J Appl Physiol 135: 60–67, 2023.
First published May 18, 2023; doi:10.1152/japplphysiol.00229.2023

american physiological society

JOURNAL OF APPLIED PHYSIOLOGY

REVIEW

Impact of Climate Change on Health and Performance

Beating the heat: military training and operations in the era of global warming

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Abstract

Global climate change has resulted in an increase in the number and intensity of environmental heat waves, both in areas traditionally associated with hot temperatures and in areas where heat waves did not previously occur. For military communities around the world, these changes pose progressively increasing risks of heat-related illnesses and interference with training sessions. This is a significant and persistent "noncombat threat" to both training and operational activities of military personnel. In addition to these important health and safety concerns, there are broader implications in terms of the ability of worldwide security forces to effectively do their job (particularly in areas that historically already have high ambient temperatures). In the present review, we attempt to quantify the impact of climate change on various aspects of military training and performance. We also summarize ongoing research efforts designed to minimize and/or prevent heat injuries and illness. In terms of future approaches, we propose the need to "think outside the box" for a more effective training/schedule paradigm. One approach may be to investigate potential impacts of a reversal of sleep-wake cycles during basic training during the hot months of the year, to minimize the usual increase in heat-related injuries, and to enhance the capacity for physical training and combat performance. Regardless of which approaches are taken, a central feature of successful present and future interventions will be that they are rigorously tested using integrative physiological approaches.

climate change; exercise; heat stress; temperature regulation; thermoregulation

INTRODUCTION

Global climate change has resulted in an increase in the number and intensity of environmental heat waves, both in areas traditionally associated with hot temperatures and in those where heat waves did not previously occur. These changes pose progressively increasing risks of heat-related illnesses in military and other occupations where regular physical activity in the heat occurs. Attempts to minimize the risks of exertional heat illnesses can lead to cancellation or altering of training sessions in the hot months, jeopardizing effectiveness of training. This is a substantial, persistent "noncombat threat" to both training and operational activities of military personnel around the world. Significant implications of this threat include health and safety of our Warfighters, and have broader implications for the ability of security forces around the world to effectively do their job (particularly in areas that historically already have higher ambient temperatures). The goal of the present brief review is to quantify and discuss the challenges of climate change from the perspective of their relevance to military training and operations around the world.

In a progressively warming world, activities that are essential for military mission success, especially those involving protective clothing, high-intensity activity, or other aspects that increase the thermal burden, represent increasingly greater risks of heat illnesses. Equally important is the burden on resources this work will represent, such as availability of potable water for hydration, power sources for air conditioning or microclimate cooling, movement of equipment and logistical processes, etc. From a military mission perspective, it is also likely that troops with the best guidance and training approaches will be at the greatest advantage when it comes to successfully maneuvering in increasing environmental temperatures and heat load.

DEFINING THE PROBLEM

Global Climate Change

Climate change denotes the alterations in temperature and weather patterns over an extended period. Although the climate has fluctuated over millennia, most of this change was the result of small perturbations to the orbit of the Earth, which affected the amount of energy from sunlight that the Earth absorbed. Over the past 80,000 years, these small perturbations resulted in eight cycles of ice ages and warmer periods. The end of the last global ice age,

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Submitted 13 April 2023 / Revised 11 May 2023 / Accepted 12 May 2023

~11,700 years ago, also marked the beginning of the modern climate era and was the beginning of human civilization (1). Since 1880, global temperature has increased at a rate not previously seen. In just the past 40 years, temperatures have risen at a rate twice that of the previous century (2).

The current trend of global warming differs from the past as it is attributed to the accumulation of greenhouse gas (carbon dioxide, methane, and nitrous oxide) emissions by humans and industry (3, 4). Sunlight in the form of short-wave radiation passes through atmospheric greenhouse gases and heats the surface of the Earth. However, these same gasses trap heat in the atmosphere and prevent its release into space, thereby further warming the surface of the Earth (5). Extreme temperatures (both highs and lows) are projected to increase in nearly every part of the United States by the middle of the 21st century. Global surface temperature increased 0.7°C during the twentieth century and is projected to cause a further 1 to 4°C increase during the twenty-first century (6, 7). Hot, dry environments also increase the number and severity of wildfires, which then further impact weather patterns and raise the amount of particulate matter in the air, contributing to air pollution and pulmonary issues (8, 9). In addition, these elevated global temperatures have been associated with increases to ocean temperatures, leading to changes in thermosteric sea level rises (10, 11).

