

REVIEW

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Methods for improving thermal tolerance in military personnel prior to deployment



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Abstract

Acute exposure to heat, such as that experienced by people arriving into a hotter or more humid environment, can compromise physical and cognitive performance as well as health. In military contexts heat stress is exacerbated by the combination of protective clothing, carried loads, and unique activity profiles, making them susceptible to heat illnesses. As the operational environment is dynamic and unpredictable, strategies to minimize the effects of heat should be planned and conducted prior to deployment. This review explores how heat acclimation (HA) prior to deployment may attenuate the effects of heat by initiating physiological and behavioural adaptations to more efficiently and effectively protect thermal homeostasis, thereby improving performance and reducing heat illness risk. HA usually requires access to heat chamber facilities and takes weeks to conduct, which can often make it impractical and infeasible, especially if there are other training requirements and expectations. Recent research in athletic populations has produced protocols that are more feasible and accessible by reducing the time taken to induce adaptations, as well as exploring new methods such as passive HA. These protocols use shorter HA periods or minimise additional training requirements respectively, while still invoking key physiological adaptations, such as lowered core temperature, reduced heart rate and increased sweat rate at a given intensity. For deployments of special units at short notice (< 1 day) it might be optimal to use heat re-acclimation to maintain an elevated baseline of heat tolerance for long periods in anticipation of such an event. Methods practical for military groups are yet to be fully understood, therefore further investigation into the effectiveness of HA methods is required to establish the most effective and feasible approach to implement them within military groups.

Keywords: Heat acclimation, Thermoregulation, Heat illness, Physiology, Human, Conditioning, Military

Background

Military units deploying abroad are often exposed to challenging environments. One is heat stress, which presents as high ambient temperature, often augmented by high humidity, resulting in heat strain. Heat strain affects many physiological systems, compromising physical and potentially also cognitive performance [1–7]. Heat has impaired military performance for thousands of years, with ancient Greek and Roman reports highlighting the dangers of warfare in the heat, largely noting that

heavily armoured troops were more affected [8–10]. It was not until British colonisation that more detailed reports were compiled outlining the dangers of transitioning into a hotter environment [11]. Those most affected by the heat were frequently new arrivals in the summer months, indicating that individuals could acclimatise to hot environments within a few months [11]. While this was still a problem during World War I campaigns in the Middle East [10, 12], by World War II an invested interest in how to prevent or limit these problems scientifically was undertaken in military groups. This interest was brought on by a wave of heat-related injuries sustained both in the field and in training camps [13, 14]. Safety regulations were implemented to adjust carried

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load and clothing worn and to dictate duration and intensity of activities based on the environmental temperature and humidity [14, 15]. Studies progressed further after World War II, looking to minimise the carried load [16] and provide better clothing for such conditions [17, 18], as well as conducting the first investigations into using heat acclimation and acclimatisation to prepare soldiers for hotter environments by eliciting chronic adaptations [19–22]. Planned acclimatisation was investigated first, allowing soldiers a period of time in a new climate to adapt to the environment [19–21, 23–26], while later developments in heat chambers allowed artificial heat exposure to induce such adaptations [27–30], a process known as heat acclimation (HA). From these investigations cardiovascular strain was determined to be a major limiting factor of performance in the heat [31–33], prompting investigations into hydration status and blood volume regulation mechanisms [34–39]. With technological advancements reducing the time to deploy troops to different climates abroad, it is important that research develops to ensure soldiers are adequately prepared when exposed rapidly to extreme climates. Therefore, the aim of this narrative review is to consider 1) the physiology of exercising or working in ambient heat stress in a military context, and 2) the effectiveness and practicality of strategies for coping in hot environments, with an emphasis on short notice deployments and HA. This review will also highlight the challenges of optimising HA within the military, which may identify and guide future directions for military-specific HA research.

Physiological response during physical work in the heat

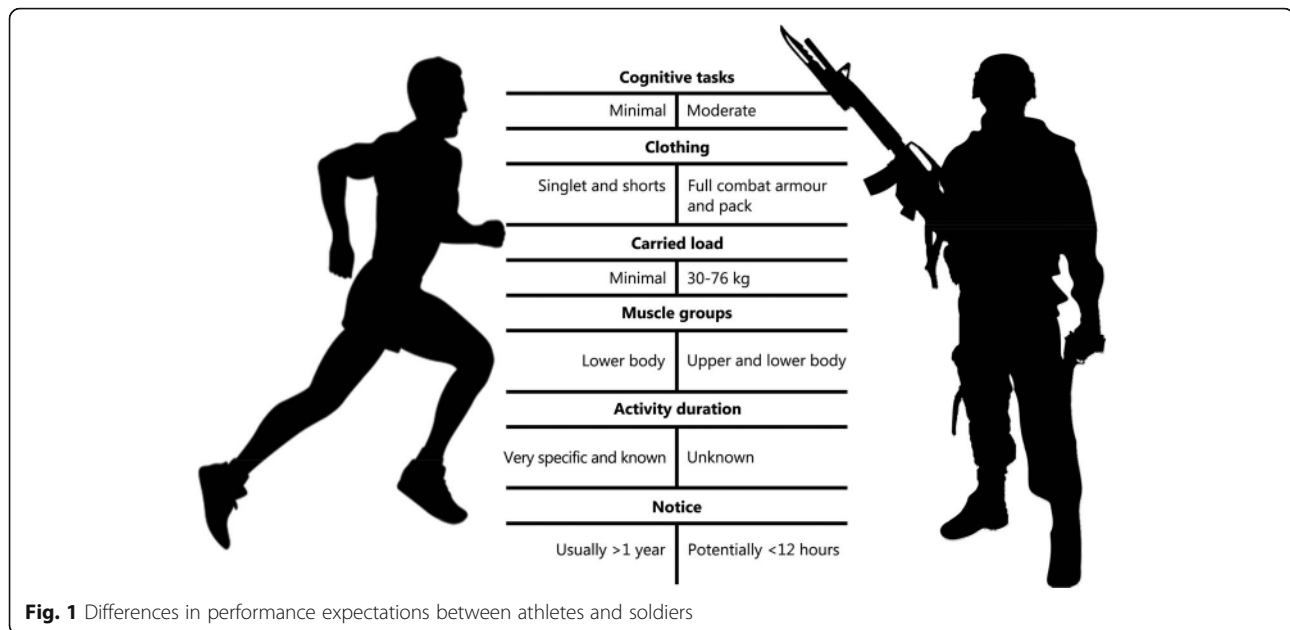
In the heat, blood flow is reduced in splanchnic [40–43], inactive muscle [40] and potentially cerebral [44, 45] circulations, to elevate skin blood flow for cooling [46, 47]. During exercise, active skeletal muscle blood flow must also increase substantially to deliver oxygen and substrates to exercising tissue [31, 48]. Work performed by exercising muscle produces heat, which usually comprises the majority of total heat load, requiring a further increase in skin blood flow to protect thermal homeostasis [49, 50]. Skin blood flow typically increases alongside core temperature, but plateaus when core temperature reaches 38 °C, at 50% of maximal skin blood flow [33, 34, 51]. Exercise is facilitated when cerebral, skin and skeletal muscle perfusion requirements are met [34, 48, 52]. However, cardiovascular demand is exacerbated by increases in exercise intensity that promote blood flow to skeletal muscle (if it has not plateaued), while increases in core or skin temperature elevate blood flow to the cutaneous vasculature [32, 34, 53]. As blood flow and volume is redistributed peripherally, central blood

