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Practical precooling strategies and cycling time trial performance

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EDITH COWAN UNIVERSITY

School of Exercise and Health Sciences

Practical Precooling Strategies and Cycling Time Trial Performance

By

Megan L.R. Ross B.App.Sci (Hons)

This thesis is presented for the award of Doctor of Philosophy (Sports Science) from the School of Exercise and Health Sciences; Faculty of Computing, Health and Science; Edith Cowan University, Western Australia

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Co-supervisor: Dr. David T. Martin (Australian Institute of Sport)

Date of Submission: 6th November 2012

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

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USE OF THESIS

This thesis is dedicated to the loves of my life,
my husband Jeremy
and
our darling little boy, Archie

In loving memory of Harvey Francis Jones
16.3.1946 – 22.12.2009

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A great poet, patriot and martyr of Cuban Independence, *José Martí (1853-1895)* stated simply that in order to have lived a complete life, a person must ‘*plant a tree, have a son, write a book*’. I am extremely fortunate to have achieved these three things in order, during the completion of this thesis.

ABSTRACT

Whole-body precooling can improve endurance exercise performance, especially in the heat; however there are logistical considerations that restrict the use of various precooling strategies prior to actual competition. Precooling is proposed to collectively reduce deep skin and body temperature and in effect, increase the heat storage capacity of an athlete, thereby allowing a greater amount of work to be completed prior to attainment of a critical core temperature. While there is a sound theoretical basis for implementing precooling to improve cycling time trial performance in the heat, the practicalities of employing effective precooling strategies in the field warrant further investigation. The purpose of this thesis was to investigate the effectiveness of various practical precooling strategies for reducing core temperature and improving cycling time trial performance in hot (32-35ºC; 50-60% r.h.) and temperate (20-22 ºC; 50-60% r.h.) conditions.

The first three studies of this thesis involved the manipulation of body temperature via a range of precooling strategies that were applied under hot and humid environmental conditions. In study 1, eight precooling strategies involving external application or internal ingestion of cold water and ice were evaluated for their effectiveness in lowering deep body temperature, with due consideration regarding their application in a practical setting. The novel strategy identified in this study, which involved the combined application of iced towels and ingestion of an ice-slurry ("slushie") made

from sports drink, was then compared with an established cooling strategy (Study 2). Both the new and established precooling strategies achieved noticeable cooling effects (*moderate* and *very large*, respectively) but only the new strategy enhanced mean power output (3%, 8W) during a 46.4 km laboratory-based cycling protocol, with performance improvements detected in the second half of the time trial. This strategy was also found to be practical to implement. In study 3, practical precooling and hyperhydration were evaluated to assess whether their combination offered further benefits to endurance cycling time trial performance, when assessed over the same laboroatory protocol. The main findings indicated that practical precooling and hyperhydration, with and without the co-ingestion of glycerol, failed to achieve a *clear* enhancement of cycling performance. However, when practical precooling and hyperhydration without glycerol was compared to the control condition (i.e., hyperhydration alone), there was a 2% (30 s) improvement in cycling performance time, which was detected in the second half (climb 2) of the time trial. These improvements may be partially explained by a lower percieved exertion, which was observed during the initial 10 km of the time trial.

Study 4 was conducted to validate anecdotal reports and laboratory-based observations of thermoregulatory strain in elite cyclists during a real-life event performed in temperate environmental conditions. The rationale for this study was to determine whether the magnitude of hyperthermia achieved during real-life cycling performed in temperate conditions was high enough to possibly benefit from precooling. Although fluid losses during racing were mild (1.3%), cyclists experienced hyperthermia, at magnitudes typically associated with heat-stress induced fatigue (>67% of observations).

Therefore, in the final study of this thesis, the effects of practical precooling on 45.6 km cycling time trial performance was examined in both hot (32˚C) and temperate (21˚C) environmental conditions. The effectiveness of practical precooling was enhanced in temperate conditions, such that there was a greater magnitude of body cooling achieved. However, this strategy failed to provide a *clear* performance benefit in temperate conditions and instead, was likely to impair performance, particularly in the first (flat) section of the time trial course (-2.3%, 8 W).

Collectively, the studies contained within this thesis have contributed to the development of a practical precooling strategy involving the combined application of iced towels and ingestion of a slushie made from sports drink. These studies confirm the effectiveness of this novel strategy in reducing skin and core temperature and enhancing heat storage capacity prior to the commencement of exercise. However, the associated reduction in thermoregulatory strain translates into a performance enhancement in hot, but not temperate conditions. This thesis has provided detailed information regarding the range of factors that may be involved in altering the efficacy of a precooling manoeuvre and offers a highly practical insight into the application of precooling strategies aimed at improving field-based sports performance specific to time trial cycling.

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LIST OF PUBLICATIONS

Many chapters of this thesis have been previously published in, or submitted to international peer-reviewed journals. These publications are outlined below.

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Ross M.L.R., Abbiss C.R., Laursen, P.B., Martin D.T., Burke L.M. Precooling methods and their effects on athletic performance: a systematic review and practical applications. Sports Medicine. *Accepted June 26 2012.* [Impact factor 5.1]

Chapter Three

Ross M.L.R., Garvican, L.A., Jeacocke N.A., Laursen P.B., Abbiss C.R., Martin D.T., Burke L.M. (2011). Novel precooling strategy enhances time trial cycling in the heat. *Medicine & Science in Sports & Exercise.* 43(1). 123-33. [Impact factor 4.1].

