

Precooling Methods and Their Effects on Athletic Performance

A Systematic Review and Practical Applications

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Abstract

Background Precooling is a popular strategy used to combat the debilitating effects of heat-stress-induced fatigue and extend the period in which an individual can tolerate a heat-gaining environment. Interest in precooling prior to sporting activity has increased over the past three decades, with options including the application (external) and ingestion (internal) of cold modalities including air, water and/or ice, separately or in combination, immediately prior to exercise. Although many studies have observed improvements in exercise capacity or performance following precooling, some strategies are more logistically challenging than others, and thus are often impractical for use in competition or field settings.

Objective The purpose of this article was to comprehensively evaluate the established precooling literature, which addresses the application of cooling strategies that are

likely to enhance field-based sports performance, while discussing the practical and logistical issues associated with these methods. We undertook a narrative examination that focused on the practical and event-specific application of precooling and its effect on physiological parameters and performance.

Data sources Relevant precooling literature was located through the PubMed database with second- and third-order reference lists manually cross matched for relevant journal articles. The last day of the literature search was 31 January 2012.

Study selection Relevant studies were included on the basis of conforming to strict criteria, including the following: (i) cooling was conducted before exercise; (ii) cooling was conducted during the performance task in a manner that was potentially achievable during sports competition; (iii) a measure of athletic performance was assessed; (iv) subjects included were able bodied, and free of diseases or disorders that would affect thermoregulation; (v) subjects were endurance-trained humans (maximal oxygen uptake [$\dot{V}O_{2max}$] >50 ml/kg/min for endurance protocols); (vi) cooling was not performed on already hyperthermic subjects that were in immediate danger of heat-related illnesses or had received passive heating treatments; (vii) drink ingestion protocols were used for the intended purpose of benefiting thermoregulation as a result of beverage temperature; and (viii) investigations employed $\geq$ six subjects. Initial searches yielded 161 studies, but 106 were discarded on failing to meet the established criteria. This final summary evaluated 74 precooling treatments, across 55 studies employing well trained subjects.

Study appraisal and synthesis methods Key physiological and performance information from each study was extracted and presented, and includes respective subject

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characteristics, detailed precooling methods, exercise protocols, environmental conditions, along with physiological and performance outcomes. Data were presented in comparison to respective control treatments. For studies that include more than one treatment intervention, the comparative results between each precooling treatment were also presented. The practical benefits and limitations of employing each strategy in the field and in relation to sports performance were summarized.

Results Clear evidence of the benefits for a range of precooling strategies undertaken in the laboratory setting exists, which suggest that these strategies could be employed by athletes who compete in hot environmental conditions to improve exercise safety, reduce their perceived thermal stress and improve sports performance.

Limitations This review did not include a systematic assessment of the study quality rating and provided a subjective assessment of the pooled outcomes of studies, which range in precooling methodologies and exercise outcomes. The wide range of research designs, precooling methods, environmental conditions and exercise protocols make it difficult to integrate all the available research into single findings.

Conclusion Most laboratory studies have shown improvements in exercise performance following precooling and the emergence of strategies that are practically relevant to the field setting now allow scientists to individualize relevant strategies for teams and individuals at competition locations. Future research is warranted to investigate the effectiveness of practical precooling strategies in competition or field settings.

1 Introduction

A considerable quantity of energy is liberated as heat when performing exercise. When coupled with high ambient temperature and/or high humidity, which lowers the gradient for heat exchange between the skin and the environment and decreases evaporative heat loss, body temperature rises [1]. In such challenging environmental conditions, research indicates that the attainment or anticipation of a critically high body temperature is the main limiting factor inhibiting exercise performance [2–4], as evidenced by a reduced central nervous system drive to skeletal muscle [5] and other adverse effects including cardiovascular strain and metabolic disturbances (for review of proposed mechanisms, see [6–9]). Indeed, the development of hyperthermia is associated with earlier voluntary termination during constant intensity exercise [3] or alterations in pacing during self-paced performance trials [10, 11].

The rapid removal of heat from the body immediately prior to exercising in thermally stressful environments,

known as precooling, is a popular strategy used to combat the debilitating effects of heat-stress-induced fatigue and enhance exercise performance. Such improvements in performance following precooling are thought to occur as a result of the body's increased capacity to store metabolic and environmental heat [6, 7, 12, 13]. Indeed, strategies that can reduce initial body temperature prior to exercise, or attenuate the rate of heat gain during exercise, have been shown to increase the time it takes to reach a critical limiting temperature and thus prolong exercise performance [3]. For instance, Gonzalez-Alonso and colleagues [3] demonstrated that voluntary exhaustion was reached at similarly high core (oesophageal; $\sim 40.2^{\circ}\text{C}$) and muscle ($\sim 40.8^{\circ}\text{C}$) temperatures and subjective ratings of exertion, despite the lowering of initial values via prior water immersion (30 min at 17°C). The authors found that sub-maximal cycling endurance was inversely related to the initial body temperature such that exercise capacity was substantially improved with precooling.

Interest in precooling practices for athletic performance has increased over the past three decades, with the available methods involving exposure to cold air, water and/or ice immediately prior to exercise. New precooling devices and practices are often adopted in sports settings based on evidence established in laboratory protocols. For instance, the effectiveness of precooling with portable plunge baths with refrigeration units [14–19], cooling garments [20–32], as well as ice-slurry beverages [14, 19, 33, 34] or combinations of these strategies [20, 35–39] has been well demonstrated in the laboratory. Even when the potential benefits to sports performance associated with such precooling strategies are based on clear evidence [3, 14, 19–33, 35–50], some techniques are more logistically challenging than others, and thus are often impractical for use in competition or field settings. For example, the feasibility of cold air cooling prior to athletic competition is limited by accessibility to portable climate-controlled facilities and the lengthy application period required for cooling. Due to logistics, comfort and cooling power, cold water and ice have become the preferred cooling agents for use in competition settings. Nevertheless, the feasibility of individual strategies, which achieve effective cooling in the field, depends heavily on the circumstances of each event.

To improve the ecological validity of research outcomes, contemporary studies of precooling for athletic performance have incorporated specific methods that simulate the true characteristics of sporting events. For example, studies have tailored precooling methodologies to replicate competition schedules [17, 18, 32, 51–53], realistic pre-competition warm-up protocols [26, 29, 54, 55] and environmental conditions (i.e. temperature, radiant heat load and appropriate wind flow) [31, 35, 43, 56] as well as incorporating performance protocols that are

relevant to athletic performance [37, 46, 57, 58]. The differences between time-to-exhaustion protocols (that measure exercise capacity or endurance) and time-trial protocols (that better reflect the demands of competitive sport) should always be appreciated [59]. This may be of particular importance in precooling studies since changes in thermal comfort may alter the pacing strategies that underpin the outcome of time-trial protocols with either beneficial or harmful results [37]. Furthermore, logistical limitations experienced in the field, such as lack of equipment, facilities and time restraints, are often considered [32, 37]. From this research, effective and practical precooling options are rapidly emerging for athletes to easily employ in the field. Despite this, there is currently an absence of actual field data to confirm effectiveness.

Therefore, the purpose of this article is to comprehensively evaluate the established precooling literature, which addresses the application of cooling strategies relevant to improving field-based sports performance, while discussing the practical and logistical issues associated with these methods. Strategies employing cold air, cold water and ice will be further characterized as to whether the cooling agent is applied externally or is ingested (i.e. internal). Furthermore, these strategies will be considered when applied in isolation (i.e. external or internal cooling) and in combination (external and external, or external and internal), possibly increasing the effectiveness of cooling. This article will provide sport scientists and coaches with direct information on how to best prepare a variety of athletes for competition in thermally stressful conditions with specific precooling strategies. This information will need to be further filtered by an understanding of the characteristics of the event and the individual athlete.

2 Methods

This review identifies relevant precooling literature located primarily through the PubMed database with second- and third-order reference lists manually cross matched for relevant journal articles, as well as internet search engines including Google Scholar, and other online journals. The following key terms were included in searches performed, but were not limited to ‘cooling’ or ‘precooling’ combined with either ‘cold air’, ‘cold water’, ‘ice ingestion’, ‘ice vest’, ‘drink temperature’, ‘exercise’, ‘performance’, ‘thermoregulation’ and ‘practical’. Articles selected were limited to those written in the English language and included journal articles, ahead of print articles, abstracts and conference proceedings. A total of 161 experimental research articles were thoroughly read to determine whether they met criteria for inclusion and further evaluation or

otherwise discarded. The last day of the literature search was 31 January 2012.