To better understand the impact of global climate change on specific US military units, Lewandowski et al. (12) recently examined trends in ambient conditions at several US Army installations. Sites were selected based on the reported historical incidence of exertional heat illness (12). Included in this analysis were Fort Moore, GA (renamed May 2023; formerly Fort Benning), Fort Jackson, SC, and Fort Leonard Wood, MO, which are three of the four initial entry training sites for the US Army. These were chosen, as recruits at those locations have ~10-fold higher incidence of heat exhaustion and approximately threefold higher incidence of exertional heat stroke (EHS) compared with nonrecruits. The fourth training site, Fort Sill, OK, did not have a high enough exertional heat illness (EHI) incidence to warrant inclusion in the original analysis. Figure 1 (adapted from Fig. 3 of Ref. 12) shows trends from 1990 to 2018 for ambient temperature, heat index and the wet-bulb globe temperature (WBGT) Index. Except for WBGT Index at Fort Jackson and Fort Leonard Wood, there were warming trends at each location and each index of ambient conditions.

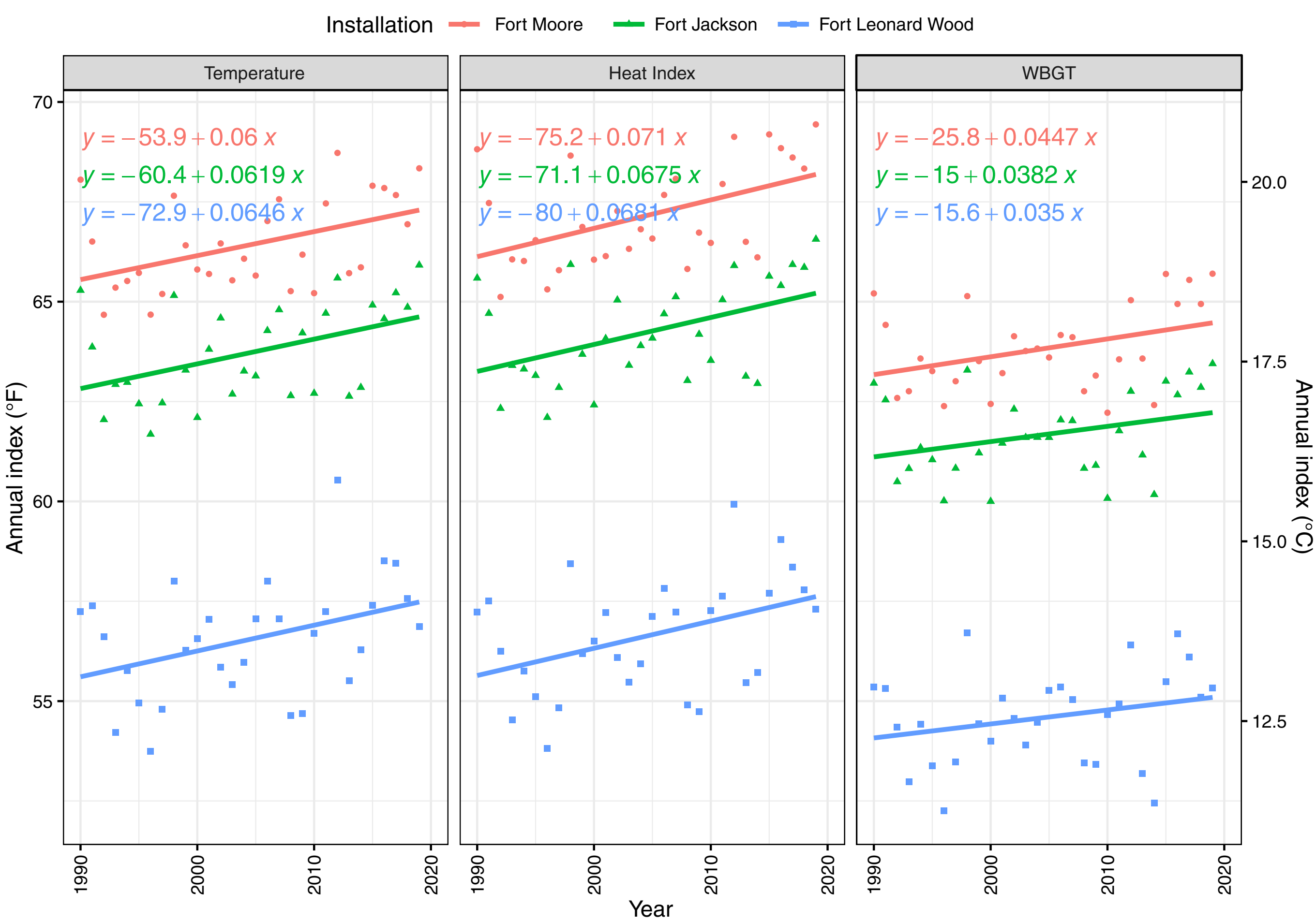

Figure 1. Annual values for ambient temperature, heat index, and wet-bulb globe temperature (WBGT) at Ft. Moore (renamed May 2023; formerly Fort Benning), Ft. Jackson, and Ft. Leonard Wood, shown in °C and °F between 1990 and 2020. All sites show steady increases in each of these variables over time. Modified from Lewandowski et al (12).

Exertional Heat Illness

In terms of military relevance, the most important biomedical issue with increasing environmental temperatures is EHI. Incidence of EHI occurs on a graded spectrum, ranging from heat exhaustion (mildest form) to EHS (most severe form), with exertional heat injury as a mid-range diagnosis between the two (13, 14). EHS is a medical emergency, which requires hospitalization and often results in long-term sequelae including organ damage and sometimes death (15). EHS is differentiated from classic (passive) heat stroke in that it occurs as a result of excessive increases in body temperature during exertion, and is most likely to occur in young, healthy individuals (16). In the military, EHS often occurs during prolonged endurance activities such as foot marches, especially when carrying heavy packs that increase metabolic demands. Data from the US Army Heat Center indicates that ~80% of all EHS casualties at Fort Moore from 2017 to 2021 occurred during foot march or running events (17).