volume declines, which can be exacerbated in long-duration exercise by sweat-induced dehydration [46, 54, 55]. If central blood volume becomes insufficient to support blood flow requirements, the cutaneous and skeletal muscular circulations compete for the limited blood supply [32, 34, 56].

During the early stages of exercise, it appears intensity is maintained by restricting skin blood flow to provide adequate blood supply to exercising skeletal muscle at the cost of reduced cooling, accelerating the rise in core temperature [32–34, 52, 57]. However, prior to termination of exercise in fixed-workload trials, skeletal muscle blood flow is reduced [31]. In self-paced exercise, a reduction in exercise intensity occurs early as an anticipatory response to limit the strain of the competing circulations and allow task completion [49, 58–60]. Although measures of integrated electromyographic activity indicate that motor unit recruitment reduces [49, 61–63], this is not accompanied by a reduction in vascular conductance in the exercising muscle [31, 32]. This indicates that the reduction in skeletal muscle blood flow is due to a drop in central blood pressure caused by exacerbated cardiovascular demand [32], secondary to high temperature of peripheral tissue [31, 64, 65]. It is unknown whether reduced motor unit recruitment occurs alongside or because of high core temperature, or whether other physiological feedback mechanisms play a more substantial role [33, 44, 66, 67].

Much of this research has uncovered physiological processes and mechanisms that have been determined within, and applied to, athletic situations, thereby under-representing military-specific factors that increase and complicate the challenges of exercising in the heat (Fig. 1). For example, protective clothing and equipment reduces skin-to-air contact, impairing convective and evaporative heat loss [47], while also affecting radiative heat gain depending on both the layers and permeability of clothing [68]. In this situation skin blood flow increases in an attempt to dissipate heat, further straining the limited blood supply while achieving little additional heat loss [69]. The combined weight of body armour, webbing and a backpack adds to physiological demand by increasing metabolic cost, elevating skeletal muscle blood flow requirements [70]. Furthermore, soldiers typically have a lower cardiovascular fitness level than the athletes used in the majority of heat research [71–73], so would likely have a lower thermal tolerance [74], even before considering carried loads and restrictive clothing. Altogether, these aspects exaggerate cardiovascular demand, diminish work capacity [75, 76] and predispose soldiers to exertional heat illnesses [10, 77, 78], although these relations remain equivocal [79].

Exertional heat illness occurs in uncompensable heat stress where the metabolic heat production of exercise is



unable to be offset by heat exchange with the environment, and exercise intensity is insufficiently downregulated by the individual, leaving them incapacitated [80]. While this often is present in the form of heat exhaustion, extreme cases can cause heat stroke, which can impair central nervous system function [81, 82], cause organ damage [83, 84] and lead to death [12, 14, 85, 86]. Investigations at a basic training facility found 2% of recruits suffered exertional heat illness during summer months [87], while others observed a 40% higher all-cause mortality at a 30-year follow-up in those with prior exertional heat illness [88]. While this could be associated with chronic organ and tissue damage [88], whether the relationship is or is not causal remains to be determined.

Strategies to combat the effects of heat

Acute heat exposure negatively affects both physical and mental performance, therefore a strategy to maintain performance and health is desirable [89]. Many military operations require relocating to hotter environments for specific missions including disaster relief and unexpected events, before being withdrawn. Deployment notice can sometimes be very short (~ 12 h) allowing minimal, if any, time for heat preparation. These scenarios highlight the importance of strategies to reduce the effects of the heat. Such strategies can occur at the level of the environment, and the level of the individual. For example, the living environment can often be modified in advance to minimise thermoregulatory requirements (i.e. air-conditioned barracks, shaded areas) [15, 90], and aid thermal recovery following exertion (i.e. ice baths, cold

water) [82]. Similarly, personal protective equipment should be designed to facilitate heat loss and minimise burdened weight [16, 91].

