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Cooling Athletes before Competition in the Heat

Comparison of Techniques and Practical Considerations

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Contents

Abstract

With the general acceptance that high ambient temperature and humidity have a detrimental effect on performance, the topic of whole-body cooling and sport performance has received considerable attention from sport scientists, particularly in the lead up to the relatively hot Olympic games of 1996 in Atlanta, Georgia, USA, and 2004 in Athens, Greece. This trend is likely to continue as athletes begin to prepare for what will likely be another hot Olympic games in 2008 in Beijing, China. To overcome the reduced exercise capacity associated with the heat, a number of precooling methods have been utilised to cool the body prior to exercise, with the greatest benefits likely associated with prolonged endurance-type exercise. An increase in heat storage capacity following a precooling manoeuvre has been suggested as the primary means of delaying fatigue during endurance exercise performance in the heat; the notion being that the increased heat storage capacity will allow an athlete to complete a greater amount of work before a critical body temperature is reached. However, the specific underlying mechanisms responsible for delaying fatigue during exercise in hot ambient conditions remains unclear. While significant research in this area has been completed in the laboratory setting, few studies utilise performance protocols, and even less address the practical and logistical issues associated with precooling an athlete prior to elite competition in the field. This review addresses evidence supporting the use of a precooling manoeuvre prior to endurance exercise, the potential underlying mechanisms responsible for improved endurance performance following precooling, and the practical issues associated with the use of precooling prior to competition for elite athletes.

Scientists have been investigating the effects of extreme ambient conditions on human performance and fatigue in both the industrial and athletic settings for many years. Recently, methods that improve athletic performance in the heat have received an increase in research attention, particularly in the lead up to the relatively hot Olympic games of 1996 in Atlanta, Georgia, USA, and 2004 in Athens, Greece. This issue of endurance performance in the heat is likely to receive more attention as athletes begin to prepare for what is likely to be a hot and humid Olympic games in Beijing, China, in 2008 (mean August temperatures = 20–30°C).

Precooling the body is potentially an effective and legal means of improving athletic performance in the heat. The use of a precooling manoeuvre prior to competition is based on the concept that starting a contest with a cooler body will enable an athlete to increase their heat storage and perform more work prior to reaching a limiting core body temperature and therefore delaying fatigue. However, the mechanisms underlying the performance effects associated with precooling are not yet completely understood. More importantly, for athletes and applied sport scientists, the optimal precooling methods for use in the competition environment for different types of events have not been determined.

The purpose of this article, therefore, is to examine the results of previous precooling research to determine if evidence exists to support the use of a precooling manoeuvre prior to endurance exercise performance in the heat. The potential underlying mechanisms responsible for improved endurance performance following precooling, as well as the practical issues associated with the use of a precooling manoeuvre for elite athletes will also be addressed.

1. Precooling History

The effect of ambient temperature on physiological variables has interested scientists for many years, with body cooling playing a major role in these investigations. As early as the 1930s, researchers have been examining the human body's response to water baths of various temperatures.[1] Much of the early research on the topic of body temperature and exercise performance was conducted in the military and industrial occupation settings.[2-10] Today, the military continues to invest significant resources into methods that enable personnel to maintain or improve their performance in hot working conditions. The practical application of these methods to elite sport, however, is limited.

With the general acceptance that high ambient temperature and humidity have a detrimental effect on performance, the topic of whole-body cooling and sport performance began to receive attention during the 1980s.[11-17] These investigators examined the effects of a range of cooling techniques on a series of physiological variables, and this research has resulted in the use of precooling manoeuvres by elite athletes, such as Australian Olympic rowers and cyclists, before competition in warm conditions.[18]