IMPACT OF HEAT STRESS ON PHYSICAL PERFORMANCE

Even in the absence of illness per se, increased ambient temperatures cause decreases in physical performance (18, 19). It is well known, for example, that most record times in distance events such as marathons occur at cooler temperatures (20); hotter events tend to be slower (21). Physiological data are consistent with this slowing effect of heat: increased cardiovascular strain associated with the "competition" for blood flow between thermoregulatory reflexes (skin blood flow, sweating) and exercising skeletal muscle always results in a "lose-lose" situation where neither is optimal (22, 23). Kenefick et al. (24) quantified the slowing effect of ambient heat and humidity on military-relevant performance, showing marked decreases in the ability to perform a 5K ruck march as both variables increased.

For most activity/environment combinations, core temperature response is independent of ambient conditions and is dependent primarily on exercise intensity, such that higher intensity results in higher heat production and a higher steady-state core temperature (25, 26). However, in conditions called "uncompensable" (where the combination of heat production and capacity for heat loss are such that heat balance is not possible), the increase in core temperature is greater than in compensable environments for the same exercise intensity (27, 28). For example, one can use the USARIEM heat strain decision aid (HSDA) model (29) to predict core temperature changes for a typical healthy male soldier (fully acclimatized 12 days, normally hydrated, 170 cm, 72 kg) wearing standard military uniform (clo = 1.08, i_m = 0.51) during rest (1.7 W·kg^{-1}) and moderate exercise (8.3 W·kg^{-1}) in five different ambient temperatures (20, 25, 30, 35, and 40°C) in hot-dry [15% relative humidity (RH)] and hot-humid (60% RH) heat (Fig. 2). Clearly, higher ambient temperatures are associated with higher core temperatures (most striking during high-intensity exercise), and therefore higher risk of heat illness. In this context, more work is needed to update models such as the HSDA, to be more representative of the broader general population, including individualized modifications [e.g., age, sex, fitness (30–33)].