Several acute strategies can be used at the level of the individual to off-set heat strain, but the unpredictable nature of military tasks and rapidly changing circumstances mean they cannot always be relied upon [92]. Nonetheless, behavioural modification (i.e. shade-seeking, rest) can prevent elevations in core temperature [86], and are often inherent within military guidelines in the form of heat index charts to minimise casualties [93, 94]. This attenuated rise in core temperature can also be achieved with cooling mechanisms, such as ice vests [95] or cold-water immersion [96], used before, during or after exercise. However, ice vests can be uncomfortable, impair body armour function, add to carried weight and requires facilities to generate ice [97, 98]. Similarly, cold-water immersion, the gold-standard method for lowering core temperature [9, 82], requires access to large quantities of cool water. When water supply is limited it should preferentially be used for drinking and hygiene. If facilities are available, consumed water should be chilled [99] and supplemented with electrolytes to prevent hyponatraemia [100] and increase palatability [101].

These strategies are all viable options, but all are limited by being potentially unavailable. Therefore, strategies such as HA that take place prior to deployment can be more controlled and develop adaptations that would be augmented by the acute strategies outlined above.

Heat acclimation

HA can prevent decrements in both physical and cognitive performance [89], and likely reduces organ damage

[102], by altering key underlying physiological variables. It is likely that subcellular adaptations to transport, stress, contractile and metabolic proteins (reviewed elsewhere [103–105]) help lower resting body temperature, enhance heat dissipation and tolerance [59, 106, 107] and potentially reduce metabolic rate [108]. Systemic adaptations also occur with plasma volume expansion increasing skin blood flow and sweat rate which help lower core and skin temperatures. These adaptations allow a higher exercise intensity to be maintained at a given core temperature, or for a lower core temperature to be maintained at a given exercise intensity, thereby improving performance and reducing injury susceptibility [3, 4, 40].

On-site heat acclimatisation over several weeks is regarded as the best-practice methodology to adjust personnel to the environment they will operate in [59, 109]. Even then, arrival in the environment for acclimatisation can pose a challenge as personnel are not adjusted to the heat. Recent research, primarily in athletic contexts, has used HA to induce adaptations comparable to on-site acclimatisation [96, 109]. However, military-specific factors may prevent the direct transfer of athletic findings to military populations (Fig. 1).

For an in-depth review on methods to minimise the effects of heat on military personnel, when ample deployment notice is given, we refer the reader to the recent review of Parsons et al. [89]. However, alternatives are required when notice is noticeably shorter; less than one week and, on occasion, less than one day [96, 109]. Therefore, this section aims to discuss the adaptations that occur as a result of HA, and how they relate to a military environment.

Physiological adaptations

Plasma volume

During acute heat exposure plasma volume is redistributed and eventually declines as fluid is lost primarily through sweat, but also respiratory losses, urine and faecal formation [110]. As a result, blood availability for skin and skeletal muscle becomes restricted, which can reduce performance in high-intensity or long duration events by limiting cooling and skeletal muscle blood flow. However, with continuous exercise, low central blood volume, reduced renal blood flow and plasma hyperosmolality stimulate aldosterone and anti-diuretic hormone secretion, upregulating fluid retention mechanisms and stimulating thirst to restore plasma and therefore blood volumes (Fig. 2) [59, 111]. When repeatedly exposed to this stimulus the increase in plasma volume exceeds baseline values, aiding resilience against subsequent exposures. HA programmes have seen plasma volume expansion in as little as two days [112]. Plasma volume increases of more than 20% have been reported [113, 114], although ~

7% is more common [115–117]. The greater blood volume likely facilitates blood supply to active skeletal muscle and cutaneous circulations simultaneously [54, 59], reducing the cardiovascular burden, therefore increasing the cardiovascular reserve to support performance at higher intensities or for longer durations.

As increasing plasma volume effectively increases the amount of blood that can be distributed throughout the body, studies have explored ways of augmenting the increase seen with HA. For instance, permissive dehydration, to exacerbate the reduction in central blood volume, is hypothesised to increase aldosterone concentration, promote fluid retention and stimulate thirst [117–119]. Garrett et al. [117] found 5 days of HA (involving 90 min cycling per day with core temperature maintained at 38.5 °C in 35 °C, 60% relative humidity (RH)) in an experimental group abstaining from fluid intake, [117] to obtain an 8% mean increase in plasma volume, compared to only a 4% mean increase in controls drinking ad libitum during sessions. Alternatively, consumption of protein supplements immediately post-exercise has been explored [120–122]. These supplements increase plasma albumin content, creating an oncotic gradient to draw fluid into the vascular space to elevate blood volume [120–122]. However, it has not been investigated as to whether supplement-derived plasma volume enhancement leads to improved performance.

Heart rate

Elevated blood volume caused by HA enables blood pressure to be maintained in the heat, even with high blood flow demands from skeletal muscle and the cutaneous circulation. While animal studies indicate that over time this could potentially invoke morphological cardiac adaptations that increase ventricular compliance and inotropic state [123, 124], the increased preload helps increase stroke volume [59] allowing heart rate to decrease while maintaining cardiac output [125, 126]. Heart rate is also independently elevated by high core and skin temperatures to increase cutaneous blood flow [127]. During HA, core and skin temperature decline, therefore heart rate is reduced. While lowered heart rate does not improve thermoregulation per se, it indicates a larger cardiac reserve, therefore a reduced cardiovascular strain, making it an optimal outcome for any HA programme. Heart rate can be seen to decline in the first few days of a HA programme, suggesting the changes underlying this occur rapidly, making them relevant to short HA timeframes desired by the military [128–130].