In an attempt to further their understanding of fatigue and thermal stress and to prepare their elite-level cyclists, Australian sport scientists documented that in professional cyclists, the maximal rectal temperature attained following a 30-minute time trial in warm (32°C) and moderate (23°C) conditions was similar (~39.5°C), despite a 6% reduction in average power output in the warm condition.[19] As a result of these findings, and the apparent advantages of precooling described by earlier research, scientists at the Australian Institute of Sport (AIS) focused on developing a practical method for implementing precooling with athletes in competition. A collaborative University (Commonwealth Scientific and Industrial Research Organisation) AIS research team developed a Neoprene™ **1** ice jacket that was utilised by a number of Australian Olympians competing in the 1996 Atlanta Olympic Games.[18]

Since 1996, a number of publications have continued to address the topic of precooling and these papers have been carefully reviewed in a recent publication by Marino.[20] After reviewing the available literature, Marino[20] concluded that "whole body precooling is able to increase the capacity for prolonged exercise at various ambient temperatures." However, Marino[20] also indicated that "further work must be completed using more practical performance protocols before firm conclusions can be drawn about the benefits of precooling for exercise performance." In particular, before recommendations can be made to coaches and athletes, research investigating precooling methods that can be used within the constraints of elite competition is required.

2. Precooling Methods

There are a number of ways that researchers have been able to artificially lower core body temperature (T_c) prior to exercise, with the most common methods reported in the literature being exposure to cold air[12,13,16,21,22] and cold water immersion.[23-28] Despite the apparent effectiveness of precooling with cold air, it does present a number of difficulties for use in the field setting. The time required to achieve a physiologically significant reduction in T_c (>0.3°C) can be considerable, taking up to 130 minutes and often requires transient rewarming periods to reduce subject shivering and to blunt the metabolic response to the sudden change in ambient conditions.[12,13,16,20] In addition, this type of precooling manoeuvre can be quite uncomfortable for the subject and, therefore, may not lend itself for use by elite athletes prior to competition.

As reported by Marino,[20] the use of cold water immersion can be used to avoid the abrupt cold stress response associated with exposure to cool air. This is achieved by gradually dropping the temperature of a water bath from ~29°C to ~22°C over a 60-minute period.[29] Although the use of water immersion avoids some of the comfort issues associated with cold air exposure, the time required to achieve a reduction in T_c is still significant (30–60 minutes), and while effective in the laboratory setting, imposes considerable logistical problems for use in the field setting. More recently, the use of practical precooling methods such as cooling jackets have been utilised. These cooling garments have been shown not only to be practical in the field, but sufficient to cool the body and enhance performance.[19,30,31]

Different precooling methods influence the body in different ways; some methods primarily reduce skin temperature (i.e. jackets, mist fans, cool air), others reduce skin temperature as well as core temperature (i.e. water bath, cold room, combination treatment), while others reduce core temperature without an effect on skin temperature (i.e. ingestion of cold water, breathing cool air, cold intravenous saline, AVA-core™[32]). However, which of these methods provides the greatest performance benefit is unknown. Previously, it was thought that a reduction in T_c was an important aspect associated with the reduced thermal strain and performance improvement following precooling. However, as recently reported by Kay et al.[26] "skin precooling in the absence of a reduced rectal temperature is effective in reducing thermal strain and increasing the distance cycled" in a 30-minute self-paced cycling time trial. While improvements in performance may be apparent when skin temperature is reduced without a concomitant reduction in T_c, it is yet to be established which is more effective at improving performance or if a greater reduction in T_c results in a greater improvement in performance.

Today there are a number of commercially available 'cooling' products available for athletes. These products include a plethora of 'cooling' jackets, including jackets that use novel fabrics and coolants, a rapid thermal exchange device, fans that produce an ice mist, plunge pools, cold showers and portable

1 The use of trade names is for product identification purposes only and does not imply endorsement.

tents with air-conditioning units that produce a cool micro-climate. However, the effect on performance of a number of these commercially available products is yet to be independently tested. In addition, each of these precooling techniques differs greatly in regards to cooling power, athlete comfort and physiological effects. Furthermore, when examining precooling techniques, a number of practicality issues need to be considered, including transport, cost, ease of application, access to power, water, refrigerators, staffing of the precooling method, athlete comfort and pre-event routine, consumption of pre-event meals, registration and other pre-event commitments an athlete may have.

