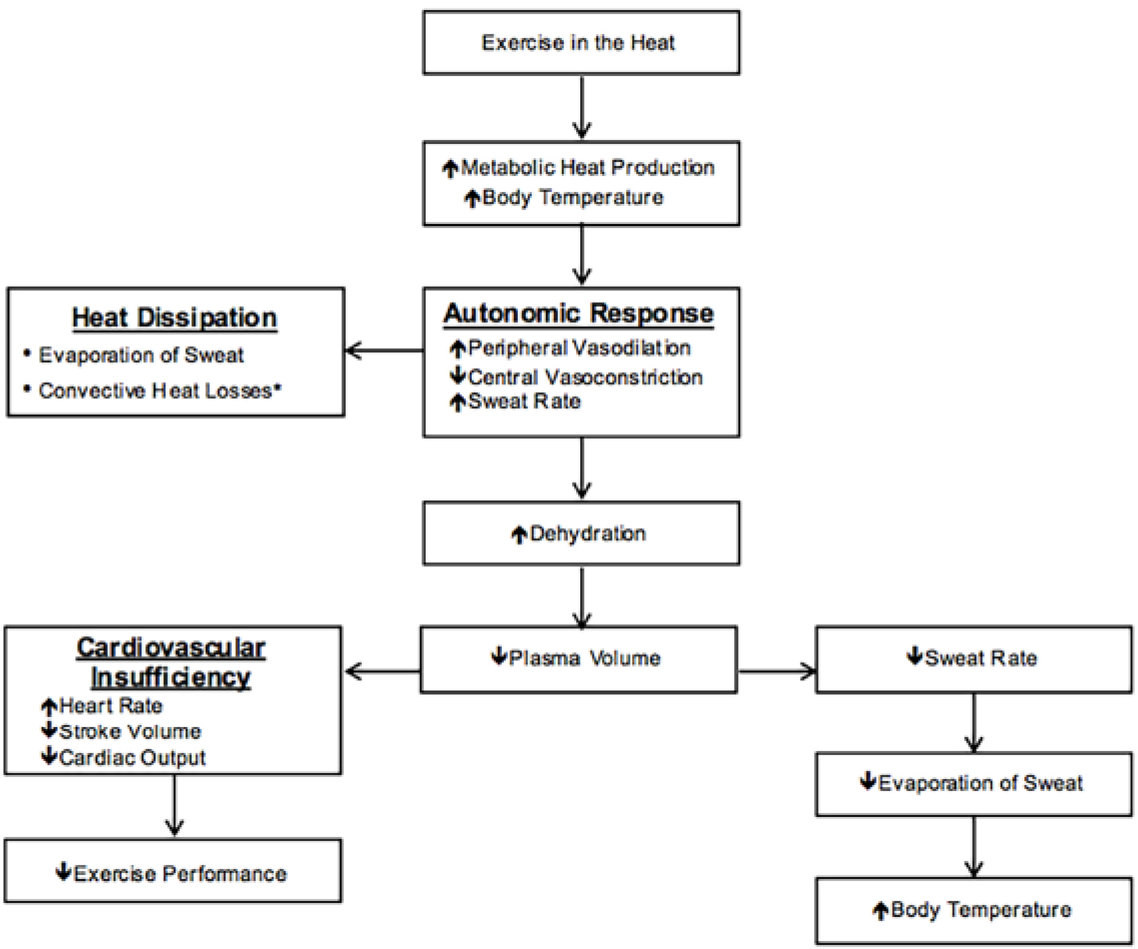

Figure 3. Physiological responses to dehydration during exercise in the heat. It is important to note that these physiological responses may occur at different magnitudes of dehydration. *Convective heat losses are negated when ambient temperature exceeds skin temperature.

With the onset of sweating during exercise, there is a concurrent net loss in total body water (dehydration), which is highly variable across the population and dependent upon factors such as environmental temperatures, exercise intensity, acclimatization status, and fitness status, to name a few (Montain, Latzka, & Sawka, 1995; Montain, Sawka, Latzka, & Valeri, 1998). With dehydration, the net loss of body water from the intracellular and extracellular spaces exacerbates the physiologic strain subjected on the body (see Figure 3) (Montain & Coyle, 1992; Sawka, 1992; Sawka et al., 1992; Sawka, Young, Francesconi, Muza, & Pandolf, 1985). Dehydration causes a reduction in plasma volume, which further increases the competition of blood flow within the body; there is an increased need for blood flow to the working muscles in addition to an increased need for blood flow to the skin for means of dissipation of stored body heat.