2.1 Inclusion and Exclusion Criteria

Relevant studies were included on the basis of conforming to strict criteria as determined by two authors, whereby (i) cooling was conducted before exercise, which may have included recovery cooling where subjects cooled after one bout of exercise (e.g. simulation of halftime) and before a second bout; (ii) cooling was conducted during the performance task in a manner that was potentially achievable during sports competition; (iii) a measure of athletic performance was assessed; (iv) subjects included were able bodied, and free of diseases or disorders that would affect thermoregulation; (v) subjects were endurance-trained humans (maximal oxygen uptake [$\dot{V}O_{2\max}$] >50 ml/kg/min for endurance protocols); (vi) cooling was not performed on already hyperthermic subjects that were in immediate danger of heat-related illnesses or had received passive heating treatments; (vii) drink ingestion protocols were used for the intended purpose of benefiting thermoregulation as a result of beverage temperature, rather than hydration status; and (viii) investigations employed $\geq$ six subjects.

2.2 Data Extraction

On initial inspection, 161 studies were identified for potential inclusion but 106 were discarded on failing to meet the established criteria. Data pertaining to the 55 relevant studies, involving 74 precooling treatment interventions, are presented in comparison to respective control treatments and are presented in Tables I–VI (please refer to Online Resource 1). Tables with specific column headings were designed to extract relevant information from each study. Key information presented includes respective subject characteristics, detailed precooling methods, exercise protocols, environmental conditions, along with physiological and performance outcomes. For studies that include more than one treatment intervention (13 studies), the comparative results between each precooling treatment are presented in Table VII (please refer to Online Resource 1). Figures 1 and 2 graphically display individual and combined, respectively, precooling protocols applied that are associated with an improvement in a subsequent exercise performance task.

Due to the large variability in the methodologies of precooling (i.e. different cooling agents, timing and duration of application, environmental conditions, nature of a pre-trial warm-up and the exercise protocol itself), a meta-analytical approach to examine the literature was not performed. Rather, this systematic review is a narrative

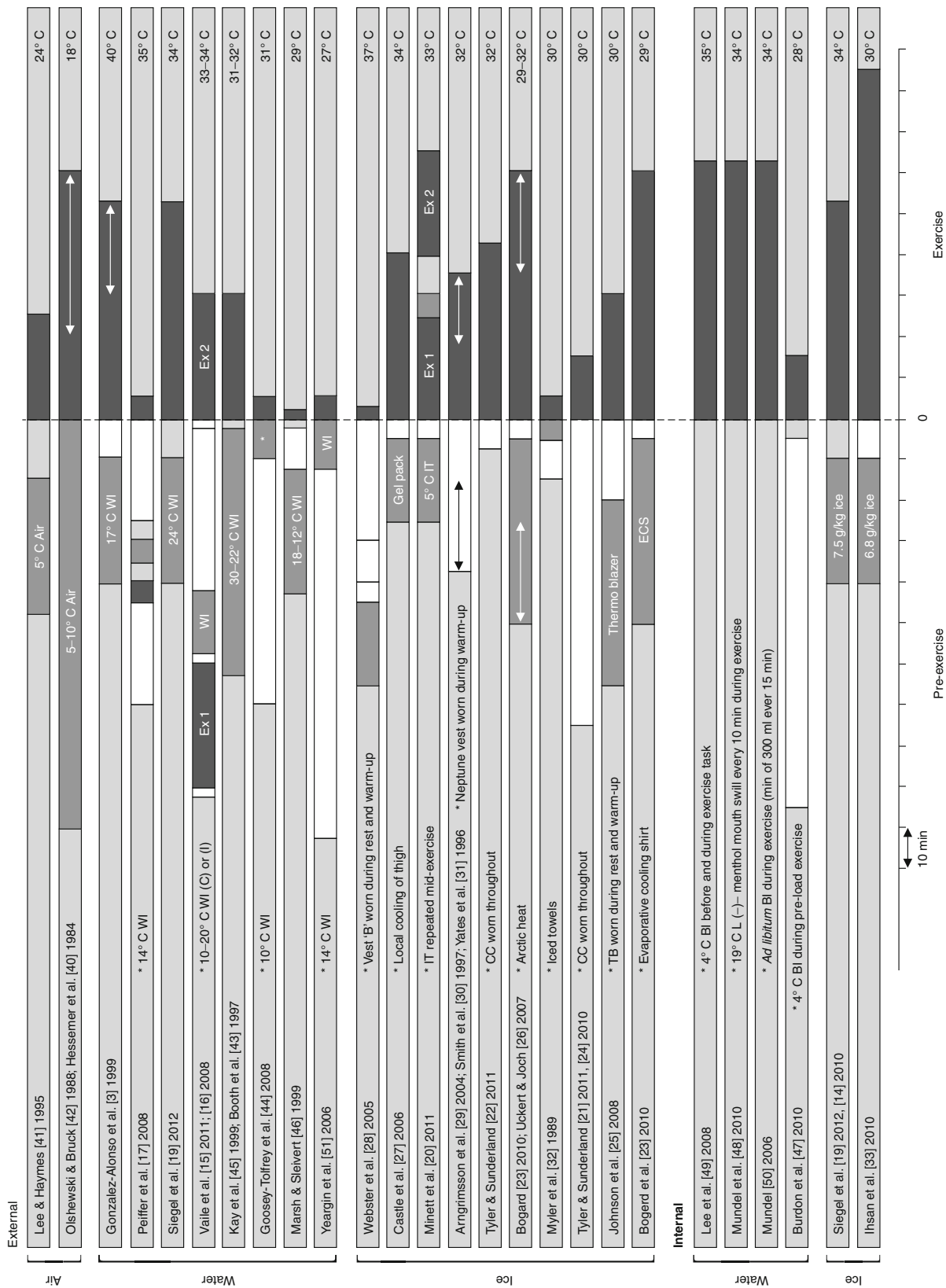
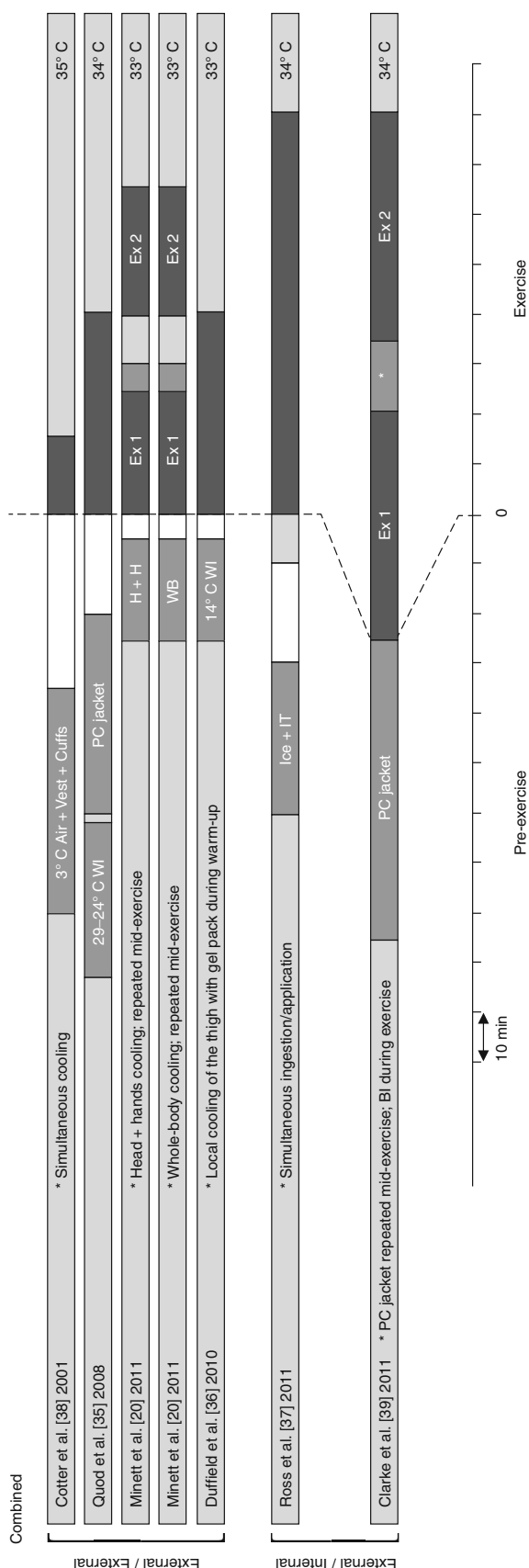


Fig. 1 Successful individual precooling methods involving externally and internally applied strategies. *BI* beverage ingestion, *C* continuous exposure, *CC* modified cooling collar. *ECS* evaporative cooling shirt, *Ex* exercise task (numbered accordingly), *I* intermittent exposure, *IT* iced-towel application, *TB* thermo blazer, *WI* water immersion, *white box* indicates submaximal exercise task or warm-up, *mid-grey box* indicates precooling intervention, *black box* indicates exercise performance task, $\leftrightarrow$ indicates range of time (precooling application or exercise duration) * indicates further clarification of employed protocol



◀ **Fig. 2** Successful combined precooling methods. *BI* beverage ingestion, *Ex* exercise task (numbered accordingly), *H + H* head and hands, *IT* iced-towel application, *PC* phase change, *WB* whole body, *WI* water immersion, *white box* indicates submaximal exercise task or warm-up, *mid-grey box* indicates precooling intervention, *black box* indicates exercise performance task, * indicates further clarification of employed protocol

examination that focuses on the practical and event-specific application of precooling and its effect on physiological parameters and performance. As such, we acknowledge a publication bias for the inclusion of studies with greater practical sports application in the competition and field setting. As well as reviewing the key physiological and performance outcomes in each study (Tables I–VII), we have summarized the practical benefits and limitations of employing each strategy in the field and in relation to sports performance (see Table VIII in Online Resource 1).

