Effectiveness of Exercise-Heat Acclimation for Preventing Heat Illness in the Workplace

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Abstract: The incidence of heat-related illness in the workplace is linked to whether or not workers have acclimated to a hot environment. Heat acclimation improves endurance work performance in the heat and thermal comfort at a given work rate. These improvements are achieved by increased sweating and skin blood flow responses, better fluid balance and cardiovascular stability. As a practical means of acclimatizing the body to heat stress, daily aerobic exercise training is recommended since thermoregulatory capacity and blood volume increase with physical fitness. In workers wearing personal protective suits in hot environments, however, little psychophysiological benefit is received from short-term exercise training and/or heat acclimation because of the ineffectiveness of sweating for heat dissipation and the aggravation of thermal discomfort with the accumulation of sweat within the suit. For a manual laborer who works under uncompensable heat stress, better management of the work rate, the work environment and health is required.

Keywords: heat stroke, exercise training, protective clothing, sweating.

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Introduction

Major health problems from working in a hot environment are features of heat-related illness. Heat illness is a general term regarding pathologic events in a hot environment, and is classified into 4 categories: heat cramp, heat exhaustion, heat syncope and heat stroke (Fig.1) [1–4]. Heat cramp is thought to be due to ingesting water with no salt during restitution from thermal dehydration and is defined clinically by a painful muscle cramp. Heat exhaustion is caused by severe fluid and salt loss due to a large amount of sweat loss that results from exposure to high environmental heat or hard work and is defined by clinical symptoms that involve a high body core temperature and signs of cerebral ischemia, such as weakness, fatigue, discomfort, anxiety, dizziness, and headache. Heat syncope reflects cardiovascular failure caused by reduced venous return to the heart due to excessive pooling of blood in peripheral dilated skin vessels with or without hypovolemia due to excessive sweat loss. Common symptoms include dizziness, fainting and pale face. Since whole-body or local heat stress cause an increase in skeletal muscle blood flow [5, 6], heating-induced muscle vasodilation may also contribute to the redistribution of blood flow from the central to the peripheral portions of the body. Heat stroke is the most severe heat-related disturbance and can be fatal. It is defined as a body core temperature greater than 40°C accompanied by hot and dry skin
indicating impaired thermoregulation. Heat stroke is also associated with delirium, convulsions, or coma, indicating impaired central nervous system function.

During the period of 1997 to 2010, 273 individuals in Japan died due to heat illness while performing manual labor [7, 8]. According to reports, 64% of the deaths occurred in the construction industry, and 59% of heat illness incidents occurred between 14:00 and 16:00 in the months of July and August. Importantly, 65% of the incidents occurred within the first three days of starting work in a hot environment. These reports suggest that the rate of heat illness can be decreased through acclimation to heat-stressed conditions. Consistent with the reported data, when six unacclimated subjects were repeatedly given a prolonged exercise load followed by a 20 min head-up tilt at 33.9°C for 8 days, fainting episodes during tilt occurred in 80% (n=5) of the subjects on the first day of the repeated exercise-heat exposures, and tended to decrease after that (2 subjects on the 2nd day, and 1 subject on the 3rd day) [9]. Lorenzo et al. [10] have recently reported that a 10-day exercise training in a hot environment increased maximal oxygen consumption, time-trial performance and power output at lactate threshold during cycle exercise in cool (13°C) and hot (38°C) conditions. These prior reports indicate the effectiveness of heat acclimation for preventing heat-related illness and for improving orthostatic tolerance and exercise performance in hot environments. In this review, we introduce findings regarding induction, decay and psychophysiological actions of heat acclimation in humans, and also discuss the ineffectiveness of heat acclimation when workers wear protective clothing.

**Induction and decay of heat acclimation**

The induction and magnitude of adaptation to heat stress depend on the intensity, duration, and frequency of heat exposure. Heat stress results from the interaction between environmental conditions (temperature, humidity, radiant heat etc), physical work (rate and duration of work) and the wearing of clothing and equipment that impedes heat loss (Fig. 1) [11]. The most effective means of adaptation includes prolonged exer-

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![Fig. 1. Pathophysiological mechanisms in heat-related illness](image-url)
Cise in the heat. During exercise training in a hot environment, the increase in core temperature is attenuated with increased sweating [12]. The increase in heart rate is also attenuated with reduced thermal strain and increased stroke volume during acclimation to heat [12–14]. When moderate exercise was repeated under hot temperature conditions of 40°C or above, sweating function was significantly enhanced after 4–5 days’ exposure to heat [15–17]. In general, full adaptation is obtained after exposure to heat for 10–14 days in succession. Compared with exercise in the heat, exercise training for 4–12 days under cool conditions of 24°C or below does not adequately improve sweating function. Heat-exercise training every 3 days could induce heat acclimation [18], while one-week intervals between each heat exposure induce no significant adaptation [19]. Heat acclimation is temporary, and gradually disappears if not maintained by continued, repeated heat exposure. William et al. reported some loss of acclimation in sedentary individuals after one week, with the loss increasing with time [20]. By three weeks, losses of nearly 100% for heart rate and 50% for core temperature were observed. Garrett et al. reported in moderately trained males that heat acclimation acquired by 5 days’ exercise training in a hot environment maintained inhibitory effects against increasing core temperature and heart rate during prolonged exercise 1 week later, but not 2 or 3 weeks later [21]. Physically trained and aerobically fit persons retain the benefits of heat acclimation longer than relatively unfit individuals [22].