Chapter Four

Ross M.L.R., Jeacocke N.A., Laursen, P.B., Martin D.T., Abbiss C.R., Burke L.M. Effects of combined hyperhydration, with and without glycerol ingestion, and practical precooling on cycling time trial performance in hot and humid conditions. *Journal of the International Society of Sports Nutrition. Submitted May 31 2012.* [Impact factor 2.7]

Chapter Five

Ross M.L.R., Stephens B., Abbiss C.R., Martin D.T., Laursen, P.B., Burke L.M. Fluid balance, carbohydrate ingestion and body temperature during men's stage-race cycling in temperate environmental conditions. *International Journal of Sports Physiology and Performance*. *Submission pending August, 2012.* [Impact factor 1.2]

Chapter Six

Ross M.L.R., Jeacocke N.A., Martin D.T., Laursen, P.B., Abbiss C.R., Burke L.M. Effect of ambient temperature with and without practical precooling on cycling time trial performance. *Manuscript in final preparation.*

Additional publications arising from Ph.D. research

Ross M.L.R., (2011). Active Voice: Precooling strategies and improvements in cycling performance in the heat. *Sports Medicine Bulletin.* March 22.

Abbiss C.R., **Ross M.L.R.**, Garvican L.A., Ross N., Pottgiesser T., Gregory J., Martin D.T. Influence of biological sex and age on cross-country mountain bike performance. *Journal of Sports Sciences. Accepted 21 January, 2012* [impact factor 1.9].

Dziedzic C.E, **Ross M.L.R.**, Knight, E., Slater, G.J., Burke, L.M. Variability of measurements of sweat sodium concentration using the regional absorbent-patch method. *Manuscript in final preparation.*

LIST OF AWARDS AND APPOINTMENTS

Recognition of the contribution of this work to Australian sport was acknowledged in the following ways:

AIS, Robert T. Withers Ph.D. Scholar Award, 2010 – *Awarded to a current Ph.D. scholar or very recent Ph.D. graduate (<1 year) who has conducted Exercise Physiology research that has had a substantial impact, or the potential to have a strong impact, on Australian Sport.*

Australian Olympic Team Selection, 2012 – Assistant Recovery Physiologist, Recovery Centre, Medical Head Quarters, London 2012.

CHAPTER 1 INTRODUCTION

1.1 Overview

This doctoral thesis contains five original studies, which will examine the physiological responses to various precooling methods in order to gain greater insight into the influence of thermoregulatory stress during exercise and to develop practical precooling strategies that may enable an improvement in cycling time trial performance. Specifically, the series of studies outlined in this thesis will devise an effective precooling strategy for elite cyclists to use prior to competition that is both practical and logistically simple to implement in the competition environment or field setting. The practical strategy to be studied throughout this thesis will be identified after extensive pilot work (Study 1), comparing a control condition (i.e., no cooling) with eight cooling techniques on their effectiveness in enhancing the heat storage capacity of cyclists prior to the commencement of a time trial performed in high ambient conditions. Studies 2 and 3 will be laboratory-based time trial simulations involving three trials performed in a randomised counterbalanced order in hot and humid environmental conditions. These studies will determine the most effective and practical strategy to reduce body temperature, measured at 12 cm rectal depth, before the start of exercise and enhance subsequent endurance performance. At this point of the thesis, it is of interest to verify whether laboratory-based observations and anecdotal reports of hyperthermia during exercise in temperate conditions exist in the field, by studying a sample population of internationally competitive cyclists during stage racing. Study 4 will present observational findings of thermoregulatory characteristics and nutritional practices during two multiple day road cycling stage races in cool conditions. The outcomes of this study may then provide further justification for the final investigation (Study 5) that will determine whether practical precooling is successful in enhancing cycling time trial performance in temperate, as well as hot conditions using a Latin square study design.

1.2 Background

It is well established that endurance cycling performance is impaired in conditions of high ambient temperature (1-6). During time trial cycling, a large amount of energy (~75%) is liberated as heat (7). As air temperature increases, the gradient for heat exchange between the skin and the environment is lowered and body temperature rises (8). There is evidence to suggest that attainment of a critically high body temperature is the main limiting factor inhibiting exercise intensity in these conditions (9), as evidenced by a reduced central nervous system drive to skeletal muscle (10). Thermoregulatory fatigue has been seen to occur at similar core temperatures (~40ºC), irrespective of starting core temperature or rate of heat storage (5, 11-13). For example, Nielsen and colleagues (12) demonstrated similar core temperatures (~39.7 ºC) at volitional exhaustion in trained cyclists exercising at 60% of maximal oxygen uptake ($\dot{V}O_{2max}$) in hot and dry (40ºC; 10% relative humidity (r.h.)) conditions, irrespective of previous exposure to heat (i.e., passive heating). In addition, rectal temperatures observed in professional cyclists at the end of a 30-min time trial performed in hot (32ºC) and temperate (23ºC) conditions with high humidity (60% r.h.) have been shown to be similar (39.1ºC), despite a significantly lower power output (6.5%, 22 W) in the hot time trial condition (2).