3 External Precooling

External precooling is defined as the application of a cold medium or material to the surface of the body and can include exposure to cold air, cold water or ice-cold garments. These strategies are the most commonly used methods of precooling observed in the literature. Their success relies on the heat-transfer principles of conduction, convection, evaporation and radiation to temporarily offset the thermal equilibrium of the body. In the defence of body temperature, the body, and largely the skin, will react to a powerful cold response through cutaneous vasoconstriction, with consequent reductions in skin perfusion in an attempt to prevent excessive dissipation of heat to the environment (see reviews [60, 61]).

3.1 Cold Air Exposure

Early precooling research established prolonged, intermittent exposure to cold (0–5°C) air as a beneficial strategy to reduce pre-exercise body temperature, as evidenced by a persistent reduction in skin and core (i.e. tympanic, oesophageal and rectal) temperatures [40–42, 62]. A total of four studies fit the inclusion criteria and are summarized in Table I. The history and methods of precooling using cold air exposure have been reviewed elsewhere [6, 7]. Briefly, the onset of cold air exposure is met with a number of natural physiological responses in order to defend deep body temperature. These include a powerful vasoconstriction and a reduction in conductive heat transfer from the core to the periphery [60]. As a result, warm blood is shunted back to the central circulatory system, where a

sharp $\sim 0.5^{\circ}\text{C}$ increase in deep body temperature has been observed [40, 42, 62], but with continued cooling, there is a decay in subject comfort. At the onset of continuous shivering, these protocols typically involve a brief period of rewarming (removal from cold air) such that there is an increase in perfusion of warm blood from the core to the periphery, and in turn, cooler blood is redistributed back to the core, resulting in a further drop in body temperature (i.e. phenomenon known as the ‘after drop’). This ‘thermal deception’ is known to acutely decrease the shivering threshold that causes a relatively small metabolic disturbance in the second cooling phase in relation to the decrease in mean body temperature. During subsequent exposure to cold air, body temperature drops further, allowing for an increase in the metabolic heat production during subsequent exercise [40, 42, 62].

To date, the majority of studies using cold air exposure as a precooling technique have reported enhancements to exercise protocols, including an increase in cycling [42] and running [41] endurance as well as improved cycling performance [40] (see Table I for specific details). It should be noted, however, that the performance tasks undertaken in these studies were conducted in mild ($18\text{--}24^{\circ}\text{C}$) ambient temperatures. Even in the study that failed to find an overall benefit from cold air exposure, there was nevertheless a $\sim 3\%$ improvement in capacity during a progressive maximal cycling test, with the benefits being more evident in the three female subjects who had lower aerobic capacity [62]. The authors in this study suggested that sex or initial fitness level may have influenced the response to and effectiveness of the precooling treatment.

Collectively, these findings support the use of cold air exposure for precooling and appear to have been embraced by sports authorities. For example, the current Australian Football League Heat Policy [63] states that when games are played in extreme heat, venues should be equipped with cooling facilities such as a cool room, fans, shade, and air conditioning. However, the effectiveness of these precooling methods is likely to be highly dependent on the ambient temperature, capacity of the facility to hold multiple players and the duration of their exposure. While controlled cold-air cooling interventions can be easily achieved in laboratory settings using facilities such as an environmental chamber, there are numerous practical limitations to the implementation of this strategy to enhance sports performance in competitive settings (Table VIII). The effect of cold air cooling on intermittent-sprint performance is currently untested and thus the influence on team-sport performance is unknown. As such, the combination of all these factors explains the relative lack of recent research on cold air exposure as a precooling technique for sport.

3.2 Water Exposure

The use of gradual cooling via whole-body immersion in water is commonly referred to as the ‘gold-standard’ cooling strategy [64] and, due to its superior cooling capability, is proposed as a preferable alternative to cold air exposure [64]. The major advantage of water immersion is that heat loss to water ($\sim 4.2\text{ kJ/kg }^{\circ}\text{C}$) is approximately four times greater than air at the same temperature ($\sim 1.0\text{ kJ/kg }^{\circ}\text{C}$). The technique of water immersion varies according to the duration of exposure, the temperature of the water, and the body surface area that is exposed.

There is a wide body of literature concerning cold water exposure that fits the inclusion criteria, with 17 studies (21 interventions) being summarized in Table II. These include investigations of whole-body immersion (12 studies) that can be further subdivided into (i) precooling using prolonged durations (30–60 min) of tepid water (temperature range $22\text{--}30^{\circ}\text{C}$) where water temperature is gradually reduced over the course of immersion; (ii) precooling using short-duration (20–30 min) cool water ($17\text{--}18^{\circ}\text{C}$) where water temperature is maintained over the course of immersion; (iii) precooling using a cold shower or water spray/mist; and (iv) recovery cooling between two exercise bouts. Moreover, part-body cooling is addressed (three studies), which includes precooling (30 min of $12\text{--}18^{\circ}\text{C}$) and recovery cooling (10 min of 10°C) strategies. Finally, a further use of water in externally cooling the body is via the wearing of various water-perfused garments (two studies) and is also discussed herein.

3.2.1 Whole-Body Immersion

One of the first studies to examine the effects of whole-body water immersion on sports performance involved 60 min exposure to cool water immediately prior to a self-paced 30 min maximal treadmill running test [43]. In this study, water temperature was gradually reduced from 29°C to 22°C , which minimized the body’s thermoregulatory defence against the cold, as evidenced by the absence of any strong, continuous shivering, little subject discomfort and only a minimal (0.2°C) initial rise in body temperature. Indeed, this protocol was found to be effective in reducing skin, core and mean body temperatures at the commencement of exercise and thus increasing the distance covered by competitive runners over 30 min. Variations of this cooling strategy, including warmer temperatures (i.e. 60 min at $30\text{--}26^{\circ}\text{C}$ [45]) and shorter periods of exposure (i.e. 30 min at $25\text{--}23.5^{\circ}\text{C}$ [19]) have resulted in significant reductions in skin but not rectal temperatures. Nevertheless, since the skin is a large organ with substantial mass, significant reductions in skin temperature can afford subjects a greater heat storage capacity, a delayed rise in rectal

temperature and reduction in sweat production during exercise. Importantly, the changes were associated with substantial improvements in submaximal running endurance [19] and enhanced cycling performance [45]. Due to time restraints, the use of shorter (30 min) water immersion protocols [19] may be more appealing for use in a practical setting than the more traditional protocols of ~60 min [43, 45].

Studies have also examined the influence of precooling in colder water temperatures (17–18°C) on exercise with somewhat conflicting results. Gonzalez-Alonso and colleagues [3] observed a 37% improvement in constant pace cycling capacity following 30 min water immersion at 17°C, which was associated with a significant, but transient reduction in initial skin (4.7°C), oesophageal (1.5°C) and muscle (3°C) temperatures. In contrast, a similar water immersion protocol (20 min at ~18°C) used by Castle et al. [27] failed to achieve a substantial improvement in intermittent sprint cycling. In fact, investigators observed ‘lower’ peak power output (~80–85 Watts [W]) during the first two of 20 sprints following precooling and a 6-min warm-up. It should be noted that the precooling protocol in this study brought about a significant cutaneous vasoconstriction, as evidenced by large and persistent reductions in skin (up to 11.5°C) and muscle (0.8°C) temperatures that were matched with increases in heart rate (~10–20 beats/min). As such, there was a less pronounced reduction in core temperature (0.3°C) than that typically achieved in water immersion protocols using warmer water temperatures [19, 43, 45]. It is possible that the reductions in intramuscular temperature observed following cold water immersion, interfered directly with metabolic [65] and force generating [66] mechanisms within the muscle fibre. While small and transient perturbations of intramuscular temperature seem to benefit capacity and performance of prolonged exercise [3], large and prolonged perturbations appear to impair sprint performance [27]. Indeed, a milder cooling agent also investigated in this study (local cooling of the thighs via the application of silicate gel packs) that achieved a more transient reduction in skin (~1.5°C) and muscle (0.6°C), but similar rectal (0.2°C) temperatures, was associated with an increase in peak power output, work done in each sprint and total work done over the same exercise protocol [27] (see Table VII for a detailed comparison of results). In fact, as will be discussed in section 3.3.2, this localized strategy is the only precooling method that has been associated with significant improvement in intermittent sprint activity in the literature. Finally, this study only assessed cycling sprint performance (peak power output and greatest work achieved in 3 s during each sprint) and may have missed the potential benefit of precooling on the submaximal work between sprint efforts as others have found [20].