Another factor limiting the application of previous precooling research to the field environment is that very few precooling studies account for the significant effect of an athletes' warm up prior to competition. Often an elite athlete, in particular an elite cyclist, can warm up for periods of >1 hour and at exercise intensities that considerably increase T_C. Studies comparing the effectiveness of each of the different types of precooling methods are yet to be completed, and very few studies published to date have taken into consideration the practicalities of using these methods in the field during actual competition.

3. Precooling and Performance

As depicted in table I, and as previously reviewed by Marino,[20] studies investigating the performance effects of various precooling manoeuvres have used exercise durations that range from 45 seconds to 60 minutes, using both intermittent and continuous protocols, and have considered the effects of a range of ambient conditions. Although the majority of these studies have reported positive performance outcomes following a precooling manoeuvre, particularly for sustained endurance exercise, the variability in experimental conditions and lack of comparative data limits our ability to determine which type of precooling manoeuvre may be most beneficial for a particular sporting event in different ambient conditions. In addition, while these laboratory studies have shown that precooling can increase the amount of work performed in a given amount of time[13,24,26,30,33] or increase the time to exhaustion during constant load exercise,[12,16,21] Marino[20] states that the "benefits for exercise performance can only be inferred given that most studies have not used performance-based exercise protocols."

Arngrimsson et al.[31] has recently attempted to address this issue with the utilisation of a practical performance protocol. The performance protocol utilised by Arngrimsson et al.[31] required subjects to run 5km on a treadmill as quickly as possible. Following the use of an ice vest during a 38-minute warm up, Arngrimsson et al.[31] reported an improvement of 13 seconds in the 5km treadmill run time. The use of the ice vest during the warm up in this study resulted in a lower heart rate (11 beats/min), a lower perception of thermal discomfort (0.6 units; 5-point scale) and lower rectal, skin and body temperatures (0.2, 1.8 and 0.4°C, respectively) at the start of the performance trial. Arngrimsson et al.[31] concluded that this reduced thermal and cardiovascular strain during the early components of the 5km run and permitted a greater pace in the final two-thirds of the run resulting in the improved overall performance following precooling. However, the exercise protocol utilised in this study fixed the speed during the first 1.6km.[31] Had subjects been able to freely choose their pace from the start of the run, a faster pace may have been adopted earlier, resulting in a greater improvement in performance following precooling. Alternatively, subjects may have selected an inappropriate pace following the precooling manoeuvre resulting in a miss-pacing of the run and ultimately a slower time. Such a selection of an inappropriate pacing strategy following the use of a cooling jacket has been recorded in research recently conducted at the AIS (unpublished data).

The lack of studies utilising performance-based protocols has limited the ability of researchers to investigate the impact of precooling on self-selected pacing strategy. Although some researchers have used altered pacing strategies as an explanation for performance benefits following precooling,[24,26,31] no research has investigated the impact of precool-