Skin blood flow

Skin blood flow translocates thermal energy to the surface, heating the skin to facilitate convective heat loss

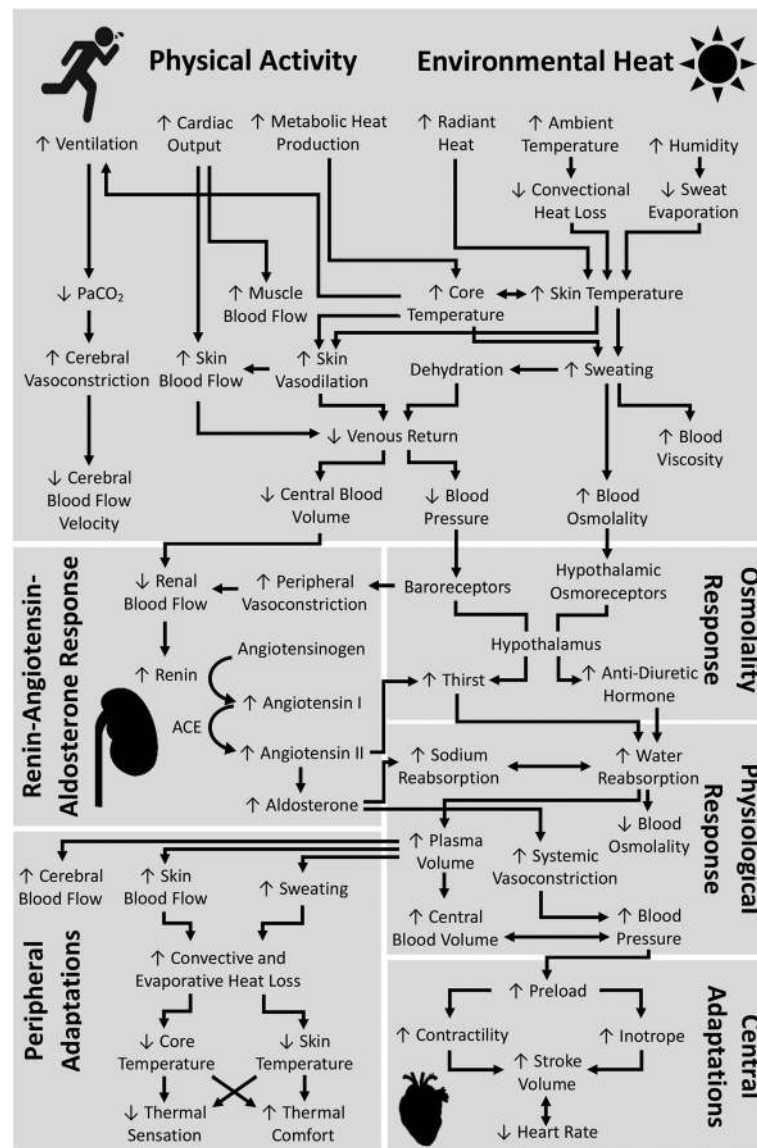


Fig. 2 Schematic detailing some of the body's major responses to exercise in the heat, from the acute responses to the chronic adaptations that occur with repeated exposures

between the skin and the air, while also facilitating evaporation (and production) of sweat, thereby cooling the blood. With elevated plasma volume, blood flow to cutaneous vasculature increases, facilitating heat dissipation (Fig. 2) [55, 131]. However, while many studies report increased skin blood flow after HA [116, 117, 120, 132] some observe decreases [41], or even no change [40, 118, 132, 133]. These inconsistencies may be due to differences in acute hydration state brought on by water restrictions in some studies. Alternatively, the plateauing of skin blood flow during exercise [34] may increase blood transit time through cutaneous circulations. Therefore, a more complete heat loss can occur, helping

to widen the core-to-skin temperature gradient, facilitating heat transfer away from the core [57].

Despite inconsistencies around changes in skin blood flow, mechanistic studies have found HA to increase skin blood flow at a given core temperature in fixed-intensity trials, helping increase the rate of heat dissipation [29, 125, 134–136]. When wearing military clothing any HA-mediated increase in skin blood flow will likely be less effective in promoting heat loss than current research would assume but may still contribute to total heat loss and slow the rise in core temperature. Within this, it is important that soldiers do not compromise the limited skin-air contact that does exist. Certain

sunscreens [137, 138] and deodorants [138, 139] can impair both convective and evaporative heat loss more than others, while similar problems may occur when using eye-black or camouflage paint.

Sweat rate

Sweating provides the main avenue of heat loss in hot environments [109, 140] and at elevated work-rates, if humidity is low enough to facilitate its evaporation [141]. Hypotonic fluid is secreted from a vast network of eccrine sweat glands located across almost the entire body surface. Sweat output and its distribution show large variability across individuals and body segments, and also varies with exercise intensity, posture, local skin pressure and temperature [142–144], while the cooling (i.e., evaporative) outcome will be further governed by overlying clothing and load carriage patterns [144]. With HA the core temperature threshold for sweating reduces [40], while sweat gland sensitivity heightens [29], thereby increasing the overall sweat response [145]. Furthermore, primate studies reveal that sweat glands undergo hypertrophy [146] and have increased blood supply [147] following HA, likely due to increased skin blood flow, which facilitates sweat production and secretion [148]. By increasing sweat production more heat is lost (assuming low humidity), reducing the rate of rise in core temperature, and enabling exercise at higher intensities or for longer durations (Fig. 2). Additionally, sweat electrolyte content decreases [54, 149], shown by reduced sodium concentration [59, 150, 151] and osmolality [152, 153], which help protect against hyponatraemia [154–156]. Sweating adjustments to HA take the longest to occur [24, 125, 157], but are seen in some short-term protocols [118, 158–164], albeit at lower magnitudes [125]. Interestingly, increases in sweat rate may not be beneficial to military personnel operating in high humidity environments where sweat cannot evaporate, or those wearing protective clothing with low moisture permeability, and in extreme cases those required to wear protective suits [5]. Such clothing can impede or prevent sweat from evaporating, raising the microclimate humidity [165, 166] and causing sweating to occur without heat loss, resulting in dehydration which is detrimental to performance [38, 82, 96, 167, 168]. As dehydration is highly likely to occur in such situations fluid intake is required to minimise negative effects on cognitive [169–171] and physical performance [74, 172, 173], whilst also helping to maintain central blood volume. Advice for hydration has already been well reviewed in current literature [167, 174–176], although for some military units access to water may be limited and those guidelines may require modification. Assuming HA is beneficial, personnel wearing restrictive clothing may benefit from shorter HA protocols that induce a lesser

sweat response, but still provide other valuable adaptations (see below).