A number of strategies have emerged to combat the debilitating effects of hyperthermia-induced fatigue for cyclists racing in hot and/or humid conditions. Among these strategies, pre-event cooling has become a popular, legal and effective way to reduce core temperature immediately prior to such exercise (for reviews, see Quod et al. (14) and Marino (15)). The performance improvements associated with precooling have been hypothesised to occur as a result of an increased capacity to store heat, thereby increasing the amount of work that can be completed before reaching critical limiting temperatures (14-17). For example, Hessemer (18) used an intermittent cold air (0ºC) exposure for ~90 min to examine performance in a 60-min cycling time trial and found that performance was improved by 6.8% as a result of a 4.5ºC reduction in mean skin temperature. In this study, the authors also found that precooling aided in body water conservation, with a 20.3% reduction in sweat rate resulting from the delayed onset of sweating (18). Together, these data provide evidence that precooling can increase heat storage capacity and in turn, enhance performance through reduced thermoregulatory and cardiovascular strain.

Early precooling strategies employed by Australian Olympic athletes during the heat of the 1992 Barcelona Olympic Games used ice to cool the skin (D.T. Martin, Exercise Physiologist, Australian Olympic Cycling Team, unpublished observations). In a related study, Myler and colleagues (19) used a 5-min application of iced packed in damp towels to cool the skin by 4.3°C immediately prior to a 6-min maximal capacity rowing test. Decrements in skin temperature persisted throughout the test, resulting in an increased distance covered by 17 m (1%; equivalent to ~5 s in a 2000-m race). As a result of this research (19), a cooling vest (Neptune Wetsuits Australia, Smithfield West, Australia) was developed by the Australian Institute of Sport (AIS) for Australian Olympic Athletes competing in the hot and humid 1996 Atlanta Olympic Games (17). Subsequent investigations provided evidence to suggest that the ice-packed ‘Neptune’ (20) and subsequently, ‘Arctic Heat’ vests (21) were effective at attenuating the rise in thermoregulatory and cardiovascular strain, thereby, improving running performance in hot, humid conditions (~32ºC; 50% r.h.). However, the practical application of these vests in the field provided some challenges (14, 15).

The Sydney Olympic Games in 2000 were undertaken in temperate conditions and the sport science activities leading up to this competition placed a reduced focus on precooling research, despite the existence of data indicating the potential effectiveness of precooling in cool (18°C) conditions (18, 22, 23). Furthermore, core temperatures in excess of 39.5°C were observed in Australian cyclists during preparation and competition in the cool conditions presented at the Sydney Games (D.T. Martin, unpublished observations). In the lead-up to the Athens Olympic Games (2004), a new precooling strategy was developed which combined 30 min of whole-body immersion in water that was progressively cooled from ~29 to 24ºC, followed by the wearing of a waist-length phase-change material cooling jacket (RMIT University, Melbourne) with long sleeves and a hood (24). In comparison to a control trial, the combination precooling treatment reduced core temperature by 0.7ºC, which persisted throughout a warm-up and 25 min into a 40-min cycling performance test; this enhanced performance by ~42 s (-1.8%). However, logistical issues encountered at the Athens Olympics changed the implementation of the practiced strategies. Athletes were unexpectedly exposed to cool air-conditioned settings during transportation to the competition venue and prerace preparation, and these cold conditions hindered the athlete’s desire to engage in their intended precooling manoeuvres (D.T. Martin, unpublished observations).

While there is a sound theoretical basis for using the previously mentioned precooling strategies, their application during major field-based cycling events is difficult (14, 15, 25). For instance, cold-water immersion in a portable pool (i.e., http://icoolsport.com) requires sufficient water to fill the pool, enough ice to cool the water, or access to electricity for a portable mains power-driven chilling system. Furthermore, this method ideally requires athletes who are dressed in non-competition clothing to be submerged in cold water for a specific duration prior to warm-up, without always having access to appropriate shelter from the outdoor environmental conditions. Alternatively, ice-vests (and jackets) are heavy (~4.5 kg), cumbersome, can increase the energy cost of warm-ups (20), require frequent ‘re-charging’, cause the athlete to become wet, and require a large amount of freezer storage space or considerable stores of ice to maintain cooling capacity during transportation. Other cooling strategies such as cold-air exposure are extremely time consuming (~90 min required), uncomfortable for the athlete and require specific refrigeration facilities. Clearly, further development of precooling protocols that are practical to implement within the rules, logistics, and environment of the competition is required.

Another precooling method that could be effective and practical to implement is the consumption of cool water. Theoretically, the ingestion of 1 L of water at 7°C by a 70-kg subject should reduce core temperature by ~0.5°C if a negative heat load was equally distributed through the body and the specific heat of the body was assumed to be 0.85 (26). When tested, the actual maximal reduction in core temperature was observed to be slightly greater than this (0.61 ± 0.13°C) at 20 to 25 min following ingestion, and remained 0.31 ± 0.13°C lower than a control trial up to 55 min after drinking the cold water (26). Furthermore, Lee et al (27) showed that the consumption of 1 L of cold (10°C) fluid during exercise in mild conditions attenuated the rise in rectal temperature during steady-state cycling, when compared with ingestion of equal volumes of warm (37°C) and hot (50°C) fluids. However, a major limitation to using this method prior to high-intensity cycling competition is the large volume of fluid required for internal cooling, which may in turn compromise gastrointestinal comfort and increase diuresis. Internal precooling with ice (cryotherapy) has emerged as an alternative strategy due its powerful heat-transfer capacity. Based on the theory of enthalpy of fusion, ice requires substantially greater heat energy to cause a phase-change from water's solid to liquid states (at 0°C), compared with the energy required to change the temperature of liquid water (28). Indeed, Vanden Hoek et al. (29) showed that intravenous infusion of a 50 $ml \cdot kg^{-1}$ body mass (BM) bolus of ice-slurry (1:1 mix of ice and fluid) cooled swine at a greater rate ($-18.2 \pm 2.9°C \cdot h^{-1}$) than chilled (0°C) 1.5% NaCl saline ($-11.6 \pm 1.8°C \cdot h^{-1}$). This demonstrates the rapid cooling effect of an ice-slurry in vivo and indicates that this may be an effective and novel method of cooling athletes prior to competition.