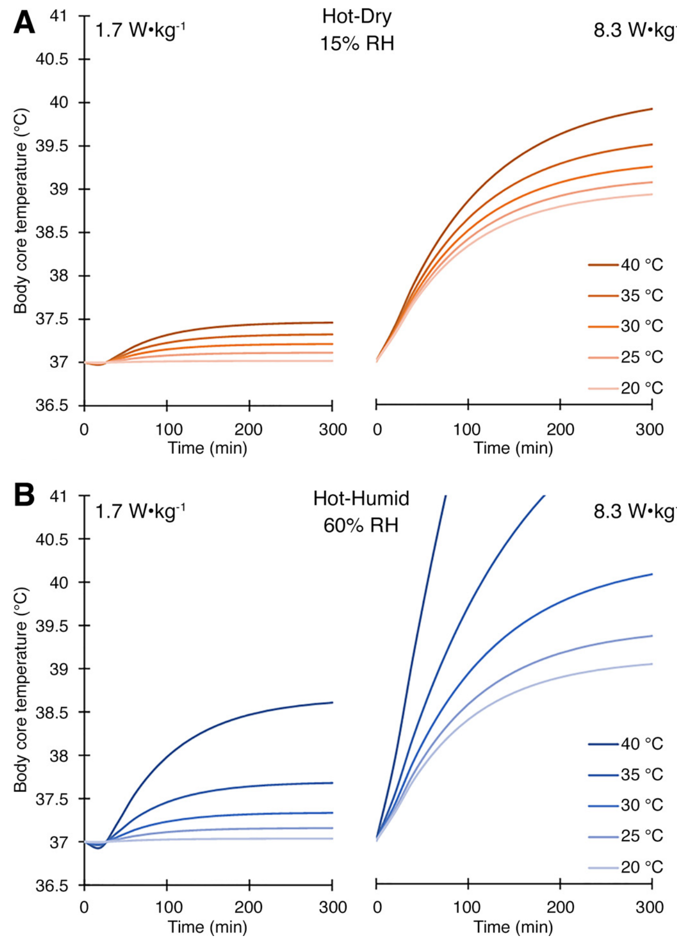

Figure 2. Prediction of body core temperatures by ambient condition (T_a) and activity rate in hot-dry [15%relative humidity (RH)] (*A*) and hot-humid (60% RH) (*B*, over 5-h period for standard man wearing military clothing during rest (*left*; 1.7 W·kg^{-1}) and exercise (*right*; 8.3 W·kg^{-1}).

Therefore, for military-specific tasks, such as the 2-mi run or 12-mi foot march (often carrying heavy packs), the chance of an individual reaching a dangerous level of core hyperthermia increases greatly with higher ambient temperatures, especially if clothing or relative humidity are such that evaporation of sweat is further impeded (34). In a practical sense, standard military training becomes progressively more thermally stressful compared with several decades ago. Furthermore, badges (Expert Infantryman, Expert Field Medic), tabs (Ranger, Special Forces), and other forms of recognition needed for promotion might be more difficult to achieve for the same overall effort as average ambient temperatures rise.

Utilizing weather data obtained from the US Air Force, which maintains the weather station at Lawson Army Airfield, Fort Moore, GA, we estimated the number of hours in 2022 that heat category 4 (WBGT 88.0–89.9°F/31.1–32.2°C) and heat category 5 (WBGT >89.9°F/32.2°C) were reached. During 2022, there were 180 heat category 4 h, and 128 heat category 5 h (DeGroot, unpublished observations). It is important to note that during those times, training would likely have been restricted, modified, or unit leadership would have had to explicitly accept increased risks of heat illness. However, there are no explicitly stated requirements to restrict or modify training based on environmental conditions, such as when a certain threshold WBGT is reached. This approach gives unit leaders the flexibility to assess the risk versus training or mission objectives.