Table I. Summary of precooling studies and associated performance outcomes

Study	Exercise protocol	Method of cooling	Change in Tc	Ambient conditions	Conclusion
Crowley et al.[34]	Wingate anaerobic power test	Water immersion, legs only (11.5°C)	0.4°C ↓ in rectal temperature	NR	Cooling reduced peak power, average power and cumulated work
Sleivert and Rowlands[35]	45 sec performance test	Torso only cooling (ice jacket) and whole-body cooling (ice jacket and water perfused cuffs around the legs)	NR	33°C 60% rh	Whole-body cooling resulted in a ~7% ↓ in both mean and peak power, whereas torso only cooling had no effect on power production
Marsh and Sleivert[27]	70 sec cycling power test	30 min water immersion, torso only (18–14°C)	0.3°C ↓ in rectal temperature	29°C 80% rh	Following precooling, mean 70 sec power output was increased by 2.7%
Bergh et al.[23]	Arm and leg exercise to exhaustion (5–8 min)	Water immersion (13–15°C)	NR	20–22°C	Performance reduced (from 6.08 to 4.36 min) after precooling
Mitchell et al.[22]	Treadmill run to exhaustion at 100% of maximal aerobic power (6–7 min)	Standing rest in 22°C exposed to fan cooling (4 m/sec) and water spraying (50 mL/min) for 20 min	~0.17°C ↓ in oesophageal temperature	38°C 40% rh	Time to exhaustion was reduced by 30 sec following precooling
Drust et al.[36]	2 × 45 min intermittent exercise periods on a non-motorised treadmill (separated by 15 min)	Cool shower (26°C) for 60 min	0.6°C ↓ in rectal temperature	20°C	No change in physiological variables after precooling
Yates et al.[33]	1000m rowing ergometer test	Cooling vest worn during warm up	NR	33°C 60% rh	3 sec (1.3%) improvement in 1000m rowing performance following precooling
Cotter et al.[30]	15 min work performance test	Ice vest and cold air exposure (3°C)	0.5°C ↓ in rectal temperature	32°C	16% improvement in mean power output after precooling
Arngrimsson et al.[31]	5km run on a treadmill	Cooling vest worn during warm up	0.21°C ↓ in rectal temperature	32°C 50% rh	5km run time was improved (1.1%) following precooling
Booth et al.[24]	Maximum distance run on a treadmill in 30 min	Water immersion (23–24°C)	0.7°C ↓ in rectal temperature	31.6°C 60% rh	Increased distance run by 4% following precooling
Kay et al.[26]	30 min cycling time trial	Water immersion (24°C)	No change in rectal temperature	31.4°C 60.2% rh	0.9km (6%) increase in distance cycled following precooling
Hessemer et al.[13]	60 min work rate test	Cold air exposure (0°C)	0.4°C ↓ in oesophageal temperature	18°C	6.8% increase in mean 1h work rate after precooling
Lee and Haymes[21]	Running to exhaustion at 82% of $\dot{V}O_{2max}$	Cold air exposure (5°C)	0.37°C ↓ in rectal temperature	24°C 51–52% rh	Improved rate of heat storage and increased time to exhaustion (121%) with precooling
Schmidt and Bruck[12]	Cycling with increasing workload to exhaustion	Cold air exposure (0°C)	1.0°C ↓ in oesophageal temperature	18°C	No significant increase in time to exhaustion
Olschewski and Bruck[16]	Cycling at 80% of $\dot{V}O_{2max}$ to exhaustion	Cold air exposure (0°C)	0.2°C ↓ in core temperature	18°C 50% rh	Time to exhaustion was increased by 12%

NR = not reported; **rh** = relative humidity; **Tc** = core body temperature; $\dot{V}O_{2max}$ = maximal oxygen uptake; ↓ indicates reduction.

ing on the pacing strategy selected by athletes during a performance trial. It has been suggested that pacing and fatigue may be regulated by both feed-forward and feedback mechanisms that supply a 'central governor' with information regarding the ambient conditions and thermal lode, exercise intensity and metabolic lode, energy stores and fluid balance; all of which are integrated to modify pacing and the sensation of fatigue to maximise performance for any given conditions.[37-40] As the use of a precooling manoeuvre may provide 'misinformation' to such central control, the ability to select an appropriate pace may be interrupted; therefore, in some circumstances, the use of a precooling manoeuvre may interfere with the regulation of effort, resulting in suboptimal performance. For example, if an athlete were exposed to cool ambient conditions (in a climate-controlled tent) in the time prior to the start of an event that is occurring in warm ambient conditions, as the athlete is not exposed to the heat and consequently 'unaware' of the prevailing conditions, they may select an inappropriately high pace to account for the actual heat load present during performance, consequently 'miss-pacing' the effort. The potential of the various precooling manoeuvres to impact self-selected pace requires attention before appropriate recommendations can be made to athletes.