The practice of consuming an ice-slurry prior to endurance exercise in the heat could benefit performance in a number of ways. Not only might the ingestion of an ice-slurry lower core temperature, but it could also assist in ensuring adequate fluid intake prior to exercise. When sweat rates are high and a fluid deficit exceeds ~2%, endurance performance may be affected (30-34). For instance, Gonzalez-Alonso et al. (35) demonstrated a greater reduction in stroke volume (20%) and cardiovascular function (13%) when endurance-trained athletes cycling for 30 min in hot, humid conditions (35ºC; 50% r.h.; low forward fan speed) were both hyperthermic and hypohydrated, compared to when hyperthermia (-8%) and dehydration (-7%) were independently assessed. An additional advantage to the consumption of an ice-slurry solution is that it could contain other ingredients that could assist with nutrition goals and fluid balance, such as carbohydrate, electrolytes and/or hyperhydrating ingredients. Indeed the co-ingestion of glycerol with a fluid load has been shown to elicit a "*large* and *substantial* hydration benefit" (34, 36), at least when consumed prior to prolonged endurance trials in laboratory-based conditions where hydration levels may be a factor (37). Glycerol ingestion works to enhance fluid retention through its direct effect on the kidney's medullary concentration gradient, and hence water re-absorption, resulting in an attenuation of free water clearance (38). Hitchins and colleagues (39) hyperhydrated cyclists prior to a 60-min time trial in hot, humid conditions (32ºC; 60% r.h.) using the oral ingestion of 1 $g \cdot kg^{-1}$ BM of glycerol in a 3.5% carbohydrate drink made up to 22 $ml \cdot kg^{-1}$ BM. The associated decrease in urine output achieved an additional 600 ml greater fluid retention than the carbohydrate drink alone and a 5% enhancement in endurance performance. This study indicates that the combined ingestion of ice-slurry (slushie) and glycerol may provide additional performance benefits during prolonged exercise in the heat.

The Summer Olympic Games in London in 2012 has called for a further refinement of precooling strategies. Although London is not anticipated to be a hot Olympic Games, there is unknown potential for the aforementioned novel precooling methods to achieve performance improvements in the potentially cooler climatic conditions likely to be experienced. Indeed, administration of precooling manoeuvres in the field indicates that athletes do not respond well when the precooling manoeuvre is carried out in cool conditions (M.J. Quod, Exercise Physiologist, Australia Cycling Team, unpublished observations). In cool resting conditions, cooling manoeuvres can increase both cardiovascular and metabolic demands as a result of neuromuscular-derived shivering-induced thermogenesis acting to counter reductions in core temperature (40-42). In anticipating the potentially cool temperatures that athletes may have to prepare and compete in at the London Olympics, there is a need to investigate the optimal environment in which to administer a precooling manoeuvre, and whether or not such a procedure can still augment performance in temperate conditions.

1.3 Significance of the Research

The research contained within this thesis will further our understanding of thermoregulatory fatigue and provide greater insight into the influence of various precooling strategies on thermoregulatory stress and exercise performance. Conducting this line of research is important for maintaining the health and safety of cyclists, while also having the potential to enhance exercise performance in competitions held throughout a range of environmental conditions. Results from this research will provide direct information on how best to prepare athletes for competition performed in hot and temperate environmental conditions. Not only will this research benefit the various disciplines of cycling, but the results may assist in understanding factors that influence performance in a variety of sports played in both hot and temperate conditions, including running, race walking, rowing, hockey and soccer. Furthermore, this research will assist in our understanding of hyperthermia-induced fatigue and thus, be translational beyond a sporting context (e.g., occupational physiology, military, etc.).

1.4 Purpose of the Research

The purpose of this Ph.D. thesis is to examine the physiological responses of various precooling methods in order to develop a practical precooling strategy that may enable an improvement in cycling time trial performance during exercise in hot and temperate conditions. In particular, this series of studies aims to formulate an effective precooling strategy for elite cyclists prior to competition that is both practical and logistically simple to implement in the field.

1.5 Research Questions

The research questions asked in this Ph.D. thesis have been separated into five separate studies, as listed below:

1.5.1 Study One (Chapter 3)

i. Can we identify a novel precooling strategy that is both practical to implement in the field, and effective at achieving reductions in core temperature prior to a cycling time trial performed in hot and humid environmental conditions?

1.5.2 Study Two (Chapter 3)

Novel precooling strategy enhances time trial cycling in the heat

i. Is the novel precooling strategy as effective as established precooling practices of elite Australian cyclists (i.e., the sequential use of cold water immersion and wearing a cooling jacket) in enhancing cycling time trial performance in hot and humid environmental conditions?

1.5.3 Study Three (Chapter 4)

Effects of combined hyperhydration, with and without glycerol ingestion, and practical precooling on cycling time trial performance in hot and humid conditions

i. Does the combination of precooling with a newly validated technique and hyperhydrating with glycerol provide a greater performance enhancement in hot and humid environmental conditions?