Core temperature

A high core temperature is associated with negative effects on comfort, inflammatory responses [177], organ function [83, 84], descending corticomotor drive [49, 178], as well as performance [40, 44, 49, 179, 180]. Typically, HA evokes a lower resting core temperature [160] and reduces the rate of rise in core temperature due to improved heat dissipation [181]. Increases in sweat rate and convective heat loss from increased skin blood flow, usually enables a lower core temperature at the same relative intensity as before HA (Fig. 2). In an investigation involving military personnel, Cheung and McLellan [74] found 10 days of HA (10 days of walking at 4.8 km/h at a 3–7% gradient for 1 h in combat clothing in 40 °C, 30% relative humidity over two weeks), to reduce resting core temperature by ~0.2 °C regardless of fitness level, in line with most studies of less than 14 days [125]. A lower resting core temperature increases the heat-sink capacity of the body, enabling more work to be achieved before cooling mechanisms are upregulated [117, 182, 183].

Skin temperature

As core temperature decreases with HA, it is important that skin temperature also reduces to ensure the core-to-skin temperature gradient facilitates heat transfer to the periphery [184, 185]. Although rarely seen at rest [183], during exercise, skin temperature lowers with HA [162, 186, 187]. However, in a military context, the influence of clothing minimises skin to air contact, mitigating the rate of cooling. Instead, benefits would likely be seen through the role of skin temperature in the perception of heat. Skin temperature initiates behavioural thermoregulation [188] and has been suggested to majorly contribute to pacing strategies [58, 65]. By lowering skin temperature with HA, perceptual and physiological enhancements help to prolong exercise [173].

Perceptual changes

Skin temperature [58, 172], heart rate and core temperature all play a role in regulating perceptual responses to heat [189, 190]. As these reduce with HA, exercise in the heat feels easier, shown by improved thermal comfort, thermal sensation and rating of perceived exertion [191–193], especially following active HA [194]. Some short-term HA studies see changes primarily in perceptual outcomes, with negligible improvements to physiological variables [195]. In military settings a combination of peer-pressure and adrenaline can easily overcome perceptual inputs, placing soldiers

in physiological danger without being aware of how their body is responding [194].

Aerobic performance

Endurance performance is impaired in high ambient temperatures [196, 197], by a combination of factors including elevated core and skin temperature [172, 189], reduced central blood volume [46, 54, 55, 65, 198], systemic low-grade inflammation [42, 177] and perceptual responses to heat [96]. Physiological changes that improve heat dissipation mechanisms enable endurance performance in the heat to be improved following HA [125, 199]. A meta-analysis by Tyler et al. [125] showed medium (7–14 days) and long term (> 14 days) HA protocols improved performance by ~20%, while short-term (< 7 days) protocols resulted in improvements of 7%. Improvements are measured either with a time to exhaustion test, or a time-trial test, with time to exhaustion tests showing disproportionately greater improvements [125]. Time to exhaustion tests have been criticised for being invalid for sporting situations compared to a time-trial which integrates perceptual responses through the self-regulation of pace [200, 201]. However, in a military setting they can be just as valid as some military tasks are conducted at fixed intensities.

Individual variation in heat tolerance

Physiological differences between people causes individual variation in the heat [202], where some perform better than others, despite similar performances in temperate conditions [80, 160, 203, 204]. Those who struggle with heat exposure, and indeed those who have had prior heat illness, should undergo heat-tolerance testing [205, 206]. These individuals may require extra medical attention after deployment, or be closely supervised during additional HA before deployment, to induce protective physiological adaptations that will help minimise heat injury risk [82, 207, 208]. Despite these efforts it is still likely that some soldiers arriving in hot environments will experience adverse effects [10, 12].

There are sub-populations of soldiers that are more prone to heat illness than others. Sex differences likely place females at a thermoregulatory disadvantage, mostly due to anthropometric differences [209, 210]. Furthermore, females sweat less than males [211, 212] which, although potentially minimises dehydration, can reduce heat loss [211]. Accordingly, it has been suggested that females may require additional HA to obtain the same adaptations as males [162, 213]. Unfortunately, limited information exists regarding the effects of menstrual cycle on thermal tolerance and adaptations [214–218] due to the majority of studies in females controlling for this by testing women at the same time-point in their menstrual cycle [161].

Aging also has an effect on thermal tolerance, with older people having higher core temperatures and lower sweat rates, increasing their risk of heat illness [219, 220] if opportunity for behavioural thermoregulation (e.g., lower pacing or resting) is constrained. While age does not appear to affect responsiveness to HA [125], the lower baseline for thermal tolerance in older personnel means they would likely benefit from extended HA protocols [219, 220]. Despite this, studies looking at heat illness incidence rates often find no relationship with age, possibly due to absolute fitness requirements [221, 222].