Specific to exercise in the heat, dehydration exacerbates both cardiovascular and thermoregulatory strain. With increasing plasma volume losses, coupled with the redistribution of blood to the periphery, the resulting reduction in central venous pressure causes a reduction in cardiac output by means of a reduced stroke volume despite the increase in heart rate (Coyle & González-Alonso, 2001; Montain & Coyle, 1992; Montain et al., 1998). Furthermore, the reduced plasma volume decreases the volume of blood traveling to the skin to dissipate heat via convection as well as both reducing sweat rate and increasing the threshold body temperature for the onset of sweating during exercise (Montain et al., 1995; Sawka et al., 1985). The reduced capability to dissipate heat as the level of dehydration greatly increases the risk of EHS.

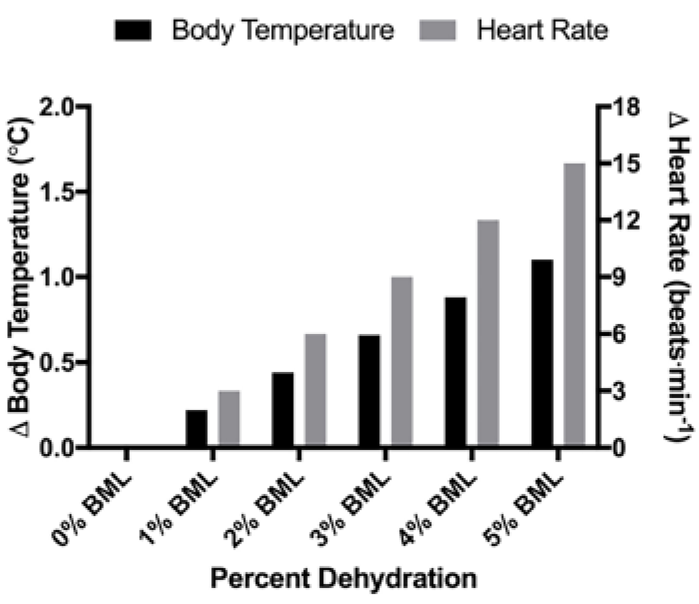

Figure 4. Theoretical model depicting the cardiovascular and thermoregulatory strain occurring with progressive dehydration during exercise in the heat. Magnitude changes in body temperature and heart rate are referenced to an individual maintaining a state of euhydration during exercise. The increase in body temperature and heart rate per every 1% BML is 0.22 °C (Huggins, Martschinske et al., 2012) and 3 beats×min^{-1} (Adams et al., 2014). BML = body mass loss; Δ = Delta change.

Examining the effects of dehydration on cardiovascular strain, evidence shows that during exercise in the heat, heart rate increases by 3–5 beats·min^{-1} for every 1% body mass loss that is attributed to water losses (Adams, Ferraro, Huggins, & Casa, 2014; Casa, Stearns, et al., 2010; Montain & Coyle, 1992; Sawka et al., 1985). Furthermore, evidence supports that during exercise in the heat, every 1% dehydration results in an increase in body temperature by 0.22 °C (Huggins, Martschinske, Applegate, Armstrong, & Casa, 2012). Controlled laboratory studies (Buono & Wall, 2000; González-Alonso, Mora-Rodríguez, Below, & Coyle, 1997; Montain & Coyle, 1992; Sawka et al., 1985) and a notable field study (Casa, Stearns, et al., 2010) found that body temperature increases in cases of progressive dehydration, despite exercising at the same exercise intensities as euhydrated counterparts (Figure 4). It must also be noted that any thermoregulatory benefits (i.e., reduced exercising body temperature, increased sweat rate, plasma volume expansion) attained by the process of heat acclimatization are negated during exercise in the heat when in a state of hypohydration (Sawka, Latzka, Mattot, & Montain, 1998). With the strong evidence showing the adverse effects of dehydration on physiologic function, specifically the increase in body temperature during exercise, it is important to develop hydration strategies to mitigate the risk of EHS. Current recommendations (Sawka et al., 2007) suggest that beginning exercise in a state of euhydration, minimizing fluid losses during exercise, and replacing remaining losses following exercise is an effective strategy to attenuate the adverse effects of dehydration from both a safety and performance perspective.

As fluid needs are highly individual, it is imperative that personal hydration strategies be implemented based on individual fluid needs during exercise based on one’s sweat rate. Furthermore, in order for these hydration strategies to be successful, appropriate policies need to be in place that allow for unrestricted access to fluids during exercise and for the appropriate time to allow for hydration during exercise. Education is also an important component in any organized athletic program so athletes are aware of their fluid needs outside of the playing field.

Conclusion

EHS is one of the leading causes of morbidity and mortality in exercising individuals. However, a prevailing number of laboratory and field studies suggest that implementation of proper policies to address heat acclimatization, environmental heat considerations, work-to-rest ratio, assessment of internal body temperature with a valid method, effective cooling methods, and maintenance of adequate hydration status may prevent EHS from occurring, or maximize the likelihood of survival. Policies based on scientific evidence have saved numerous lives of EHS patients; however, further efforts need to be placed to implement these policies as loss of a life from EHS should not be acceptable.

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