1.5.4 Study Four (Chapter 5)

Body temperature, fluid balance and carbohydrate ingestion during men's stage-race cycling in temperate environmental conditions

i. What are the typical fluid and charbohydrate intakes of highly competitive cyclists, and the thermoregulatory stress experienced during multiday stage races performed in temperate environmental conditions?

1.5.5 Study Five (Chapter 6)

Effects of ambient temperature on the thermoregulatory responses during a precooling manoeuvre and subsequent cycling time trial performance

ii. Does the established precooling manoeuvre benefit an athlete's performance in temperate compared with hot environmental conditions?

iii. How does the environmental temperature influence the effect of an established precooling manoeuvre on the associated thermoregulatory responses prior to a cycling time trial?

1.6 Research Hypotheses

The research hypotheses tested in the five studies that make up this Ph.D. thesis, are as follows:

1.6.1 Study One

i. From the strategies examined, a novel and practical precooling strategy that is effective at reducing core temperature in hot, humid environmental conditions will be identified.

1.6.2 Study Two

i. Both the established precooling manoeuvre (i.e., the combined used of cold water immersion followed by wearing a cooling jacket) and the new precooling technique identified in study one will reduce rectal temperature prior to the start of exercise and enhance subsequent prolonged endurance performance compared to the control condition (no cooling).

1.6.3 Study Three

i. The combination of glycerol hyperhydration with practical precooling will provide further performance enhancements in cyclists competing in a simulated time trial in hot and humid conditions.

1.6.4 Study Four

i. Elite cyclists will demonstrate how well normal race practices conform to existing recommendations of fluid and carbohydrate intake during stage-race cycling in temperate conditions.

ii. Laboratory-based observations and anecdotal reports of the occurrence of hyperthermia during exercise in temperate conditions will be confirmed or refuted by field by observations of core temperature measured while racing during two multiple day road cycling stage races.

1.6.5 Study Five

i. Cyclists will show improvements in cycling performance when a precooling manoeuvre is performed in both temperate and hot conditions. However, the physiological response to a precooling manoeuvre will be more favourable when the precooling procedure is performed in hot, compared with temperate conditions.

1.7 Limitations

A number of limitations in the methods employed in the current series of studies are acknowledged. Cycling performance in studies 2, 3 and 5 was assessed under controlled laboratory conditions. However, in order to enhance the application of these findings to the field, race conditions were simulated in the laboratory as closely as possible (i.e., wind exposure, terrain, event schedule). As blinding of the precooling treatments was not possible, the influence of a placebo effect on performance in the studies contained within this thesis cannot be determined. The fluid intake of subjects was controlled in studies 1 – 3 and 5, which may differ from the volume that athletes typically consume under *ad libitum* conditions on an actual race-day. However, it was important to control fluid intake and drink temperature for these studies in order to eliminate the impact that differences in hydration status can have on changes in body water, thermoregulation and in turn, cycling performance. In addition, Studies 2, 3 and 5 did not include a fixed cycling workload component, in order to observe if precooling treatments affected pacing strategy. Study 4 determined the changes in body temperature, fluid and carbohydrate status during actual competitive events. However, due to various external factors and the lack of an appropriate control condition, the influence of such factors on performance cannot be determined.

1.8 Delimitations

The logistics of implementing a precooling strategy on race days at major events is challenging, as significant restrictions are routinely placed on athletes at international level competition. Final preparations leading up to major championship events can be interrupted by a range of factors imposed on a cyclist in the hours before a race start. These can include extensive travel to an event, a regulated timeline of activities prior to the event, and a lack of facilities at the venue. Performance can be affected if cyclists are exposed to hot and humid conditions during these unpredictable preliminary periods. This thesis has attempted to implement worst-case real-world limitations in order to provide cyclists with performance enhancing strategies that are highly practical and logistically simple to implement in the field when pre-race conditions are adverse. However, the results of this research are only limited to the methods and conditions employed in these studies, and it is acknowledged that real-life major event preparation will vary according to the logistics imposed by each specific event. Only well-trained male cyclists were included in these studies due to the sex-related differences in thermoregulation between men and women (43). Therefore the results within this series of studies are only directly applicable to this group.

1.9 Definitions of Selected Terms

Δ:	Delta; Change
ANOVA:	Analysis of variance
AUD:	Australian dollar
BI:	Beverage ingestion
BM:	Body mass
BMX:	Bicycle motocross, cycling discipline
C:	Continuous, precooling exposure
CC:	Cooling collar (modified)
CHF:	Swiss franc
CO_2:	Carbon dioxide
CHO:	Carbohydrate
CI:	Confidence interval
CL:	Confidence limits
CON:	Control trial; no precooling treatment apart from the *Ad Libitum* consumption of water
CON_{Hot}:	Control trial performed in hot environmental conditions; no precooling treatment intervention; Study 5
CON_{Temp}:	Control trial performed in temperate environmental conditions; no precooling treatment intervention; Study 5
CONT:	Control trial; no precooling intervention; Study 1
CSU:	Charles Sturt University
CV:	Coefficient of variation
d:	effect size
ECS:	Evaporative cooling shirt
Ex:	Exercise task, numbered accordingly; figure 2.1 and 2.2
F:	Female
GBP:	British pound
GPS:	Global positioning system
H+H:	Head and hands, precooling exposure
HR:	Heart rate
I:	Intermittent, precooling exposure
IT:	Iced towel application
M:	Male