**Psychophysiological actions of heat acclimation**

Table 1 sums up the psychophysiological actions of heat acclimation. Heat acclimation improves endurance exercise performance in the heat and thermal comfort during a given exercise [10, 23, 24]. These improvements are achieved by improved sweating and skin blood flow responses, better fluid balance and cardiovascular stability (Table 1) [11].

**Sweating function**

Endurance exercise training enhances the increase in the sweating rate as the core temperature increases during exercise and inhibits the rise of core temperature at a given absolute exercise intensity [25]. The magnitude and mechanisms of changes in sweating function are dependent upon environmental temperature and intensity and duration of exercise training. When healthy young volunteers underwent short-term (6–9 days) exercise training in the cool (22°C) [26] or heat (36°C) [27], the slopes of the relationship between sweating rate and core temperature during heat stress did not change, but the core temperature threshold for initiation of sweating decreased after the heat acclimation program [26, 27]. These findings suggest that heat acclimation increases the central sudomotor activity at a given core temperature.
It has also been reported that exercise training in a very hot environment (>40°C) could improve peripheral mechanisms (i.e., sweat gland function) in the sweating response [28–31]. Daily repeated 2-h immersion of an arm in hot water of 43°C increased sweating capacity and resulted in resistance to hidromeiosis in a hot-humid environment in the immersed arm compared with the opposite control arm [28, 30]. When local sweating was blocked by pretreatment with botulinum toxin in the forearm during a 10-day exercise-heat acclimation program, the heat acclimation increased sweat gland function at the untreated control sites but not at the treated sites, demonstrating that sweat glands must be active during heat acclimation to increase the capacity to sweat [32].

The sodium (Na+) concentration in sweat increases linearly with increases in the sweating rate, because the Na⁺ secretion rate increases proportionally more than the Na⁺ reabsorption rate in the ducts of sweat glands [33]. A 10-day exercise-heat acclimation program decreased the Na⁺ concentration in sweat at a given sweating rate [34]. Aldosterone increases Na⁺-K⁺-ATPase activity in sweat glands [35], thereby promoting Na⁺ reabsorption in the ducts. Since the plasma aldosterone level is decreased by heat acclimation [36], it is thought that the increased sensitivity of the sweat glands to aldosterone is responsible for the decrease of the Na⁺ concentration in sweat after heat acclimation. Exercise-heat acclimation also decreases calcium, copper, magnesium and zinc concentrations in sweat [37]. These heat acclimation-induced alterations to the composition of sweat help to inhibit mineral loss due to sweating.

**Cutaneous vasodilator function**

Heat acclimation alters the cutaneous vasodilator response in nonglabrous skin. Short-term (6–10 days) exercise training in the heat or endurance exercise training for several weeks in a temperate environment decreases the core temperature threshold for cutaneous vasodilation. Since the decrease in the core temperature threshold after exercise training is due to an altered active vasodilator system [38], heat acclimation does not influence vasomotor function in glabrous skin that is not innervated by the system [39]. A reduced core temperature during rest is primarily responsible for the decrease in the core temperature threshold after exercise training [40]. Heat acclimation inhibits a rise of core temperature during heat exposure but does not alter the tolerable upper limit (about 40°C) of core temperature during prolonged exercise in a hot environment [41, 42]. A reduction of resting core temperature due to heat acclimation expands the temperature range for lasting exercise in the heat, and therefore is effective for heat adaptation.

**Blood volume**

Exercise training in a cool or hot environment increases circulating blood volume by 10% [43–45]. The increased blood volume is mainly due to plasma volume expansion in the early phase (approximately 2 weeks) of training, and erythrocyte volume increases after 2-3 weeks of training. Whole-body heat exposure at rest for 2 h/day for 8 consecutive days increases plasma volume by 4.9%, and exercise training for the same duration that gives a similar increase in core temperature increases plasma volume by 12% [46]. That is, 40% of the hypervolemia induced by exercise training can be attributed to a thermal stimulus; the remaining 60% appears to be due to non-thermal factors related to exercising. Blood volume linearly correlates to maximal oxygen consumption, and increased blood volume contributes to increases in endurance exercise performance [47]. As a result, heat acclimation improves maximal aerobic exercise performance [10, 24]. In addition, increased blood volume in trained subjects inhibits vasoconstriction in the splanchnic vascular bed and thereby confers greater protection against gut endotoxin leakage in severe heat stress [48]. Cellular adaptations related to the expression of heat shock proteins and cytokine profiles reduce the impact of increasing heat stress and help maintain gastrointestinal barrier integrity in trained subjects [48, 49].