Fitness is tightly linked with improved performance in the heat [74, 223], with those with a higher fitness level being more economical [224] and having enhanced cardiovascular capacity that helps combat the effects of heat [59]. However, fitness is not a substitute for HA [202] and does not affect the degree of heat adaptation [125]. Finally, there are other important factors impacting on thermal tolerance, and although considered beyond the scope of this review, include medication [225], disease [226, 227], skin coverings such as camouflage paint and tattoos [228], sleep restriction [229], and jet-lag [230]. It is important that group leaders are aware of these factors during deployment so they can assess and monitor each individual and adjust activity levels and exposure (if possible). Furthermore, in the event of a heat illness, additional monitoring is required to safely manage symptoms until appropriate medical attention can be administered [231]. Monitoring technology may enhance this [232–234], but may not be useful in extreme scenarios, emphasising the importance of pre-deployment heat adaptation.

Cognitive performance

As acute cognitive performance has been reviewed elsewhere, both during exercise [235–237], and in passive (non-exercising) heat stress [238–241] this section will focus on areas relevant both to the military and HA.

Military tasks require a diverse cognitive workload rarely seen in athletic situations, which along with the complex nature of cognitive testing [242], may be why this area of performance has received comparatively little attention. Retrospective military reports indicate that cognitive errors are more common in higher temperatures [241, 243], but these claims are not supported by experimental studies in the wider literature [238, 240, 244, 245]. The discrepancy likely centres around task-specific responses to low-risk, lab-based, cognitive testing [246, 247], and a lack of standardisation in regard to the heat stimulus [239]. Furthermore, many studies have a delay between exercise termination and cognitive testing [92, 248–250], and therefore do not capture

cognitive performance during exercise. The recovery period likely enables cognitive function to recover and improve compared to performance during exercise [235, 237], which may make them invalid and potentially misleading for military applications in which critical decision making can occur during exercise.

The effects of HA on cognitive performance are less clear. Studies have shown improvements in reaction time [92] and correct responses to rapid visual processing [92], no effect on visual inattention [246] and simple motor performance [92, 246] while time perception has improved [251] or worsened [246] in different studies. Certain adaptations to HA may aid cerebral function by way of constraining hyperthermia, maintaining cerebral blood flow or lessening discomfort and therefore distraction effects. Although cerebral blood flow increases with exercise intensities up to 60% $\dot{V}O_{2max}$, it declines at higher intensities [252–254]; a relationship likely further influenced by exercise duration and exacerbated by high body temperature [45, 255]. Therefore, increased plasma volume may be thought to improve cognitive function through increased cerebral blood flow at these intensities, for reasons mentioned above. However, alterations in cerebral blood flow do not appear to affect cognitive performance. Cerebral autoregulation enables cerebral blood flow to be maintained despite changes in mean arterial blood pressure brought on by both exercise and heat reducing cerebral blood flow [57, 126, 253]. Brain oxygen, glucose and lactate uptake are not related to reduced cerebral blood flow, but do decline at very high intensity exercise [253, 256]. The continued uptake of nutrients may explain why when manipulating cerebral blood flow with hypercapnia there are minimal changes to cognitive performance [257]. Other mechanistic findings indicate that cerebral neural activation [257] or alterations in cerebral metabolism [258] may play a larger role. The lack of understanding as to why cognitive performance appears affected, and may be improved, is an aspect of HA that is yet to be properly investigated. While it is hard to recreate military decision making in the manner it would be encountered in the field, it is important to use tasks of a similar nature to better understand the foundational cognitive processes being undertaken and how they might be affected both by heat and with HA. Recent studies have offered new insights using brain imaging technology to analyse cognitive function in the heat, even showing that head cooling may help overcome the negative impact of hyperthermia [259]. Future studies should extend this by adding exercise to the paradigm, to develop a greater understanding of what causes impairments to cognitive function in the heat.