Increased water temperatures pose a significant risk to military divers and other activities such as land-based water crossing (35, 36). Fully or partially immersed conditions impose unique and exacerbated risks of thermal strain, as avenues of heat exchange (such as evaporative heat loss) are significantly reduced or completely removed (37, 38). Rising water temperatures increase the risk in these conditions, as individuals working can produce much more heat than can be exchanged with the environment, leading to the potential for significant and rapid increases in body core temperature (39, 40). Looney et al. (39) showed significant increases in rates of body core temperature rise and time to exhaustion during military diving in progressively warmer water conditions (34.4–38.6°C). Areas with strategic military importance, such as the Persian Gulf, often reach surface temperatures of 35°C now and continue to rise (41); while globally water temperatures are increasing and have been observed at ~0.6°C increases per year (41, 42).

There are important interactions between thermal stress from the environment and hypohydration (dehydration) as well. Dehydration increases hyperthermia during exercise in the heat by impairing thermoregulatory heat dissipation (sweating and skin blood flow). Such influences of dehydration may increase the risk of EHS during physical activity in the heat (43, 44); however, maintaining hydration does not equate to removal of risk (i.e., people can become dangerously hyperthermic even if they are well-hydrated). Relevant to the present discussion, the impact of dehydration on exercise performance in the heat is dependent on the environmental temperature (19, 45), where higher ambient temperature augments the effect of dehydration to impair aerobic exercise performance.

RISK AND INCIDENCE OF EHI/EHS IN UNITED STATES AND ISRAELI MILITARY FORCES

Comprehensive quantification of the financial and human resource burden of EHI on the military health system, and subsequent impact on unit readiness, is difficult to achieve for several reasons, including inconsistent reporting and variability in definitions of illness across medical treatment facilities. Heat exhaustion and other minor heat illnesses do not require transport to a medical treatment facility. As a result, if a record is created for a given incident, it may still be absent from the electronic medical records and subsequent surveillance activities. The US Armed Forces Health Surveillance Division publishes an annual update on heat illness incidence, based on data from electronic medical records (46). Although these reports underestimate the true burden, they do provide valuable insights into various risk factors and vulnerable populations.

Year over year, reports are consistent that new recruits, members of the US Army or the US Marine Corps, those younger than 20 yr (who likely are also new recruits) and those in combat-specific military occupational specialties have the highest incidence of heat exhaustion and EHS (47). Others have reported that Black individuals, those who are overweight or obese, are tobacco users or are from northern states are at an increased risk (48, 49). The role of prior heat illness as a risk factor for future EHS is unclear. For example, a prior serious heat illness was shown to be a predictor of a future mild heat illness, but the existence of prior mild heat illness did not increase the risk (48). In addition, others have observed that a prior EHS episode as a risk factor for a future EHS is not supported by evidence (50); the paucity of data demonstrating abnormal thermoregulatory function after an EHS event supports that conclusion (51).

Potential differences between the sexes have gained increased attention in recent years. In terms of mechanisms of thermoregulation, women could be seen to have either advantages or disadvantages with regard to risks for EHI. Women are smaller, resulting in a higher body surface area (BSA) to mass ratio, which is a biophysical advantage to heat dissipation in compensable environments (52–54). Women have lower maximal capacity for sweating (55) but during most submaximal levels of exercise/heat stress (which are most of what a soldier or athlete would routinely encounter), sweating levels are similar between men and women. Estradiol augments vasodilation and in general tends to promote lower body temperatures (56). Overall risk of EHS, therefore, would reflect the balance of these advantages and disadvantages. This was the conclusion of a recent analysis by Giersch and coworkers, who conducted a retrospective analysis of 745 incidences of EHS in the US Army over a 5-yr period (2016–2021). When controlling for multiple potential contributors, women and men had similar risk and incidence of EHS in this cohort (57).