Adding further confusion to the applicability of laboratory-based precooling results to competitive events is the few studies that address the potentially confounding effects of an athlete's warm up. Completing a warm up prior to competition is thought to enhance performance by increasing oxygen delivery to the working muscles,[41] enabling the performance task to begin with an elevated oxygen uptake ($\dot{V}O_2$),[42] increasing nerve conduction rate[43] as well as providing some psychological effects such as increased preparedness.[44] Consequently, few athletes begin endurance competition without conducting a warm up. However, as the name implies, conducting a warm up increases the athlete's core body temperature,[44] which, for endurance exercise in the heat, may result in reduced performance if the rise in core body temperature during the warm up results in a greater thermoregulatory strain during the event.[19,44-46] The effect of a warm up on body temperature appears to be in direct contrast with the desired outcome of a precooling manoeuvre. In fact, it may be possible to obtain performance gains similar to those reported following precooling during competition in the heat by adjusting an individual's warm up to avoid excessive heat load. It is entirely possible that subjects in the Arngrimsson et al.[31] study may have been able to improve their 5km run time by a similar degree if the warm up was reduced to provide a similar physiological effect as the precooling (i.e. performed a warm up that resulted in a lower heart rate [11 beats/min], lower rectal [0.2°C], skin [1.8°C] and body [0.4°C] temperature and lower perception of thermal discomfort [0.6 units]). Consequently, the benefit of modifying a traditional warm up prior to competition in hot ambient conditions compared with the use of a precooling manoeuvre may warrant investigation.

In addition to the lack of precooling studies utilising performance-based protocols that also address pacing issues and the potentially confounding effects of a warm up, the significant impact of air velocity on heat storage is often overlooked. In the field, air velocity is typically at least as fast as the athlete's rate of forward progression and although an increase in heat storage capacity is often touted as a mechanism for improved performance following precooling, few, if any precooling studies provide adequate wind flow during experimental trials or even report wind speed at all. As recently demonstrated by Saunders et al.,[47] the impact of air velocity on rates of heat storage can be profound. In this study, rates of heat storage while cycling in ambient conditions of 33°C and 60% relative humidity (rh), were halved when air speed was increased from 0 to 10 km/hour (80.8 ± 22.4 to 42.5 ± 17.2 W/m^2/hour) and reduced by a further 10.4 W/m^2/hour when air speed was increased to 100% of calculated road speed (~33.5 km/hour).[47] Consequently, the potential performance benefit following precooling reported in studies that do not incorporate an appropriate air velocity into the experimental design may be somewhat overstated, particularly for sports such as cycling, where the facing wind speed can be substantial (45–55 km/hour).

It is apparent from the published literature that the use of a precooling manoeuvre can influence exercise capacity in the laboratory. However, the nature of this impact on performance is affected by several factors including the extent of body cooling (method, duration and intensity), the type of exercise (duration, mode and intensity), ambient environmental conditions, and the training status and heat tolerance of the individual. In addition, the ability to apply the results of precooling research to the field setting is reduced as a result of methodological inadequacies; in particular, the lack of comparable air speeds and performance-based protocols. Further research is required to determine which cooling methods are most effective for particular types of exercise and this research needs to consider some of the important practical applications for elite athletes in competition, particularly the potentially confounding effect of an athlete's warm up, as well as adequate air flow and consideration of an effect on pacing strategy.

4. Proposed Mechanisms

An appreciation for the mechanisms that underlie enhanced performance following a precooling manoeuvre will likely assist the coach and sport scientist to prescribe appropriate precooling methods for different athletes competing in different events in different ambient conditions. The underlying mechanisms that delay the onset of the sensation of fatigue during exercise following precooling are multifactorial and beyond the scope of this article. However, the primary potential mechanisms that have been suggested are discussed in sections 4.1–4.3.