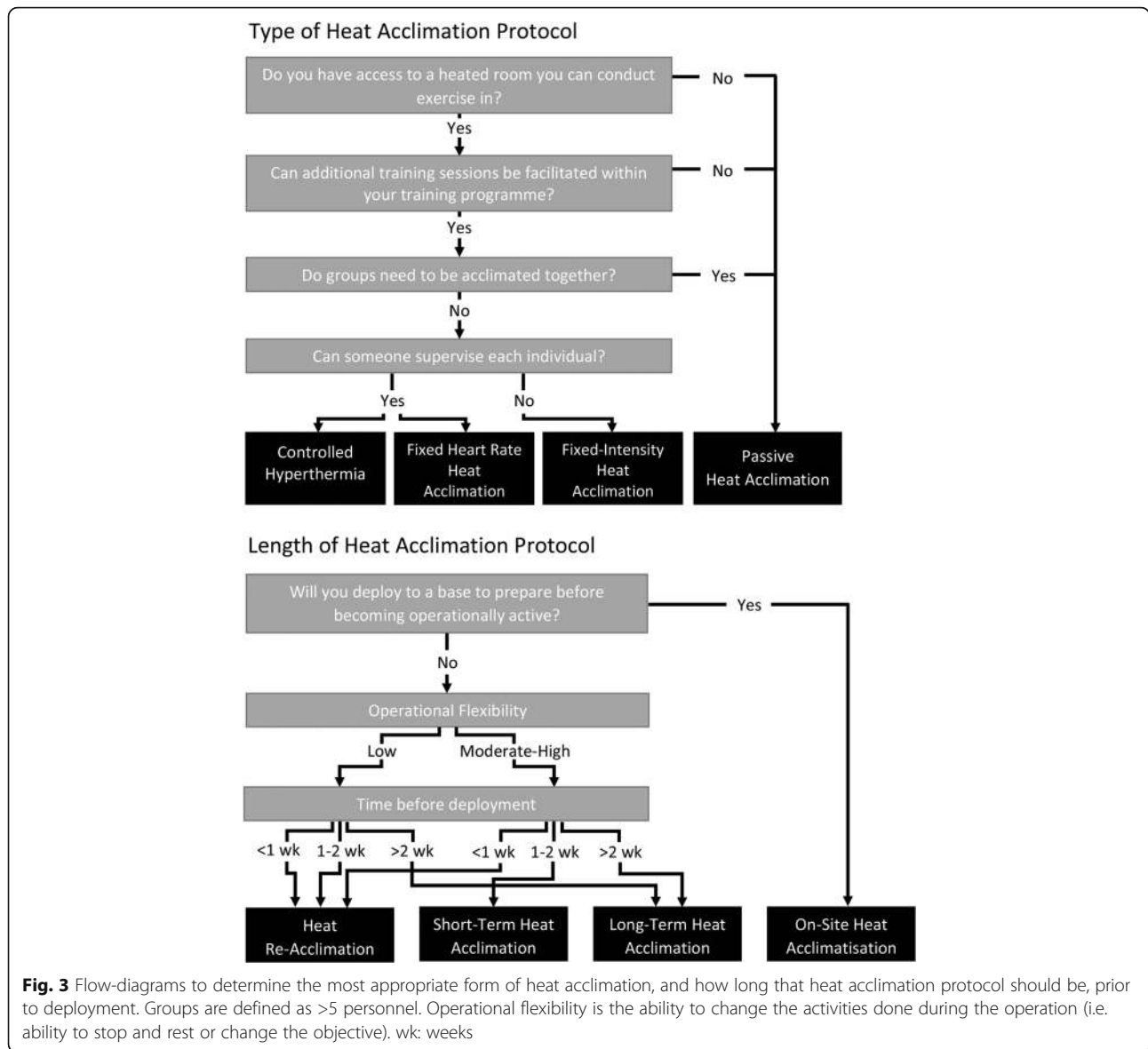
How to achieve heat acclimation

The efficacy of several different HA protocols has been reported in the literature. Many factors, such as the heat modality, ambient conditions, frequency of sessions, number of sessions and duration of each session can be adjusted to influence the physiological response to heat and exercise. Furthermore, while these factors have often been chosen or adapted to produce the best outcomes in sporting applications, they can be impractical for military contexts. For example, most HA protocols involve exercising in a heat chamber, allowing environmental conditions to replicate that of a desired environment [118, 128, 160, 161, 183, 260]. However, these facilities are often hard to access and cannot accommodate large numbers of participants. Within each session most studies use low or moderate intensity exercise (45–65% $\dot{V}O_{2max}$) [2, 116, 158, 159, 186, 261, 262], with sessions lasting at least one hour [117, 118, 128, 132, 152, 158, 161, 183, 187, 261]. For the military this would mean adding extra exercise sessions, which may impair other training [177, 263], and could result in overtraining [264].

Recent athletic HA studies have made an effort to maintain the thermal strain during exercise across a HA regime using the controlled hyperthermia technique, i.e. intensity is adjusted regularly to ensure core temperature is maintained at 38.5°C during exercise sessions [114, 117, 118, 128, 152, 161, 162, 183, 186, 260, 262, 265, 266], but this requires additional equipment and vigilant monitoring of participants using invasive equipment (Fig. 3). Furthermore, typical HA programmes take two weeks to see meaningful changes in sweat responses [109, 152, 163, 164, 178, 267], which does not suit military groups with short deployment notices.

Short-term heat acclimation

Recent literature has focused on optimising short-term (< 7 days) HA [2, 41, 117, 118, 120, 128, 158–162, 177, 183, 195, 260, 268–272] to minimise the barriers present in HA and prevent potential interference with higher priority training objectives [158, 195, 263]. However, this method adds additional training sessions, which may promote fatigue and overtraining, while also requiring access to facilities, such as heat chambers [183, 186]. The reduced programme length also limits the magnitude of adaptations [125]. While a lack of increase in sweat rate might limit dehydration, this may occur at the cost of other adaptations, and would soon develop upon deployment [160]. While short-term HA may be practical for athletic groups (and some military situations), the reduced magnitude of changes makes it less desirable for groups deploying with ample notice, and the length of the programme is likely incompatible for



short-notice deployment units (Fig. 3). For deployments of slightly longer notice, it might serve as a primer for more chronic adaptations to develop during deployment.

Passive heat acclimation methods

Passive heat exposure modalities, such as saunas or hot-water immersion facilities, allow groups of people to acclimate at once (Fig. 3), and can be installed easily. Passive HA may alleviate concerns that essential training may be impaired by additional sessions being conducted in the heat (Fig. 3), although to what extent normal training can be affected is currently unclear. Passive heat methods have typically been employed post-exercise, allowing exercise to elevate core temperature that can be maintained or further increased by passive heat [273–275], while there may also be benefits to having exercise

metabolites in the circulation during passive heating [276]. The following sections consider passive heating methods currently in use and the evidence surrounding their physiological and functional effectiveness.

Sauna Saunas are a hot-dry (65 °C - 110 °C, 10–30% relative humidity) room designed to induce cardiovascular strain and a sweat response [277]. Increases in peripheral blood distribution help invoke cardiovascular and hormonal adaptations that are beneficial for coping in the heat (Fig. 2). Scoon et al. [273] reported four 30-min post-exercise saunas (90 °C) per week for three weeks increased plasma volume by 7%, while improving time to exhaustion by 32%. Supporting this, Stanley et al. [278] found a plasma volume increase of 18% after four 30-min post-exercise sauna exposures (87 °C, 11% RH). The larger

increase could be due to sessions occurring on consecutive days, although further comparison between studies is limited by the lack of a performance test.