An underappreciated risk factor is individual behavior and motivation; that is, a highly motivated athlete or military service member is much more likely to "push through" physical sensations that would normally serve as warning signs and put themselves at increased risk of illness (58). Data from athletics in the United States supports this idea, with a higher incidence of heat illness reported during competition versus practice (59). Over 50 years ago, it was observed that "...the tragedy of heatstroke is that it so frequently strikes highly motivated young individuals, under the discipline of work, military training and sporting endeavors. Under other circumstances these same individuals would have rested when tired, drank when thirsty or remained home when ill..." (60). As previously noted, we recently observed that a significant proportion of heat casualties at Fort Moore, GA occur during foot march or running events (17). Such events are often conducted as milestones during initial entry training or as a service member is attempting to earn a skill badge or tab, such as the Ranger qualification tab, the Expert Infantryman Badge, the Air Assault badge, and others. With regard to potential sex differences in the role of behavior or motivation, we have recently shown that EHI/EHS risk was not different between men and women in a group of over 4,500 service members (57). In addition, previous work suggests that women exhibit better behavioral strategies related to thermoregulation compared with men, both in the laboratory (61) and in competition (62). Whether these latter sex differences translate to the military training environment has yet to be demonstrated and is an area for future investigation.

EXISTING COUNTERMEASURES AND PLANNING FOR THE FUTURE

Numerous strategies are available to individual service members and to leaders to mitigate the risk of EHI. In the training environment, it may be possible to reduce the load carried, modify the uniform configurations (e.g., "de-blousing"), reduce the pace of foot marches or run events, change the time of day of the event, and ensure that individuals are euhydrated. Individuals with certain risk factors, such as lack of acclimatization, poor aerobic fitness, excess adiposity, or taking certain medications can be educated on the increased risks. In the operational environment, or in settings in which modification is otherwise not acceptable (e.g., Ranger School training), rising global temperatures will increase the risk of exertional heat illness in our service members.

Once the service member is in a situation where high core temperatures have occurred or are occurring, there are existing countermeasures in place in many training locations to decrease the risk or severity of heat illness, should it occur. Many of these are related to cooling the surface of the body to ultimately decrease mean body temperature. During extended training events, arm immersion cooling has been used with success. Although submersion of the forearms in ice water does not (biophysically) decrease body core temperature too much, the effect of stopping exercise for a few minutes plus immersion of arms in water is beneficial (63, 64).

After collapse in the heat has occurred, the fastest way to decrease core temperature is to immerse the individual in a cold-water bath (65). However, this is not always possible in military training or field settings. Therefore, at settings such as Ft Moore in GA, the standard for cooling is a specific procedure called "iced sheets," where bed sheets soaked in ice water are wrapped around the person and changed out every 3 min until emergency medical services arrive. The standard operating procedure for iced sheeting, as published in TB MED 507 (66), was recently evaluated in the laboratory in both thermal manikin models and humans after hyperthermic exercise. The authors concluded that iced sheeting provided significant cooling in scenarios where the thermal gradient for cooling was smaller than what it would be in a "real-world" EHS scenario (67, 68). Furthermore, we recently reported that in profoundly hyperthermic (real-world) EHS casualties, the ice sheeting methodology during prehospital care provided a cooling rate of $\sim$0.16°C·min^{-1}, thus meeting the recommended minimum of 0.15°C·min^{-1} (69, 70). In addition to the direct biophysical benefit of the large thermal gradient provided by the ice water, there are additional hemodynamic benefits of cooling the skin. Lower skin temperatures help decrease the total amount of vasodilation in the skin, which can help to prevent blood pressure from going too low during a heat collapse, thereby helping maintain hemodynamic stability until the patient can be transported to a hospital setting (71, 72).

Heat acclimation is also an important risk mitigation strategy for military service members. There are a number of recent reports detailing different approaches to heat acclimation and the benefits and drawbacks of each (73–79). The possibility of "short term" heat acclimation (4–5 days vs. 8–14 days) has received increased attention in recent years, although more information is needed regarding the practicality of specific approaches for this.

In military units, there can be a practical need for acclimation strategies when a group of individuals may be moving rapidly from a cooler environment to a hot environment for training or mission-related activities. These include patrolling Army, Navy and Marine Corps units, and Marine expeditionary units (MEU), specialized air-ground task force units positioned around the world and tasked with providing rapid deployment for military or humanitarian actions. Particularly on short notice, such units may not have time, or the resources needed for any level of acclimation to the heat before travel. This has led to interest in nontraditional acclimation protocols, such as overdressing protocols, tailored to provide sufficient heat stress to induce acclimation without themselves causing EHI (80–82).