**Protective clothing and heat stress**

Workers use personal protective equipment in certain occupations, such as firefighting and radioactivity decontamination work. The equipment protects those whose regular or specified tasks involve great risk of exposure to thermal hazards and biological, chemical, or radiological agents. While the use of protective
equipment reduces injuries in such occupations, wearing protective clothing increases heat stress, potentially causing heat illness in hot environments [50, 51]. Physical and psychophysiological challenges from wearing protective clothing with lower vapor permeability increase subjective perception of heat and reduce work performance [52–54]. Compared with normal clothing, protective clothing further increases core and skin temperatures, heart rate and warm sensation during physical work (Fig. 2). During the recovery period after physical exertion, semi-impermeable clothing slows the recovery of body temperature and heart rate to pre-exercise levels by disturbing the evaporation of sweat and decreasing the temperature gradient from core to skin in a hot environment (Fig. 2). Thus, wearing protective clothing aggravates heat stress even when workers take a short break during physical work.

**Influence of heat acclimation on heat tolerance in workers wearing protective clothing**

As mentioned above, adaptation of the body to heat-stressed conditions is a practical countermeasure for preventing heat illness during work, but most prior studies have shown adaptive effects in experiments with semi-nude or lightly dressed volunteers. Does wearing protective clothing have a beneficial influence on heat acclimation? Aoyagi et al. [52, 53] examined the effects of 8 weeks’ exercise training at 20–22°C and 6 days’ exercise training at 40°C (heat acclimation) on heat tolerance and psychophysiological strain in exercising men wearing protective clothing against nuclear, biological and chemical agents in a climatic chamber (40°C, 30% relative humidity). Exercise training and heat acclimation improved the ratings of perceived exertion and thermal discomfort in the normal clothing condition but not in the protective clothing condition.

![Fig. 2. Effects of wearing a protective suit on changes in esophageal temperature, mean skin temperature, heart rate and thermal sensation during a 15 min cycle ergometer exercise at 80W in a hot climate (35°C dry bulb temperature, 60% relative humidity). A young male volunteer (N=1) exercised while dressed in a nuclear, biological, and chemical protective suit (●) and in normal clothing (○). Wearing the protective suit lead to greater increases in body core and surface temperature, heart rate and warm sensation during exercise, and the different responses between clothing types were more remarkable in the resting period after exercise rather than before exercise.](image-url)
Heat acclimation slightly reduced the increase in rectal temperature during exercise but did not significantly change the tolerance time in the protective clothing condition [52]. Training- or acclimation-induced increases in sweat secretion were not accompanied by any significant increase in sweat evaporation when wearing protective clothing. The researchers concluded that neither endurance training nor heat acclimation does much to improve exercise tolerance when wearing protective clothing in hot environments, because any added sweat secretion decreases blood volume and increases discomfort without augmenting body cooling [52, 53]. In follow-up studies, exercise-heat tolerance in an uncompensable heat-stressed environment was not influenced by a 2-week program of aerobic exercise training but was significantly improved by high aerobic fitness from exercise training for several years [55, 56]. Additionally, when core and skin temperatures were increased by using a water-perfused suit during a head-up tilt test before and after 6 days’ exercise training in the heat, exercise-heat acclimation did not significantly improve orthostatic tolerance under an uncompensable heat-stressed condition [27]. Thus, if workers wear protective clothing with limited vapor permeability, the benefits of short-term heat acclimation or short-term exercise training are relatively small, and it is necessary for such individuals to lower their work rate and take as many breaks as possible. During rest and physical work, cooling of the inner sites of protective clothing by fanning and an ice vest and cooling of the limbs have been found be effective for heat strain relief [57–60].

Finally, workers and the general public should be educated about the psychophysiological mechanisms of heat illness and specific countermeasures, including cooling the body [61–65], fluid intake [66–69], and heat acclimation. For physical work under uncompensable heat stress, better management of the work rate, the work environment and health is required, because the benefits of heat acclimation are limited under such conditions. As future directions for researches, it is necessary to elucidate the influences of aging on psychophysiological adaptation and heat tolerance during work under a hot environmental condition in both females and males, because aged workers show increased susceptibility to heat illness.

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Prevention of Heat Illness and Exercise


労働現場における熱中症予防のための運動による暑熱順化の有効性

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要 旨：労働現場における熱中症の発生は、労働者が暑熱環境に順化しているか否かに関係される。暑熱順化は暑熱環境下での持久性作業能力および一定の作業強度における温熱的快適感を改善する。これらの改善は発汗と皮膚血流反応の増大、より良い体液バランスおよび心臓血管系の安定化によって達成される。暑熱ストレスに体を順化させる効果的な手段の1つとして、日常的に有酸素運動トレーニングを行うことが推奨される。これは体温調節機能や血液量が体力の増進とともに増大するためである。しかし暑熱下で防護服を着て作業する労働者において、短期間の運動トレーニングや暑熱順化によってもたらされる心理生理学的な利益は少ない。なぜならば汗の蒸発が妨げられて防護服内に汗が蓄積し、温熱性不快感が増悪するためである。補償できない暑熱ストレス下で作業する肉体労働者のために、作業強度、作業環境および健康状態のより厳密な管理が求められる。

キーワード：日射病、運動トレーニング、防護服、発汗。