The use of showers or water spray offers an alternative technique to water immersion for whole-body cooling. Only one study has investigated showers as a precooling method; this involved an exposure for 60 min as the water temperature was progressively reduced from 28 to 24°C [57] and was effective in reducing rectal temperature by 0.6°C. Indeed, this reduction in core temperature appears meaningful and is similar to that observed in whole-body water immersion protocols [15, 17, 43, 51]. However, the protocol failed to achieve substantial changes in psychological (rating of perceived exertion), thermoregulatory, metabolic (oxygen consumption), physiological (heart rate, sweat production) or performance outcomes during a 90-min intermittent soccer-specific activity conducted in a temperate environment (20.5°C, 68% relative humidity [rh]).

The evaporative effect of cooling via a fan and water sprayed in a fine mist over the body (20 min) has been shown to be effective in reducing skin (6°C) and oesophageal (0.5°C) temperatures [67]. However, this protocol was found to ‘reduce’ the time athletes could sustain running at $\dot{V}O_{2\max}$ by ~8% (30 s) [67], with subjects reporting ‘heaviness’ in the legs and ‘lack of spring’ during the trial following precooling. It is unclear whether the lack of performance enhancements in the studies of precooling with showers or water mist is due to the protocols themselves, the type of exercise involved (single and repeated maximal effort), the requirement to stand for prolonged periods (20–60 min) prior to exercise, the impact of a limited warm-up (maximal duration was 2 min) or the irrelevance of precooling for exercise in temperate environments. Thus, the practical transfer of these strategies to actual competition may be somewhat limited. However, since the shower and water mist cooling protocols were both effective in reducing body temperature, further research examining their effect on performance of prolonged exercise in hot and humid environmental conditions is warranted.

A separate but relevant body of literature examining the effects of whole-body cooling in exercise performance involves the use of water immersion during the recovery phase between repeat bouts of exercise [15–18, 51]. This cooling technique is applicable to sporting events requiring repeat maximal (or near-maximal) efforts such as competition involving heats and finals (e.g. rowing), sports played in quarters or halves (e.g. Australian Rules football, soccer or hockey) and sports where athletes may be required to compete in more than one event or discipline within the same programme (e.g. track cycling, athletics or swimming). Since cooling is conducted between exercise bouts, this method of cooling may act not only as a recovery strategy following the initial bout of exercise, but also as a precooling strategy for subsequent exercise performance.

Despite this, the physiological response of post-exercise recovery cooling may differ to precooling and therefore, should not be directly compared [16].

Cooling protocols used during the recovery periods in sport often differ to precooling strategies in that they need to be much shorter in duration (5–15 min) to fit within the time constraints of the imposed breaks in play or activity. In order to achieve cooling within the shorter time frame, recovery cooling often involves either intermittent [16] or continuous [15–18] exposure to cooler water temperatures (10–20°C) than those used in precooling research (17–30°C). When such cooling is performed on already hyperthermic ($\sim 38.5^\circ\text{C}$) subjects, substantial reductions in core temperature [15, 17] or mean body temperature [16] have been observed, along with positive performance outcomes. Furthermore, it has been shown that repeated performance tasks where subjects remain normothermic ($\sim 37.2^\circ\text{C}$) and thus are not likely to be limited by excessive heat gain (i.e. 1-km cycling time trial) incur no additional benefits from recovery cooling [18].

It is believed that rapid heat loss in hyperthermic subjects is associated with a reduced thermoregulatory defence against cold exposure (i.e. vasoconstriction and blood shunt). In support of this theory, Scott et al. [68] showed that prior warming via 15-min submaximal cycling or warm water immersion predisposed subjects to a more rapid heat loss, experiencing a larger decline in core temperature when subjects were subsequently exposed to cold water immersion. Increasing cardiac output and/or skin and core body temperatures prior to precooling may increase skin blood flow and thus increase the exposure of warm blood to external cooling. As such, it may be worthwhile to expose athletes to hot, humid conditions and/or increase endogenous heat generation prior to a precooling manoeuvre in order to improve the effectiveness of cooling, while minimizing the protective response to the cold. Indeed, contrast water therapy is thought to promote blood flow and internal body temperature changes during recovery from exercise [69, 70]. In this case, cooling with one of these strategies may be associated with pleasurable sensations and high levels of heat removal. The only existing study examining the effects of whole-body cooling on exercise performance in the field showed that 12 min of whole-body water immersion (5°C and 14°C) following 90-min submaximal running, substantially reduced rectal temperatures, although values were still above baseline [51]. In this study, immersion in 14°C, but not 5°C, was associated with an improvement in 2-mile running performance, with runners reporting muscle stiffness and uncomfortable sensations of coldness following the cooler immersion protocol. It is therefore probable that the colder water temperature resulted in the attainment of below optimal muscle temperatures. Somewhat supporting this,

Vaile et al. [15] identified a large negative correlation ($r = -0.70$) between changes in rectal temperature and subsequent performance following whole-body recovery cooling. Despite this, further research is needed in order to better understand the influence of core and particularly muscle temperature on explosive and endurance performance.

3.2.2 Part-Body Immersion

A limitation of whole-body external precooling is that direct cooling of the active musculature may inhibit local metabolic enzyme activity and/or result in vasoconstriction redirecting blood flow away from the working tissue. This may have negative effects on muscle and tendon function [40], especially prior to short-duration exercise involving a high-power production and anaerobic energy contribution, such as sprinting. An alternative to whole-body water immersion is to submerge sections of the body in water (Table II), with variations including the immersion of non-active (i.e. torso [46] and hands [44]) and active body parts (i.e. legs [71]). Additionally, water-perfused garments [72, 73] have been used to precool selective body segments. With part-body cooling, reductions in skin and possibly body temperature, which allow for greater capacity for heat storage and/or perceived reductions in thermal strain, can be achieved without direct cooling of active muscle tissue. Furthermore, cooling of inactive muscle tissue may result in localized vasoconstriction, possibly altering blood flow redistribution and improving blood delivery to active tissue. Indeed, the use of part-body cooling has been shown to be effective in reducing heart rate prior to subsequent exercise [44, 46]. Irrespective of the mechanism, studies have shown improvements in high-intensity cycling protocols following cold water immersion of non-active body parts including the torso [46] or the hands [44], but not when applied to the exercising muscle of the legs [71]. Table II provides further details of these investigations.

The use of water-perfused garments allows for the controlled cooling of various body parts prior to and during exercise. Despite the relatively small surface area of the head, wearing a 1°C water-perfused hood for 60 min has been shown to be sufficient in lowering thermal strain in 33°C heat during prolonged submaximal running, as indicated by transient reductions in core temperature, heart rate and sweat rate [73]. Despite reduced thermal strain, this protocol did not result in a significant improvement in distance covered during a subsequent 15-min running time trial. Likewise, maximal or mean power output during intermittent 10-s sprints was unaffected by 75-min precooling using a water-perfused jacket with a hood and long sleeves, despite the achievement of lower skin and body temperatures [72]. Collectively, these data indicate that the

ergogenic benefits of upper body precooling using a water-perfused jacket may be limited. Furthermore, the practical application of water-perfused garments in the field may be cumbersome due to the lack of portable equipment, the large amounts of time required to effectively cool athletes and the physical limitations related to athletes being tethered to a water pump/reservoir/chilling system (refer to Table VIII).

3.3 Exposure to Ice or Ice-Products

Due to its powerful heat transfer capacity, the application of ice directly to the skin has emerged as an effective precooling strategy to assist in the preparation of athletes. Heat from the skin and surrounding tissues is absorbed by the ice and, as a result, the ice changes to water through a process called fusion (melting). Based on the enthalpy of fusion theory, ice requires ~ 80 times more thermal energy to increase the temperature of water by 1°C due to the phase change that must occur when water changes from its solid to liquid state (at 0°C ; 333.55 kJ vs. 4.18 kJ without phase change) [74]. As a result, cooling with ice may be achieved with lower amounts of integument [75], at a faster rate [76] and to a greater magnitude [77], when compared with water. Moreover, ice offers practical advantages for cooling, as it is highly portable and can be incorporated into a range of garments to target specific regions of the body. However, the availability of ice at competition venues may influence the accessibility and practicality of this cooling technique.

There is currently a wide body of literature involving the external application of ice and ice products that fit our search requirements, with 20 studies (26 interventions) being summarized in Table III. All studies of garments and strategies considered to be ‘ice’ or ‘ice-like’ products have been included, although, the different thermodynamic properties of some items (i.e. the lack of phase change in gel-based products) is acknowledged. These include investigations with iced towels, ice vests, cooling vests, phase-change jackets, evaporative cooling garments and gel-based cooling packs. Aside from the theoretical effectiveness of external cooling with ice or ice products, the practical intervention of these strategies in the competition or field setting is directly related to each garment’s availability and operational demands (see Table VIII); for some, the logistically demanding preparation outweighs the limited benefits that may be achieved.