4.1 Critical Core Body Temperature

Continuous exercise results in an increase in body temperature that is proportional to the metabolic rate, and steady-state levels of exercise can be maintained when heat production is matched by heat loss.[20] The rise in T_c while exercising is exaggerated in warm ambient conditions. This is primarily due to the decreased ability of the body to maintain its heat loss, as a result of the reduced temperature gradient between the body and the environment. In these conditions, it appears that the body will intuitively adapt a pacing strategy or adjust the workload to ensure a critical T_c is not exceeded.[20,25,48] This concept is supported by Tatterson et al.[19] who found that T_c at the conclusion of a 30-minute cycling time trial was similar despite a 6% reduction in power output in ambient conditions of 32°C compared with 23°C and this concept of a critical core temperature (~40°C) that limits exercise performance has been widely reported.[20] This behavioural response, that is observed across a number of species, reduces metabolic heat production when a critical T_c is reached, and may be a mechanism that protects physiological integrity at times of high endogenous and/or exogenous heat load.[49] This notion of a critical T_c limiting exercise is further supported by reports that individuals tend to stop exercise at a similar T_c irrespective of hydration status,[50] glucose availability[51] or starting T_c.[25]

The notion that fatigue ensues once the critical T_c is reached has recently been challenged. It has been proposed that fatigue does not set in once a critical temperature is reached, but rather, the rate of heat gain is sensed by the body, which then anticipatorily adjusts the work rate to ensure the exercise task can be completed within the homeostatic limits of the body.[39,40,48,52-54] This anticipatory concept is supported by the findings of a recent study by Tucker et al.[46] In this study, subjects were required to complete two 20km self-paced time trials, one at 35°C (hot) and one at 15°C (cool). In the hot time trial, subjects reduced their pace after only 30% of the time trial was completed, well before the attainment of a critically limiting T_c and in the absence of any thermal stress. Tucker et al.[46] proposed that this early reduction in power output in the heat is a component of an anticipatory response that ensures the maintenance of thermal homeostasis. Such an anticipatory process is also supported by recent work by Marino et al.[48] who reported that runners exposed to warm ambient conditions reduced their running speed well before T_c became excessively hot (T_c <38.5°C). Therefore, reduced performance in the heat may not be so much a fatigue process, but rather an 'anticipatory regulation process influenced by rates of heat storage'.[55]

A number of authors have reported increased heat storage capacity in association with an increase in performance.[16,21,24,26] Kay et al.[26] used water immersion to pre-cool the skin without a concomitant reduction in T_c and reported an increase in heat storage from 84 to 153 W/m^2 during exercise. In addition, Booth et al.[24] reported an increase in heat storage from 113 to 249 W/m^2 after reducing T_c by 0.7°C with cold water immersion. This 'artificially enhanced capacity for heat storage' has become one of the most prominent explanations for improvements in performance following a precooling manoeuvre. While it is possible that a lower starting T_c that results from the use of a precooling manoeuvre may enhance performance by enabling an athlete to maintain a greater rate of heat gain (exercise intensity) before homeostatic temperature limits are reached, the influence of precooling on the potential underlying fatigue mechanisms while exercising in hyperthermic conditions are not yet completely understood.

Cheung and Sleivert[55] have suggested that there are two potential areas that may contribute to a reduced ability to exercise in the heat. Thermal strain and the associated increase in brain temperature may directly contribute to fatigue by impairing central arousal and/or the voluntary activation of muscle. Also, the considerable degree of cardiovascular strain and impaired blood flow to the brain and splanchnic tissues may enhance fatigue in hyperthermic conditions.