Thinking outside the Box for Future Training Paradigms

The current training strategy in many countries around the world to reduce the occurrence of heat-related injuries in the military is to modify Warfighter training activities in extreme heat conditions and to suspend training entirely in some circumstances (66). To balance the need to train in the heat with the need to minimize risk of EHI, training schedules are often altered to decrease the time during which the trainees are working in extreme temperatures. This raises the concern that the Soldiers' health, fitness, and training routine may be impaired by the heat, especially in the hot months. For example, if the alteration of training schedule results in an increase in sedentary behavior, certainly overall fitness levels (and potential mission readiness) would suffer. Furthermore, progressive increases in temperature across the globe with ongoing climate change would only serve to augment these effects. This situation requires new strategies to modify physical activity and training during the hot months, and, in particular, for new recruits in basic combat training, who are more vulnerable to EHI.

We hypothesize that reversing sleep and wake hours (effectively "switching" day and night) will decrease both heat-related illness/injury and lost training days over the course of the basic training program. In this context, quantitative data collection will be necessary to assess the applicability and ability of new recruits to adapt to an inverted sleep-wake schedule. We recognize that there would be multiple effects of such a modification on systems across the span of integrative physiology and that a complex and comprehensive study (or studies) would be required to evaluate the effects of this inverted sleep-wake schedule on physical and mental health and on physiological and cognitive performance.

RISK ASSESSMENT AND MONITORING

Although multiple risk factors for EHI have been identified, there is a lack of sufficient evidence to support the development of a numerical scoring system or similar approach for an individualized quantification of risk factors (66). A given EHS casualty can be interviewed later to identify the risk factors that may have contributed to the collapse. However, the ability to do so a priori, and to provide recommendations on activity modification, is not currently feasible.

Although a wide range of thermal indices exist (83), simple and sophisticated human thermal models can be used to predict those individuals who may be at increased risk of potential heat illness (29, 84–86). In addition, an alternative approach is to utilize noninvasive physiological monitoring that allows medical personnel to actively assess thermal work strain in real-time (87–89). Such an approach has the potential to overcome the limitations of relying solely on individualized predictive risk assessment and takes into account dynamic changes or differences that may have been missed in a premission assessment.

SUMMARY AND CONCLUSIONS

Prevention of heat illness in military service members has been an ongoing challenge for physiologists, engineers, and military leaders throughout history. In recent decades, significant advances in both the science of heat illness prevention and the strategic approaches to its management have improved, but much work remains to optimize future training and battlefield operations for service members. Current risk mitigation approaches include tailored work/rest cycles, traditional and nontraditional heat acclimation approaches, cooling during training in the form of arm immersion or after a suspected heat illness in the form of iced sheets or water immersion. There are some important areas of heat illness risk for the military that are not as well studied. These include sex/gender, where it appears that the potential advantages and disadvantages associated with female sex balance out to result in no net difference in EHI risk between the sexes. Another poorly understood area is behavioral/motivation risk. This is a challenging one, as we need to balance the many positives associated with high levels of motivation with the negatives associated with excessive risk-taking in these individuals. Moving into the future, with the added challenge of ongoing climate change, it will be important to think creatively to continue to stay ahead of the challenges posed by environmental heat stress.

ACKNOWLEDGMENTS

The authors thank Stephanie Arnett for help in creating the graphical abstract.

GRANTS

Our work is funded by the Military Operational Medicine Research Program at the US Army Medical Research and Development Command (USAMRDC) (to N.C., D.W.D., and A.W.P.); D.S.M. received no funding for this work.

DISCLAIMERS

Drs. DeGroot, Potter, and Charkoudian are employees of the US Army. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the US Army or the Department of Defense. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

D.S.M., D.W.D., A.W.P., and N.C. conceived and designed research; D.S.M., D.W.D., A.W.P., and N.C. analyzed data; D.S.M., D.W.D., A.W.P., and N.C. interpreted results of experiments; D.S.M., D.W.D., A.W.P., and N.C. prepared figures; D.S.M., D.W.D., A.W.P., and N.C. drafted manuscript; D.S.M., D.W.D., A.W.P., and N.C. edited and revised manuscript; D.S.M., D.W.D., A.W.P., and N.C. approved final version of manuscript.

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