3.3.1 Iced Towels

Myler and colleagues [32] established a benchmark for practical precooling research by identifying a simple and

effective precooling strategy that delivered benefits to sporting performance. Ice packed in damp towels and applied to the head, face, neck, arms and thighs was used to provide conductive cooling; even a very brief (5-min) application of this treatment was beneficial in enhancing rowing performance. The effectiveness of such a simple technique was confirmed in a recent study where precooling was achieved by the application of towels soaked in 5°C water to the head and neck for 20 min prior to the commencement of exercise and for 5 min during a simulated half-time break [20]. Despite no change in gastrointestinal temperature and only a transient reduction in skin temperature during precooling, the ice towel treatment was associated with an improvement in total running distance and ‘hard-running’ distance in the second half of a 70-min intermittent sprint running protocol. Collectively, these data suggest that iced towels may be effective in lowering skin and/or core temperature, while having a significant effect on performance in the heat.

3.3.2 Iced Garments

Early research on precooling with iced towels [32] was the precursor to the commercial production of various vests aimed at precooling athletes during the warm-up prior to competition in hot and humid conditions. Differences in the efficacy of these vests can result from the type of cooling agents used, including ice and/or silica-based gels. Moreover, there is a trade-off between the cooling efficiency and the weight of the vest, as the cooling power is related to the amount of coolant contained in the vest. As such, vests have incorporated a number of design features to modulate the convective cooling of the torso by emphasising (i) fitted designs to increase the area of contact between the torso and the vest; (ii) wet cooling to increase the rate of heat transfer between the body and the vest; and (iii) silica-based gels to further promote evaporative cooling.

The practical benefit of wearing a vest is that they often allow athletes to simultaneously precool while fulfilling their normal competition preparation activities [25, 29–31, 54, 78]. However, the additional weight (~ 4.5 kg) and the increase in energy cost associated with weight-bearing activities, such as running [28, 29], may have an impact on the feasibility of using ice vests prior to competition in some sports. Research indicates that the thermoregulatory advantages that can be achieved by wearing a cooling vest prior to exercise is largely dependent upon the duration of exposure and the protocol of the cooling vest application. Indeed, sustained exposure (15–65 min) to a cooling vest worn during a warm-up results in localized cooling of the skin [29, 30]. Additionally, increases in whole-body blood flow as a result of the warm-up assist in redirecting cooler blood away from the region that is cooled. In turn, mean

body [29] and core [25, 29, 31] temperatures have been found to be lower than control conditions, but not lower than baseline levels, indicating that the vest effectively absorbs excess heat produced during the warm-up rather than cooling the body *per se*. In contrast, precooling protocols whereby subjects have worn cooling garments, including jackets [35], vests [23, 26] and evaporative shirts [23] for 20–45 min when passively sitting, have been shown to be less effective in lowering core temperature due to the lower whole-body blood flow that occurs. The duration and level of cooling typically results in relative reductions in mean skin [26, 35] and body [23] temperature, as well as skin blood flow [23], in absence of a reduction in core temperature [20, 23, 32]. This indicates that the transfer of heat between the body and the garment occurs primarily from the skin, and less the core.

Collectively, research has consistently shown that improvements in maximal endurance rowing [31], cycling [23, 25, 30] and running [28, 29] performance (range 7.5–60 min), after active and passive precooling with a cooling vest have been observed when skin but not deep body temperatures are lowered. In turn, preliminary data suggest that there is limited performance advantage gained by wearing external cooling garments under the following conditions: (i) when using cooling protocols that involve brief periods of intermittent exposure [53]; (ii) when environmental conditions are mild [25, 54, 79]; (iii) when precooling is employed too far in advance of the performance task, such that a possible washout of the cooling effect may prevent the occurrence of a clear outcome [39]; (iv) when cooling involves the sole use of a phase-change garment [35]; (v) when cooling involves the use of an alcohol- and menthol-based evaporative cooling solution [79]; (vi) prior to intermittent sprint cycling [27, 53] and running [39, 78] performance tasks; and (vii) when athletes self-select poor pacing strategies as a result of a lack of experience or insufficient education such that group mean performance data are inconclusive [54]. Further research in each of these areas is warranted to confirm these findings.

A further benefit of cooling garments is that they can be used for part-body cooling prior to, or during, a subsequent exercise task. However, their use during exercise is highly dependent on how each garment can be effectively incorporated into outfits worn by athletes within legal regulations of the sport and without detriment to the outcome of performance. As such, simple strategies such as the application of gel-based ice-cold packs to active [27] and non-active [21, 22, 24] regions of the body have been examined, with relative success, especially when thermoregulation is challenged. A novel finding across the external precooling literature in many respects is that precooling via a 20-min application of gel packs to the thighs increased cycling peak power output such that there

was a 20% increase in work done during each of 20 sprints observed during an intermittent sprint protocol. As such, the reductions in rectal and local muscle temperature may be attributed to the sustained, but only mild, cooling of the skin by the gel-filled packs. Furthermore, wearing a potentially practical cooling collar around the neck during running activities (warm-up and/or the performance task itself) has been shown to significantly enhance 15-min maximal running performance [21, 24], as well as running capacity [22] in hot environmental conditions (30–32°C; 53% rh). Although precooling with a collar was successful in cooling the neck region, it did not alter physiological or hormonal responses to running performance. It did, however, reduce subjective ratings of thermal strain, leading the authors to suggest that the improvements in thermal comfort may have improved running performance by masking the thermal strain of the body. However, there was no further benefit to performance observed when the cooling collar was periodically refreshed/renewed, compared with when it was left on after losing its effectiveness [21], suggesting that there may be a limit to the extent of thermal deception.

4 Internal Precooling

Internal precooling is defined as taking a cold medium into the body through the mouth (and/or nose, in the case of breathing) and can include the inhalation of cold air and the ingestion of cold fluids or ice. The inhalation of cold air is typically not used as a precooling strategy for enhancing sports performance. However, due to its practical and logistical simplicity, the ingestion of cold fluids and ice has gained considerable recent attention as a method of improving sports performance [14, 19, 33, 34, 47]. Cold beverages ingested into the stomach readily gain heat from the body, in order to equilibrate with the surrounding tissues. The benefits of ingesting cold beverages are that they may provide cooling, deliver nutrients (fluid, carbohydrate and electrolytes) and promote sensory advantages (discussed subsequently) while maintaining the integrity of the cardiovascular system to support athletic performance.

4.1 Air Inhalation

The use of cold air inhalation as a precooling strategy is relatively unexplored and, as such, we are unaware of any studies that meet our criteria for inclusion. However, it would be remiss not to briefly outline the application of cold air inhalation as a potential precooling strategy. The theory underpinning cold, dry air breathing is to increase the heat loss from the respiratory tract through evaporation of water vapour and convection involving displacement of

warmed air from the lungs during respiration. Specifically, the greater contribution to heat loss is due to the water vapour, since the latent heat of vaporization (~ 2260 kJ/kg) is considerably greater than the specific heat of air (~ 1.0 kJ/kg $^{\circ}\text{C}$), and collectively they contribute $\sim 10\%$ of the total body heat loss [80]. Although cold air breathing has been reported in the literature [81–84], it is yet to be evaluated for its feasibility for use in the field and as an effective precooling strategy that is capable of enhancing sports performance.

Indeed, a preliminary laboratory-based study shows promise, whereby subjects breathed 3.6°C air, promoting a 9-fold increase in respiratory heat exchange during sub-maximal cycling in hot humid conditions (38°C ; 90–95% rh) [81]. As such, the exercise-related rise in core temperature was attenuated, resulting in a 0.4°C lower rectal temperature at exhaustion that was matched with reductions in the usual perturbations in heart rate and respiratory frequency. Subjects rated this novel cooling strategy as ‘beneficial’ and, on request of the investigators’, two subjects verified their beliefs by cycling 15% longer before exhaustion was reached. Furthermore, in a separate investigation, convective and evaporative respiratory heat losses were increased with elevations in core (aural) temperature above 37°C and were attributed to increases in minute volume [84]. Therefore, individuals who experience increases in metabolic and environmental heat gained during exercise in high-ambient temperatures, and when ventilation requirements are high may benefit from cold air inhalation as a precooling strategy. Subjects breathing cold air did not report any incidence of respiratory distress, nor did it pose any danger of damage to the respiratory tract [81, 83]. However, the practical implementation of this strategy is not yet known.