Hot-water immersion Hot-water immersion works similarly to sauna and has also been used to maintain an elevated core body temperature after exercise. For six consecutive days Zurawlew et al. [274] had an experimental group bathe in 40 °C water for 40 min following training, allowing for an additional ~ 1 °C rise in rectal temperature, compared to controls bathed in 34 °C water. In a heated (33 °C, 40% RH) 5-km running time-trial the intervention group improved 4.9%, linked to lower core and skin temperature, and an earlier sweat onset. Similar findings were observed in a subsequent study, by the same research group, which also saw reductions in end-exercising heart rate and $\dot{V}O_2$, and no significant change in plasma volume [275]. Brazaitis et al. [279] produced similar findings using immersion in 44 °C water up to the waist for 45 min on alternating days over a two-week period, without prior exercise. Although no performance test was conducted, this resulted in lower core temperature (\downarrow 0.3 °C), heart rate (\downarrow 12 beat/min) and psychological strain, and an increased sweat rate (\uparrow 40%) during hot-water immersion on day 14 when compared to day 1 [279].

In summary, both sauna and hot water immersion provide a heat exposure stimulus without requiring additional exercise, which may benefit military groups with heavy training schedules. These two passive heating modalities are yet to be directly compared in a HA context, so it is unclear whether they offer unique adaptations that may help before travelling to stressful environments. Furthermore, no study had compared either method to a more traditional, exercising HA programme, so it is unclear what differences exist in maximal adaptive capacity as well as the rates of adaptation each offer. Further investigations are required to evaluate the performance of both passive heating methods and to optimise their ability to induce heat adaptations.

Heat re-acclimation One method that could enable rapid HA in military personnel is re-acclimation. This topic has recently been thoroughly reviewed elsewhere [280], and so will only be discussed briefly here. Heat re-acclimation occurs following a period away from heat after completing an initial HA programme. Here, a few HA sessions are used in attempt to restore, or maintain, heat adaptations which otherwise begin to decay [59]. As studies in this area are relatively limited, results vary, with some studies finding a day of HA is lost with every two days without heat stimuli [178], while a single HA session every 5 days can sustain adaptations [59, 281]. Within a military context, where deployment time can be unknown, re-acclimation could maintain a heat-acclimated state for a

long period of time. Despite this area of research still being in its infancy, the potential to regain the adaptations of a previously completed heat-acclimation regime in a very short space of time (Fig. 3), or to continuously maintain them is promising. Within the military, maintaining these adaptations after acclimatising on deployment or during training in a warmer climate are both convenient and feasible. This would allow heat-acclimated soldiers to deploy to hotter climates at very short notice with minimised heat-related performance impairments.

Recommendations

On-site acclimatisation in the operational environment allows all-day exposure to the environmental conditions that will be worked in, and therefore is often the most desirable way to adjust to the heat. However, this is not always possible, and indeed deployment to this environment must also be considered. In more temperate environments where soldiers typically train, HA is an effective way to induce physiological adaptations to protect the body against thermal disturbances to homeostasis. Traditionally heat chambers are used for HA [54, 125], although this does require additional training sessions and can make it hard to acclimate large groups of people [263]. However, if these limitations are irrelevant then use of heat chambers for HA is well supported [125]. Whether or not supervision (both by person and technical equipment) is available to support these sessions dictates whether controlled hyperthermia or fixed-intensity exercise should be conducted (Fig. 3).

Controlled hyperthermia is currently considered the best-practice method for HA [152, 186], although it does require invasive and expensive equipment to provide real-time measures of core temperature, and because of this has often been overlooked in favour of fixed-intensity protocols [89]. Alternatively, when such facilities are unavailable, or additional training is undesirable, passive heat acclimation can provide an effective alternative (Fig. 3). While further studies are required to determine the best use of this approach, the results from recent studies are promising, demonstrating both performance enhancing and protective adaptations [274, 278, 282].

When considering the length of the heat acclimation protocol it is important to consider how HA integrates with other training requirements. This may impact the length of the HA protocol as conducting sessions on consecutive days may become impractical [263]. Furthermore, the overall load and fatigue state of soldiers during HA phases also requires attention as arriving at the deployed destination with in an over trained state will render adaptations meaningless [6, 222]. If operational flexibility is low (i.e. mission objectives are fixed and must be completed within a precise timeframe) soldier fatigue state becomes even more desirable than usual for HA adaptations

to be as complete as possible as there is limited opportunity for behavioural adjustments to the heat [58]. Therefore, the use of a long-term HA protocol to generate these adaptations is ideal, although if notice before deployment is short re-acclimation would be more suitable (Fig. 3). The re-acclimation would require having already conducted a long-term HA protocol, and then maintaining those adaptations for a prolonged period, to hold an elevated baseline heat tolerance. As such a strategy exists in a unique situation of long-term planning but short notice, this would likely only be used in special units that know they could be called upon at any time to deploy into different climates. If operational flexibility is moderate-high, then heat acclimation prior to deployment would likely act as a primer to minimise the effects of heat immediately upon arrival and provide a baseline heat tolerance that would be enhanced in the coming days (Fig. 3). Regardless, if ample notice is given prior to deployment, it makes sense to obtain maximally beneficial adaptations, if other training allows it.

Conclusions

Both physical and cognitive performance are impaired during exercise in the heat. With HA underlying physiological adaptations enhance thermoregulatory and cardiovascular function, which are responsible for at least part of the improved performance in the heat. While HA studies to date inform strategies for athletes preparing for competition in the heat, there is minimal consideration of military specific factors such as restrictive clothing, carried loads, large groups being acclimated, or short deployment notice. For military units that might expect to deploy at short notice (< 1 day) the options regarding heat acclimation are limited, beyond proactive planning to maintain heat adaptations for a prolonged and unspecified period. However, this approach has received limited attention in the literature due to this unique set of circumstances. Therefore, further investigations are required to optimise HA for military application. Specifically, the identification of effective, practical and feasible methods of HA, or re-acclimation, which can be undertaken by large groups of military personnel at short notice to prepare for deployment to hot environments.

Abbreviations

HA: Heat acclimation; RH: Relative humidity

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