MAP:	Maximal aerobic power
MVC:	Maximal voluntary contraction
NaCl:	Sodium Chloride
NEW COOL:	New precooling practice, treatment intervention combining consumption of an ice slurry while applying iced towels
NZD:	New Zealand dollar
O_2:	Oxygen
OR:	Odds ratio, statistical parameter
P:	Probability
PC:	Precooling, treatment intervention combining 14 g·kg^{-1} BM ice slurry and application of iced towels over 30 min period; Study 3
PC_{Hot}:	Precooling treatment performed in hot environmental conditions, treatment intervention combining ice slurry ingestion and iced towel application over 30 min period; Study 5
PC_{Temp}:	Precooling treatment performed in temperate environmental conditions, treatment intervention combining ice slurry ingestion and iced towel application over 30 min period; Study 5
PC+G:	Precooling and glycerol hyperhydration, treatment intervention involving precooling (PC) following hyperhydration with 1.2 g·kg^{-1} BM glycerol in 25·kg^{-1} BM solution; Study 3
PhC:	Phase change, jacket
PVC:	Polyvinyl chloride
r:	Correlation co-efficient
r^2:	Co-efficient of determination
r.h.:	relative humidity
RHL:	Radiant heat load
RPE:	Rating of perceived exertion
rpm:	revolutions per minute
SD:	Standard deviation
SRM:	Schoberer Rad Meßtechnik: A portable power monitoring system for bicycles
STD COOL:	Standard precooling practice, treatment intervention combining whole body water immersion followed by wearig a cooling jacket; Study 2
t:	Time
TT:	Time trial
T_b:	Body temperature
TB:	Thermo blazer, precooling garment
T_c:	Core temperature

T_{calf}:	Temperature of the skin on the calf
T_{chest}:	Temperature of the skin on the chest
$T_{forearm}$:	Temperature of the skin on the forearm
$T_{GI\ peak}$:	Peak gastrointestinal temperature
T_{re}:	Rectal temperature
T_{sk}:	Skin temperature
T_{thigh}:	Temperature of the skin on the thigh
USD:	United States dollar
USG:	Urine specific gravity
$\dot{V}O_{2max}$:	Maximal oxygen consumption
$\dot{V}O_{2peak}$:	Peak oxygen consumption
W:	Watt, measure of power
WI:	Water immersion
WB:	Whole body, precooling exposure
WBGT:	Wet bulb globe temperature
XC:	Cross-country, cycling discipline

CHAPTER 2 REVIEW OF LITERATURE

PRECOOLING METHODS AND THEIR EFFECTS ON ATHLETIC PERFORMANCE: A SYSTEMATIC REVIEW AND PRACTICAL APPLICATIONS

This review of literature provides information relevant to the studies of this Ph.D. thesis. The main topic discussed pertains to describing the various precooling strategies that have previously been observed. This review also discusses possible factors influencing the combination of such strategies.

2.1 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. **Purpose:** 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. A narrative examination, which focused on the practical and event-specific application of precooling and its effect on physiological parameters and performance, was undertaken. **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 literature search was January 31 2012. **Study selection:** Relevant studies were included on the basis of conforming to strict criteria, including 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^{-1}·min^{-1} 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 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 summarised. **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 individualise 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.

2.2 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 (8). 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 (5, 9, 44), as evidenced by a reduced central nervous system drive to skeletal muscle (10) and other adverse effects including cardiovascular strain and metabolic disturbances (for review of proposed mechanisms, see (14, 15, 45, 46)). Indeed, the development of hyperthermia is associated with earlier voluntary termination during constant intensity exercise (5) or alterations in pacing during self-paced performance trials (2, 4).

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 (14-17). 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 (5). For instance, Gonzalez-Alonso and colleagues (5) demonstrated that voluntary exhaustion was reached at similarly high core (oesophageal; ~40.2˚C) and muscle (~40.8˚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 submaximal 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 (47-52), cooling garments (6, 19-21, 53-61), as well as ice-slurry beverages (47, 52, 62, 63) or combinations of these strategies (24, 53, 64-67) 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 (5, 6, 18-21, 23, 24, 47, 52-62, 64-76), 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 (19, 50, 51, 77-79), realistic pre-competition warm-up protocols (20, 21, 80, 81) and environmental conditions (i.e., temperature, radiant heat load and appropriate wind flow) (24, 61, 69, 82) as well as incorporating performance protocols that are relevant to athletic performance (65, 72, 83, 84). The differences between time to exhaustion protocols (which measure exercise capacity or endurance) and time trial protocols (which better reflect the demands of competitive sport) should always be appreciated (85). This may be of particular importance in precooling studies since changes in thermal comfort may alter the pacing strategies which underpin the outcome of time trial protocols with either beneficial or harmful results (65). Furthermore, logistical limitations experienced in the field, such as lack of equipment, facilities and time restraints, are often considered (19, 65). 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 review 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 characterised 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 (i.e., 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.

2.3 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’. The selected articles 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 literature search was January 31 2012.

2.3.1 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 $ml \cdot kg^{-1} \cdot min^{-1}$ 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 six or more subjects.