There is growing support for the notion that a reduced CNS drive may play a significant role in the development of fatigue in hot environments.[46,49,52,53,55-59] In a recent investigation by Nybo and Nielsen,[60] it was reported that a high internal body temperature caused muscles that were not utilised during a primary exercise task to reduce their force output, and that this impairment in performance was associated with a reduction in the voluntary activation percentage of the muscle.

There are two potential mechanisms that may contribute to a reduced central drive; the descending impulses from higher cortical structures to motor neurones may be reduced and/or afferent feedback (type III/IV afferent fibres) may reduce excitability of motor neurones subcortically.[55] As comprehensively reviewed by Febbraio,[61] some of the factors that have been suggested to be involved with this central limit to exercise performance in the heat include the influence that a higher than normal temperature plays on the CNS and neurohumoral responses. Nielsen et al.[56] reported reduced brain activity (specifically, reduced β-wave activity [13–30Hz]), similar to that observed during sleep, while subjects exercised in hot compared with cool ambient conditions. This reduced brain activity may reflect a reduced state of arousal resulting in decreased exercise performance in hyperthermic conditions.[55,56] A reduction in neural activity at the point of fatigue in the heat may also be related to changes in neurohumoral factors.[52,53,59] Disturbances in neurotransmitter levels, particularly dopamine and serotonin, have been implicated in central fatigue, as serotonin influences levels of arousal, and dopamine is involved in the initiation of movement and may also inhibit serotonin production.[55] Recently, Watson et al.[62] found that by inhibiting the reduction in dopaminergic activity via a dopamine reuptake inhibitor during exercise in the heat, subsequent performance improved. Furthermore, Robson-Ansley et al.[63] found that administration of exogenous recombinant interleukin-6, a polypeptide messenger molecule that is actively produced during exercise, resulted in increased serum prolactin concentration and a subsequent reduction in performance. As prolactin has previously been used as a marker for serotonin activity, the reduction in performance may have been related to reduced arousal as a result of increased serotonin activity.[63] However, Nybo et al.[64] have recently reported that after prolonged exercise in hyperthermic conditions, the cerebral tryptophan balance, the transporter of serotonin across the blood-brain barrier, was not different when compared with normothermic conditions. This led these authors to conclude that serotonin might not be related to the enhanced perception of effort and the fatigue associated with exercise in the heat.[64]

Alternatively, it has been suggested by Nybo et al.[58] that central fatigue may be related to glycogen depletion in the brain. This suggestion was based on the finding that glucose uptake in the brain was enhanced during recovery from hyperthermic exercise.[58] This assumption is supported by earlier findings from the same group of researchers[65] who reported an 18% reduction in global cerebral blood flow in exercising hyperthermic subjects compared with normothermic subjects. This reduction in global cerebral blood flow may potentially lead to the glycogen depletion in the brain during exercise in the heat and, therefore, may contribute to central fatigue. Consequently, it is likely that a reduced central drive during exercise in the heat is the result of reduced descending impulses as opposed to a subcortical reduction in motor neurone excitability. The use of a precooling manoeuvre prior to exercise may, therefore, reduce body temperature and delay the onset of a CNS-related ‘protective’ mechanism that reduces exercise intensity as the body approaches high core temperatures.

It is apparent from the literature that central fatigue plays a role in reduced performance during hyperthermic conditions and while the underlying components of this fatigue are yet to be completely elucidated, they are likely to be multifactorial. The use of a precooling manoeuvre prior to exercise in the heat may be a useful model to help understand some of these central mechanisms associated with fatigue in the heat.