4.2 Beverage Ingestion

It is well established that fluid ingestion plays an important role in supporting exercise performance in the heat via the maintenance of fluid balance [85] and fuel status [86]. Although less emphasis is placed on the influence of beverage temperature and its effect on subsequent performance, recent research in this area is forthcoming. The literature consists of six studies that fit the inclusion criteria and are summarized in Table IV. It should be noted that the ingestion of cold beverages, including ice (discussed subsequently) are known to affect skin temperature and associated physiological variables (e.g., skin blood flow and sweat rate), suggesting that the detection of cooler internal temperatures also plays a role in conserving body temperature, but the mechanisms involved are not yet clear. The sympathetic nervous system has been implicated, and the role of cholinergic nerve co-transmitters to affect the

thermoregulatory reflexes that control skin blood flow in response to a hot or a cold stress has been raised [60, 61]. As such, possible candidates have been identified; however, contrary evidence exists [87, 88] and, thus, the exact mechanism remains unclear.

Our discussion regarding this literature is intended to complement two literature reviews that have summarized, first, the beneficial effects of beverage temperature on voluntary consumption of fluids around exercise [89] and, second, the mixed results of beverage temperature on exercise performance in the heat [90]. Since this latter review [90], an additional study has been published [47], such that five studies (see Table IV) have investigated the effects of drink temperature on body temperature and its effect on subsequent endurance cycling performance in well trained subjects [47, 49, 56, 91, 92]. A practical benefit of strategies involving consumption of cold beverages is that fluid ingestion before and during competition is already a habitual practice for many trained athletes. Furthermore, attention to hydration is included within the rules of many sports, which may allow for the controlled manipulation of beverage temperature. Although athletes of all levels can benefit from the practical simplicity this strategy offers, it may only be at the highest levels of competition that control over the temperature of beverages is feasible. For instance, designated cyclists drop behind other competitors to receive additional fluid from team cars during a professional road race, ‘preferred start’ runners provide their own fluid options at drink stations during road and marathon races, Australian Football League players drink *ad libitum* throughout a game from bottles provided to them by team personnel who are permitted on the ground during play in elite level matches and professional tennis players access refrigerated beverages courtside during the intermittent rest breaks held during play.

As such, the general characteristics associated with many organized sports, which include staffing, logistical support and equipment availability, may determine the potential to achieve such competitive advantages. However, the actual conduct of a specific event will further shape the implementation of mid-exercise cooling strategies when these opportunities are variable and unpredictable (as provided in the examples above) rather than when they are static and pre-determined (e.g. as in the organized breaks between periods of a game). Therefore, scientists working with individuals or teams may need to consider the incentives for improved sporting performance achieved by the use of cold beverages against the lack of predictability or the interference that a strategy like this may cause during competition.

Research protocols of precooling with cold fluids have involved consumption of beverages during 90-min sub-maximal pre-load exercise, much like drinking during a

prolonged warm-up before racing. An additional benefit of the consumption of cold beverages prior to exercise is that fluid and fuel can be co-ingested to provide nutritional support for the subsequent exercise task. Different protocols have been studied, with cold fluid (~ 1.0 – 1.6 L) being consumed in small boluses over a period of 10 min [92], 60 min [91] and 90 min [47] prior to the respective performance tasks. However, it is most likely that the beverage temperature is the major distinguishing factor influencing changes in body temperature, subsequently leading to improvements in endurance cycling performance. Indeed, serving the beverage at 4°C [47] induced a greater heat sink compared with the results of studies that used fluids of 10°C [91, 92], such that reductions in skin (0.7°C) and mean body (0.5°C) were achieved before the start of the performance trial, and were associated with a 5% greater work output (mean increase of 12 W) during a 15-min cycling time trial in hot environmental conditions (28°C , 70% rh). These findings are in agreement with the work of Lee et al. [49] who observed a reduction in thermoregulatory strain following the ingestion of a 4°C beverage before (3×300 ml over 30 min) and every 10 min (100 ml) during submaximal exercise, compared with drink served at normal body temperature (37°C). As such, there was a reduction in rectal temperature (0.5°C) and heart rate (8 beats/min) upon the commencement of exercise, and a lower rise in skin temperature ($\sim 0.96^{\circ}\text{C/h}$) after the first 20 min exercise, which resulted in a 23% longer cycling time to exhaustion (11.9 min) in hot environmental conditions (35°C , 60% rh). Further research is warranted to understand the importance of total relative beverage volume and timing of ingestion, environmental conditions, pre-load or warm-up intensity and the selection of performance tasks, when cold beverages are used to precool an athlete.

Cold beverage ingestion is one of a limited number of strategies that can also practically provide cooling while exercise is being executed. It would not be ideal for athletes to solely rely on cooling via this strategy, however, especially when exercise intensity is high and hence the gastrointestinal discomfort may be increased. Nevertheless, Mundel et al. [56] demonstrated that a cold beverage (4°C) was more palatable and positively influenced fluid intake such that 23% (300 mL/h) more fluid was ingested than when the same beverage was served at a more neutral temperature (19°C). While a heat sink effect should still be considered, on further inspection of the data, Marino [93] pointed out that the absolute difference in drink volume ingested was only ~ 160 ml between the cold drink and control conditions, and questioned whether this small volume could explain any differences in temperature response and account for a 7 min increase in cycling capacity. Consumption of the cold beverage attenuated the

rise in rectal temperature (0.4°C/h) and heart rate (6 beats/min/h) that was associated with steady-state cycling in hot conditions, such that six of eight subjects cycled longer before exhaustion was reached, with a mean improvement of $\sim 13\%$. These data indicate that a feed-forward mechanism was involved whereby the anticipatory regulation of impeding thermal limits was altered in response to the cold stimulus to delay the reduction of central drive associated with fatigue [93].

In addition to the heat sink induced by cold beverages, there is also strong evidence to suggest a possible sensory effect of temperature provided by ingesting cold beverages. Guest et al. [94] have previously shown that oral temperature sensitive regions of the brain are activated in response to perceived pleasant sensations of a cold (5°C), compared with when a warm (50°C) fluid was placed in the mouth, as recorded by functional magnetic resonance imaging. Moreover, the cold sensation of a periodic 19°C menthol mouth rinse during exercise has been shown to enhance cycling capacity by 9% (5 min), albeit not associated with typical changes in body temperature, but in response to an 8 L/min increase in ventilation and a 15% reduction in cardiopulmonary rating of perceived effort [48]. The authors attributed this improvement in performance to the stimulation of oropharyngeal cold receptors by menthol. Menthol exerts its cooling effect by making the subsequent oral stimuli (i.e. air inhaled and water consumed) feel cool and this pleasant sensation may enhance central drive such that athletic performance is improved. A practical benefit of this strategy may appeal to athletes who would otherwise be disadvantaged by increases in body mass if large volumes of drink were to be ingested, or when hydration or fuel status are not compromised by lack of beverage ingestion. Future research is required to further our understanding and differentiate the underlying mechanisms that underpin performance following the ingestion of beverages that are cold or perceived as cold.

4.3 Ice Ingestion

The ingestion of large volumes of fluid before and during exercise may be impractical in many sports. However, the ingestion of an ice-slurry (slushie) provides an alternative strategy for inducing a similar magnitude of internal cooling from a smaller volume of ingested beverage. A total of five studies fit the inclusion criteria and are summarized in Table V. Recently, the consumption of 6.8–7.5 g/kg body mass (BM) slushie, given in small boluses during seated rest in the 30 min prior to exercise, improved running capacity [14, 19] and cycling endurance performance [33]. Indeed, Siegel et al. [14] showed that all ten subjects ran longer, with a mean improvement of 9.5 min ($\sim 23\%$) following slushie ingestion, when

compared with a 4°C beverage. Ice ingestion manifested in a moderate reduction in rectal [14, 19, 34], gastrointestinal [33] and skin temperatures [14], which allowed for a greater heat storage and level of thermal comfort during the respective exercise tasks. However, in a separate study, the authors [19] noted slightly different physiological responses to slushie ingestion despite similar applied methodologies to their previous study [14]. The notable difference was the environmental conditions that subjects were exposed to during precooling (25 vs. 34°C) with larger and more sustained reductions in skin and rectal temperature being achieved when precooling was performed in the cooler environmental conditions (25°C) [14]. Greater heat exchange between the body and the slushie would be expected in cooler conditions due to the lack of competition for absorption of environmental heat [19]. Nevertheless, there was a ~13% (6 min) increase in running capacity following the ingestion of the slushie, than when the same beverage was served at 37°C. However, we cannot directly compare the performance improvements between these studies as different subject pools were used.

The possibility of an oral sensory effect of an ice puree mouthwash in improving maximal cycling performance has also been explored. For example, Burdon et al. [47] gave 30 ml of an ice puree every 5 min during a 90-min cycling trial. While there was a 0.4°C reduction in mean body temperature, there was no improvement in performance during a 15-min maximal cycling time trial. In turn, a single bolus of 1.25 g/kg slushie attenuated the reduction in repeated 2-min sustained maximal voluntary contraction torque development of the elbow flexors, compared with ingesting warm (40°C) fluid, following hyperthermia induced by running in hot conditions (34°C, 50% rh) [95]. In lieu of a change in rectal temperature, a positive sensory effect of the cold internal stimulus was proposed for the improvement in neuromuscular function observed. Although, the possibility of a placebo effect cannot be ruled out as the precise mechanisms remains unclear. Future research is warranted to determine if the possible sensory effects observed in this study [95] could also be observed during more dynamic, whole-body exercise performance.