2.3.2 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 2.1-2.6 (Appendices A-F). 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 2.7 (Appendix G). Figures 2.1 and 2.2 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 review is a narrative 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 2.1-2.7), we have summarised the practical benefits and limitations of employing each strategy in the field and in relation to sports performance (Table 2.8 - Appendix H).

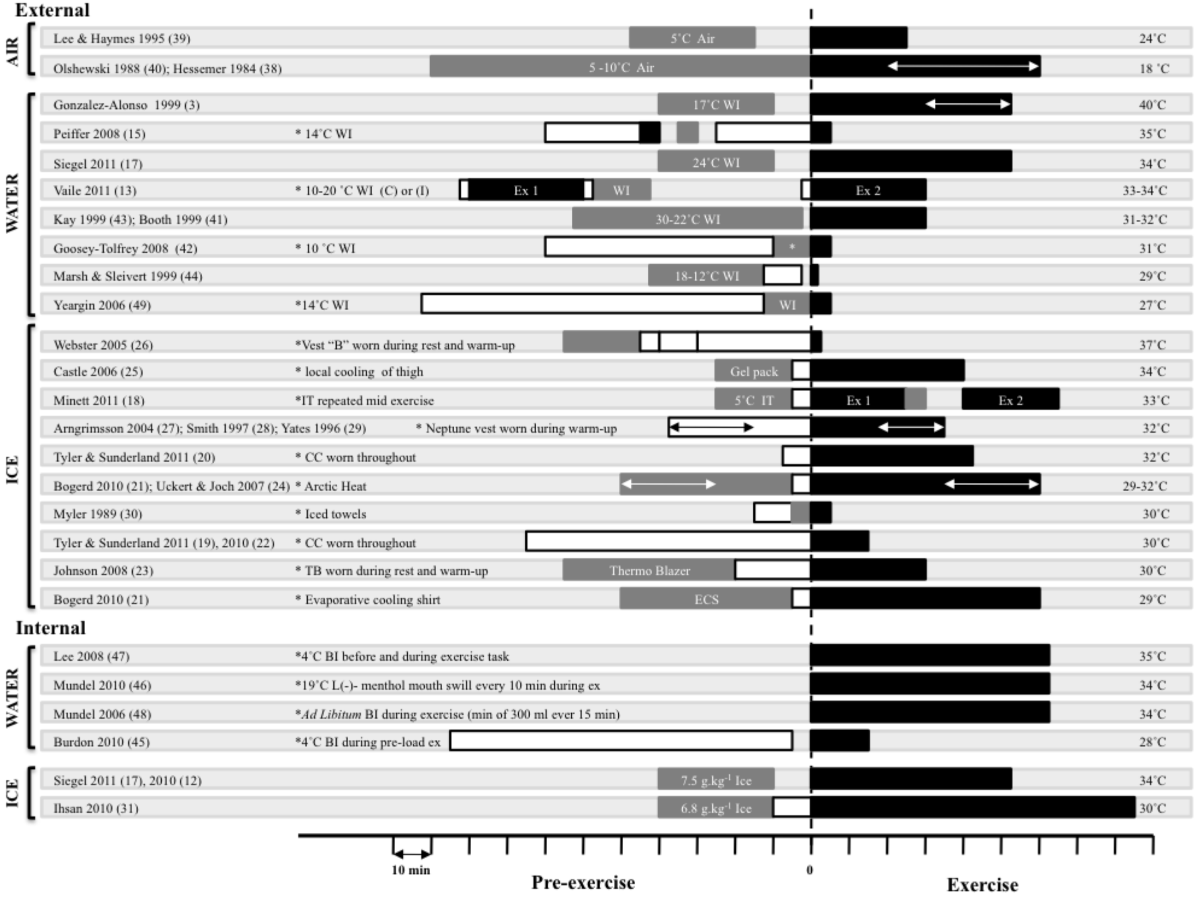

Figure 2.1. Successful individual precooling methods involving externally and internally applied strategies, where: BI = beverage ingestion, C = continuous exposure, CC = modified cooling collar; ECS = evaporative cooling shirt, Ex = exercise task (numbered accordingly), I = intermittent exposure, IT = iced-towel application, TB = Thermo Blazer, WI = water immersion, empty box (□) = sub-maximal exercise task or warm up, filled charcoal box (■) = precooling intervention, filled black box (■) = exercise performance task, filled gray box (□) = environmental conditions, Arrow (↔) = range of time (precooling application or exercise duration).

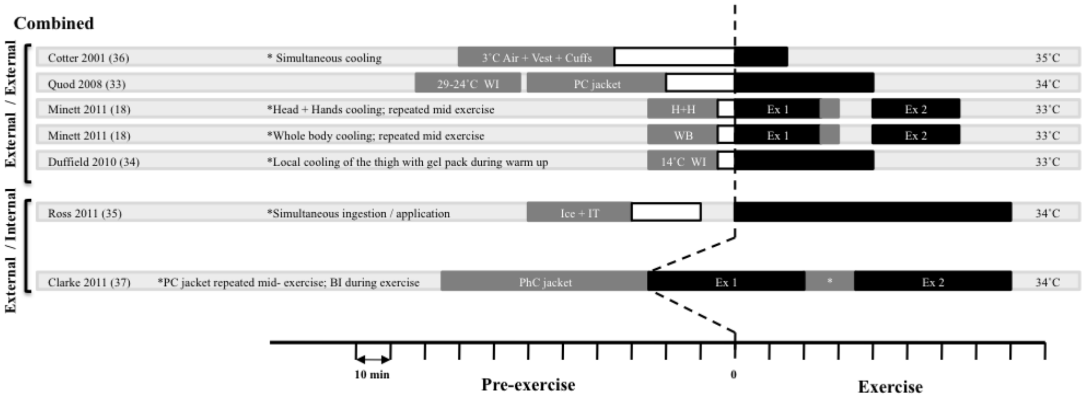

Figure 2.2. Successful combined precooling methods, where: BI = beverage ingestion, Ex = exercise task (numbered accordingly), H+H = head and hands, IT = iced-towel application, PhC = phase change, WB = whole body, WI = water immersion, empty box (□) = sub-maximal exercise task or warm up, filled charcoal box (■) = precooling intervention, filled black box (■) = exercise performance task, filled gray box (■) = environmental conditions.