4.2 Thermoregulation, Cardiovascular Strain and Endotoxaemia

The second potential mechanism that reduces an athlete’s ability to perform exercise in the heat is the influence that heat strain plays on the cardiovascular system. In hot environments, the body’s heat dissipation mechanisms compete with active muscle for blood flow. This increased blood flow to the skin for heat dissipation results in a greater cardiovascular strain for a similar workload in the heat compared with cool environments[45] and a number of studies have shown that exercise heart rate for a given workload is reduced following precooling.[12,13,21] When skin and core temperature are reduced, it is likely that less blood flow is required for heat dissipation,[30] resulting in an increased central blood volume, an increased stroke volume and an associated reduction in heart rate for a given exercise intensity after a precooling manoeuvre.[13,14,20-22,31] A reduction in blood flow required for heat dissipation may have additional positive effects. Sakurada and Hales[66] have reported a marked reduction in gastrointestinal blood flow in sheep when exercising in hyperthermic conditions. This redirection of blood flow from the abdominal region to enable necessary cooling can result in a leakage of endotoxins from the gut into the circulation resulting in an endotoxaemia triggered cytokine response. As reviewed by Davis and Bailey,[67] CNS fatigue has been reported to be influenced in the presence of such a cytokine response. In addition to an effect on central activation, the presence of cytokines may produce a more direct influence on fatigue within the active muscle. Supinski et al.[68] reported a 20–40% reduction in maximal force-generating capacity of skinned rat muscle when exposed to endotoxins, and these authors speculated that this reduction in maximum force was a result of alterations in the contractile proteins. It is possible that the reduced thermal strain during exercise after precooling may minimise any reduction in abdominal blood flow, thereby delaying the leakage of endotoxins into the circulation and consequently contributing to improved performance.

4.3 Metabolic Disturbances

Disturbances to metabolism and cellular processes have also been suggested as potential mechanisms associated with reduced performance in the heat.[61] Metabolic perturbations are typical during exercise in the heat, and it has been reported that exercising in a hot environment augments the endogenous release of adrenaline (epinephrine) and this in turn enhances carbohydrate utilisation via the β-adrenergic stimulation of glycogen phosphorylase.[23,69,70] Therefore, it has been suggested that blunting the rise in core temperature during exercise in the heat may result in an attenuation of net muscle glycogen utilisation.[20,61,71] However, muscle glycogen content at the point of fatigue in the heat has been reported to be greater than at the point of fatigue in comfortable ambient conditions, indicating that glycogen depletion is not likely to be a cause of fatigue in the heat.[72,73] In addition, Booth et al.[28] reported a reduced body temperature and cardiac frequency after whole-body precooling, but found no differences in muscle glycogen, triglyceride, adenosine triphosphate, creatine phosphate, creatine or lactate contents following 35 minutes of exercise in 35°C and 50% rh compared with control conditions; this suggests that precooling does not markedly impact on metabolism. In addition, $\dot{V}O_2$ and the respiratory exchange ratio have been reported to be unchanged following precooling, and there appears to be no relationship between $\dot{V}O_{2max}$ and exercise performance after precooling.[21,24,26]

5. Summary of Proposed Mechanisms

While it is generally accepted that increasing the body's heat storage capacity is a primary mechanism that enables precooling to improve endurance exercise performance in the heat, the influence of increased heat storage capacity on brain activity, neurohumoral factors, cardiovascular strain and metabolism requires further investigation. Finally, the placebo effect of a precooling manoeuvre, that would be difficult to entirely mask, can never be discounted as playing a partial role in the improved performance commonly witnessed following precooling.

6. Conclusion

The popularity of summertime sports and the likelihood of another warm Olympic games in Beijing in 2008 will likely result in sport scientists investigating methods that limit the detrimental effects of hot ambient conditions on human athletic performance. Despite substantial precooling research being conducted over the last 25 years, few practical recommendations can be made to athletes competing in hot ambient conditions. Precooling the body prior to endurance exercise in the heat has been shown to have positive effects on exercise performance, and while it is well accepted that an increase in body heat storage capacity is the general mechanism responsible for the improvement in exercise performance with precooling, the precise mechanisms responsible are not fully understood. Thus, before practical advice can be provided to athletes and coaches, research is required to identify which precooling strategies are optimal (physiologically, perceptually and logistically) during different types of elite endurance competition.

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