5 Combination Precooling

Combining two or more practical precooling methods can provide mutually potentiating effects on performance through enhanced heat storage and decreased thermoregulatory and cardiovascular strain. Early research in this area demonstrated further improvements in cycling capacity in non-heat acclimatized and untrained subjects when combining the effects of wearing an ice vest and drinking ~15°C water, compared with when either strategy was

used in isolation. Ross et al. [37] showed greater effects of cooling using the combined strategy of ingesting a 14 g/kg BM slushie and wearing iced towels during pilot research, as evidenced by larger changes in rectal temperature (0.12–0.76°C) than seven different cooling strategies that were applied singly. As such, the emergence of combination precooling strategies that involve the use of external and internal strategies have been evaluated under conditions designed to simulate typical high-level sporting events.

The body of research on combination precooling strategies involves multiple use of externally applied strategies (external and external; nine studies, involving ten interventions) or the application of an external strategy with beverage ingestion (external and internal; two studies). Together, these studies are summarized in Table VI. Furthermore, combination strategies can be further distinguished by the relative timing of their use, whereby one precooling technique may be used to maintain the cooling induced by the other (sequential use) or when multiple techniques are used at the same time (concurrent use).

5.1 External and External

Established strategies of combined external pre-cooling have involved the sequential use of cold water immersion followed by the application of ice garments including iced towels [96], cooling jackets [35, 58], cooling vests [78] and gel-based packs [36]. Although in some studies the application of the cooling garment has been to maintain the reduction in systemic [96] or local temperatures [36] induced by prior water immersion, the potential for an additional effect on thermoregulation cannot be discounted. Further, the practical advantages of wearing a cooling garment to maintain lower body temperatures until the commencement of exercise [35, 37, 78] and during simulated breaks in play [58, 78], offer greater ecological validity for athletes interested in optimizing the use of cooling agents for field or competition conditions.

Other techniques of combined external precooling have involved the concurrent application of two or more methods to increase the total cooling effect [20, 38, 55]. Although, no consistent strategy for combining precooling techniques exists, a common element underpinning the various techniques is to increase the surface area of cooling on the body. While this enhances the effectiveness of the cooling that can be achieved, the downside is a reduction in the practicality for field use. This depends, of course, on the sites chosen for precooling. For instance, the practical and logistical difficulties of using combined strategies involving the head and hands [20] are considerably less than whole-body methods [20, 38, 55] that involve the combination of three to four individual strategies.

With the exception of the work by Hornery et al. [58], all combination precooling strategies examined to date

have demonstrated a powerful cooling effect in terms of improved thermoregulatory (core, skin and/or body temperature), cardiovascular (heart rate, sweat rate) and psychological (thermal sensation of comfort, rating of perceived exertion) measures [20, 35–38, 55, 78, 96] (see Table VI). However, overall performance improvements were generally confined to protocols involving prolonged exercise [35, 36, 38], providing further evidence that pre-cooling has smaller effects on brief protocols involving maximal sprint [55] or intermittent sprint performance [78, 96]. Minett et al. [20] reported an attenuation in the decline in sprint time during the second half of a 70-min intermittent sprint running protocol following a combination external pre-cooling strategy. They used 20-min precooling and 5-min mid-exercise cooling using a number of techniques (iced towels around the head, immersion of the hand in 9°C water, a cooling vest and frozen gel packs applied to the thighs). Furthermore, whole-body and combined head and hand precooling strategies from this study enhanced the total running distance covered during the protocol due to an increased distance achieved during hard running and jogging sections of the protocol [20]. In contrast, Ross et al. [37] showed a very large cooling effect using the combined effects of 10-min water immersion in 10°C water followed by the wearing of a cooling jacket. However, the authors suggested this method may have promoted a poorer pacing strategy when cyclists subsequently undertook an ergometer protocol simulating the hilly ~46 km course of the Beijing Olympic Games road cycling time trial; although a performance benefit was seen on the first segment of the course, this pace could not be sustained during the second phase of the trial, with large reductions in performance compared with the control condition. As such, the effect on overall performance in this study was unclear. Finally, a combination cooling strategy employed by Quod et al. [35] that involved 30 min of water immersion (gradual reduction from 28.8–24°C) followed by 40 min of wearing a cooling jacket, achieved lower rectal, skin and mean body temperatures to allow a greater negative heat storage than use of the jacket alone. Of practical significance, cyclists rode 26 s faster during a time trial after receiving the combined cooling compared with the jacket only, although this improvement in performance did not reach statistical significance ($p = 0.06$). In summary, the effectiveness of combined pre-cooling techniques on the performance of subsequent exercise may be determined by the type of exercise that is undertaken.

5.2 External and Internal

The current literature includes investigations of external and internal precooling techniques that have been employed sequentially [39] as well as concurrently [37].

These studies are also summarized in Table VI. Although the focus of combined external and internal precooling interventions is the optimization of thermoregulation, beverage ingestion strategies may offer the additional ergogenic and sensory effects associated with ingesting ice and/or carbohydrate. The combination of external and internal strategies has been shown to achieve large reductions in core temperature to improve thermal sensation prior to the commencement of exercise, resulting in improvements in performance [37, 39] and mental concentration [39]. Of note, detectable improvements in performance are sustained for a long period and persist even after the cooling effect has disappeared. For example, the combination of slushie ingestion and the application of iced towels to both upper and lower body for 30 min prior to exercise produced an overall mean increase of 3% (8 W) in power output during the subsequent ~46-km time trial [37]. The improvement in pacing was most evident in the second half of the time trial (3.6% increase, 10 W) despite a lack of difference in core temperatures between trials over this period. Similarly, the combination of wearing a cooling vest for 60 min before plus 15 min during exercise and ingesting fluids (beverage temperature not detailed) during 90 min of an intermittent sprint protocol created a sustained benefit that allowed subjects to then run 1.2 km/h (10.6%) faster in a self-selected speed test and 28 s (40%) longer during a running capacity test compared with a control condition [39]. This finding of persistent benefits may have practical relevance for athletes who compete in events of 60–90 min duration (e.g. cycling criterium/time trial, running or race walking events less than 21 km) or for events of shorter duration where precooling could be performed earlier in their preparation schedule, (e.g. before arriving in the competition location) to prevent disruption to warm-up activities. In turn, this may ease the need for logistically demanding techniques that would be challenging to perform in the field.

It has been proposed that at least part of the increase in performance achieved via internally applied cooling strategies may be associated with activation of brain regions that are linked to motivation and reward, in response to the oral stimulation of temperature and/or carbohydrate [94, 97]. Although the temperature of the beverage ingested in the recent study conducted by Clarke et al. [39] was not reported, the improvements in exercise performance and mental concentration detected following the combination of wearing an ice vest and consuming a carbohydrate-electrolyte beverage was greater than wearing the same vest, but while consuming a placebo beverage. As such, the combination of external and internal cooling strategies offer the potential of greater ergogenic outcomes if benefits accrued from the two separate mechanisms related to enhanced thermoregulation and central drive are additive. Further research in this area is warranted.

6 Limitations of the Current Literature Review

Our goal was to review the available literature to investigate whether pre-cooling techniques are directly relevant to the performance of high-level sport. Therefore, the success of our review depends on the selection criteria for including studies in our critique and the degree to which the information from these studies can be integrated. Several weaknesses must be acknowledged in both the principle and the application of this style of summary.

Relevant studies were selected from the wider literature based on strict but self-selected criteria; these included details of subject characteristics, such as specific fitness (i.e. aerobic capacity) and experience (i.e. sport played, competition level, training volume). Our aim was only to review studies in which a subject population was representative of high-level competitors in various sports. An acknowledged limitation of the selection criteria used to include studies in this review is that the characteristics used to describe specific fitness, such as aerobic capacity, are more discriminating when applied to endurance athletes than to other athletes. For example, performance of single or repeated sprint tasks by participants of team sports are more likely to be related to anaerobic qualities, such as maximal effort power or speed; information on these characteristics of athletic calibre are not always available in subject populations. As such, a lack of important details about subject characteristics and athletic capabilities prevented appropriate discrimination across the range of sports studied in precooling research, and we may have included studies in our review that failed to meet our stated criteria.

Second, we acknowledge the difficulties associated in summarizing the results of studies using a narrative approach, in that we cannot provide a single and definitive conclusion regarding the true effect of various precooling interventions that would be typically generated from a meta-analysis. This review has not included a systematic assessment of the study quality rating and has provided a subjective assessment of the pooled outcomes of studies, which range in research design, precooling methodology, exercise protocol, environmental conditions and outcomes of exercise. While we have included a number of studies that have assessed exercise capacity (i.e. progressive maximal tests and time trials to exhaustion); nevertheless, the majority of precooling studies we reviewed have employed performance tests that are more ecologically valid (i.e. discrete tests set for time or distance). However, even then, the direct transfer of laboratory research findings to the field are compromised by issues including the lack of high calibre subjects, lack of realistic training and dietary preparation, exclusion of realistic warm-up protocols and failure to include factors that mimic true field conditions

(i.e. radiation from the sun, relative wind speeds). Currently, only one true field study exists, evaluating the benefits of various water immersion strategies on thermoregulation and running performance in a protocol simulating the characteristics of a competitive event [98]. Finally, due to the inability for scientists to blind precooling research by using a true placebo, a subject's expectations of a beneficial effect from using precooling techniques before a test of exercise performance in hot conditions cannot be eliminated. Despite the limitations of our review, we feel that our summary provides some observations that are valid and useful for sports scientists who work in the areas of athletic performance.

7 Practical Implications of the Current Literature on Precooling for Athletic Performance

Collectively, the literature supports the benefit of external and/or internal precooling methods using air, water and ice for reducing deep body and/or skin temperatures to increase heat storage capacity and improve exercise tolerance in temperate to hot conditions (range 18–40°C). Although the precise mechanisms responsible for the benefits remain unclear, the current studies illustrate that a variety of precooling methodologies offer theoretical benefits for the enhancement of sports performance, particularly involving prolonged submaximal activities. Less consistently, however, is the beneficial effect of established precooling strategies on activities of higher intensity and shorter duration (i.e. endurance exercise at higher percentages of $\dot{V}O_{2\max}$ and sprint-type exercise). The translation of the theoretical benefits into actual performance enhancement is likely to be dependent on matching a practical precooling strategy that provides a thermal or perceptual advantage to a sporting activity that is limited by fatigue associated with thermal challenges. More than one strategy may be suitable, but it will be important for the sport scientist to work with athletes to identify and refine the strategy of choice. This is likely to be specific to the individual and the event.

Some of the earliest research on precooling for sports performance involved a practical pre-cooling technique, an environment and performance test simulating a true competition scenario, and application to a specific competitive event involving elite athletes. In this study [32], high-level rowers tested the application of a simple technique (5-min application of ice packed in damp towels), after the completion of a warm-up and immediately prior to a 6-min maximal capacity rowing test. This precooling strategy was effective in reducing skin (4.3°C) and tympanic (0.7°C) temperature, which persisted throughout the exercise test, resulting in a 17 m increase in distance covered (1%;

equivalent to ~ 5 s in a 2000 m race). Although this research developed an effective precooling strategy, the authors acknowledged some logistical challenges, suggesting that “in the actual competitive arena, treatment of the skin with ice packed in towels might not always be practicable” [32] since access to large volumes of ice may not always be available or accessible by athletes where it is needed. Since then, sports scientists and commercial manufacturers have developed a large range of precooling strategies and associated products with a range of advantages and disadvantages (detailed in Table VIII) according to the scenario of their application. The scientific literature and marketing sales suggest that at least some of these are successful.

Effective strategies for precooling in athletic competition are likely to be more widely used if they are practical and cause minimal effort or disruption to the athlete's preparation. While some strategies may be practical at one event, they may, in turn, be too difficult to employ at another. Important considerations for using precooling strategies at the competition location include the logistics (e.g. necessary equipment, access to amenities, transport, requirements for athletes to change clothing, timing of application), the cost (e.g. purchase and maintenance of equipment, consumables), staffing/assistance (e.g. number of personnel required to implement the strategy effectively), the effectiveness (e.g. cooling power, a ‘washout’ effect associated with a high-intensity warm-up), practicality (e.g. gastrointestinal comfort, necessity to change clothing before competition) and prior use (e.g. athlete belief, familiarity with physiological perturbations and sensations, competition practice). External and internal cooling strategies, alone or in combination, are optimized by the powerful cooling properties of ice. More recently studied techniques involving the application of iced garments and/or the ingestion of cold/icy beverages now provide a new range of practical tactics for scientists to use in precooling athletes in the field.

With the emergence of more practical choices for precooling, particularly involving the use of cold water and ice, precooling is becoming more accessible for athletes to employ in the field. Immersion in water and the application of iced garments to the skin have been the most common strategies used to precool athletes. A range of techniques have been shown to achieve improvements in the performance of prolonged exercise and, in some cases, intermittent sprint performance. The most practical techniques typically involve 30-min whole-body immersion in tepid ($30\text{--}22^\circ\text{C}$) water, or part-body immersion of non-active body parts to cooler ($10\text{--}18^\circ\text{C}$) water temperatures. While commercially available vests can provide effective cooling from 15–65 min of application, they are inherently difficult to implement in a field setting due to refrigeration, transportation and logistical requirements. An alternative

external precooling strategy involves shorter application (5–20 min) of iced towels, prepared by rotating the placement of towels that have been dunked in an ice-slurry and wrung dry. This is a logistically simpler and cost-effective option for use in the field. Gel-based packs that are milder than ice have also been effective for localized cooling of the skin, and may provide sensory effects that are beneficial to performance if applied (i.e. draped around the neck) during exercise.

A recent focus for practical precooling has been the incorporation of the ingestion of cold beverages; this strategy provides the benefits associated with cooling while co-ingesting nutrients (i.e. fluid, carbohydrate and electrolytes) that provide ergogenic or nutritional benefits in their own right. Indeed the pre- or mid-exercise ingestion of a large (> 1 L) bolus of cold ($\leq 4^\circ\text{C}$) fluid has been associated with improved endurance performance. Substantial cooling power is added if this liquid is served in the form of a slushie. The ingestion of ice has been shown to not only increase exercise capacity, but may also allow the athlete to achieve a higher rectal temperature at the point of exhaustion. Furthermore, preliminary data indicate that a sensory effect of a stimulus in the mouth that is perceived as cold (i.e. menthol used as a mouth wash) can improve exercise performance, without changes in body temperature. Together, these data provide evidence to implicate the brain in temperature regulation during precooling and subsequent exercise performance. However, these data warrant further research before practical recommendations using these strategies can be made.

Finally, the combination of external and internal precooling strategies can be used to enhance cooling effects and can be applied sequentially (i.e. for one strategy to maintain the cooling achieved by the first strategy) or concurrently (i.e. both strategies are applied simultaneously). Examples of two external precooling strategies being applied sequentially include cool water immersion followed by wearing an iced garment. Alternatively, external plus internal cooling strategies that can be applied concurrently include the ingestion of a cold or ice beverage while wearing an iced garment. Together, these combination strategies provide a sustained cooling option that is associated with improved endurance performance well after deep-body temperatures have dissipated. Strategies where external and internal cooling are used concurrently may provide a better practical option for athletes in the field, by limiting the time before an event, which is dedicated to precooling.

8 Future Directions

Future research is needed to determine the transferability of performance improvements seen with the use of practical

precooling strategies in the laboratory environment to the field. Although current strategies are evolving from laboratory-based techniques into practical precooling options for field application, further refinement is required to optimize effectiveness and to simplify logistical requirements. Future studies should employ precooling strategies under the constraints of actual competition, by simulating event schedules, environmental conditions and practical limitations that are experienced in real-life situations. Furthermore, scientists are encouraged to employ closed-loop performance tests, if not, performances in an actual competition to investigate the magnitude of performance changes. The use of highly motivated, well trained subjects is important in ensuring that research outcomes can be translated into meaningful performance improvements in high-calibre athletic populations. We applaud the contribution of high-impact research publications to our understanding and development of precooling techniques. While it is important to isolate the mechanisms that underpin the outcomes of individual precooling strategies, however, a less reductionist approach that uses combined precooling strategies, focuses on performance outcomes rather than physiological monitoring and allows a real-life environment rather than controlled baseline conditions should also be considered to be an important part of the research endeavour.

9 Conclusion

It is generally accepted that lowering or attenuating a rise in core temperature by implementing a cooling strategy prior to exercise in the heat increases the body's ability to store exogenous and endogenous heat, and can lead to an improvement in exercise performance. Nevertheless, the precise mechanisms associated with the improvements in performance following precooling are not well understood. This article brings together the current available literature on practical precooling methods that have been used in studies employing well trained subjects. We found clear evidence that a range of whole- and part-body precooling strategies enhance the performance of prolonged exercise performed in the heat. Options include the application (external) and ingestion (internal) of cold modalities, including air, water and ice used either separately or in combination. Most laboratory studies have shown improvements in exercise performance following precooling and the emergence of strategies that are practically relevant to the field setting now allow scientists to individualize relevant strategies for teams and individuals at competition locations. Collectively, practical precooling strategies offer athletes who compete in hot environmental conditions, the possible benefits of improved safety,

reductions in perceived thermal stress and improvements in exercise performance.

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