2.4 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 (86, 87)).

2.4.1 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 (18, 22, 23, 68). A total of four studies fit the inclusion criteria and are summarised in Table 2.1. The history and methods of precooling using cold air exposure have been reviewed elsewhere (14, 15). 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 (86). As a result, warm blood is shunted back to the central circulatory system, where a sharp ~0.5°C increase in deep body temperature has been observed (18, 22, 23), 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, which 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 (18, 22, 23).

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 (23) and running (68) endurance as well as improved cycling performance (18) (see Table 2.1 for specific details). It should be noted, however, that the performance tasks undertaken in these studies were conducted in mild (18 - 24˚C) ambient temperatures. Even in the study which failed to find an overall benefit from cold air exposure, there was nevertheless a ~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 (22). 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 (88) 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 2.8). 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.

2.4.2 Water Exposure

The use of gradual cooling via whole-body immersion in water is commonly referred to as the ‘gold-standard’ cooling strategy (89) and, due to its superior cooling capability, is proposed as a preferable alternative to cold air exposure (89). The major advantage of water immersion is that heat loss to water (~4.2 kJ·kg^{-1}·˚C) is approximately four times greater than air at the same temperature (~1.0 kJ·kg^{-1}·˚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 summarised in Table 2.2. These include investigations of whole body immersion (12 studies) which can be further subdivided into i) precooling using prolonged durations (30 - 60 min) of tepid water (temperature range 22 - 30˚C) where water temperature is gradually reduced over the course of immersion, ii) precooling using short duration (20 - 30 min) cool water (17 - 18˚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 (3 studies), which includes precooling (30 min of 12 - 18˚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 (2 studies) and is also discussed herein.

2.4.2.1 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 (69). In this study, water temperature was gradually reduced from 29 to 22˚C, which minimised 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 deep 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 - 26˚C (71)) and shorter periods of exposure (i.e. 30 min at 25 - 23.5˚C (52)) 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 (52) and enhanced cycling performance (71). Due to time restraints, the use of shorter (30 min) water immersion protocols (52) may be more appealing for use in a practical setting than the more traditional protocols of ~60 min (69, 71).

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 (5) 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. (59) failed to achieve a substantial improvement in intermittent sprint cycling. In fact, investigators observed *lower* peak power output (~80 - 85 W) during the first two of twenty 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^{-1}). 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 (52, 69, 71). It is possible that the reductions in intramuscular temperature observed following cold-water immersion, interfered directly with metabolic (90) and force generating (91) mechanisms within the muscle fibre. While small and transient perturbations of intramuscular temperature seem to benefit capacity and performance of prolonged exercise (5), large and prolonged perturbations appear to impair sprint performance (59). Indeed, a milder cooling agent also investigated in this study (local cooling of the thighs via the application of silicate-gel packs), which 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 (59) (see Table 2.7 for a detailed comparison of results). In fact, as will be discussed below, this localised 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 (53).

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 (83) 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 (48, 50, 69, 77). 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% r.h.).

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 (92). However, this protocol was found to *reduce* the time athletes could sustain running at $\dot{V}O_{2\ max}$ by ~8% (30 s) (92), 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 (48-51, 77). 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 program (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 (49).

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 (49) or continuous (48-51) 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 (~38.5˚C) subjects, substantial reductions in core temperature (48, 50) or mean body temperature (49) have been observed, along with positive performance outcomes. Furthermore, it has been shown that repeated performance tasks where subjects remain normothermic (~37.2˚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 (51).

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. (93) 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 minimising 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 (94, 95). 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 (77). 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. (48) 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.

2.4.2.2 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 (18), 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 2.2) with variations including the immersion of non-active (i.e., torso; (72) and hands; (70)) and active body parts (i.e., legs; (96)). Additionally, water-perfused garments (97, 98) 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 localised 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 (70, 72). 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 (72) or the hands (70), but not when applied to the exercising muscle of the legs (96). Table 2.2 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 (98). 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 (97). 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 2.8).

2.4.3 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) (28). As a result, cooling with ice may be achieved with lower amounts of integument (99), at a faster rate (100) and to a greater magnitude (101), 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 summarised in Table 2.3. 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 2.8); for some, the logistically demanding preparation outweighs the limited benefits that may be achieved.

2.4.3.1 Iced Towels

Myler and colleagues (19) 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 (53). 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.

2.4.3.2 Ice Garments

Early research on precooling with iced towels (19) 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 (6, 20, 58, 61, 80, 102). However, the additional weight (~4.5 kg) and the increase in energy cost associated with weight-bearing activities, such as running (20, 60), 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 localised cooling of the skin (6, 20). 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 (20) and core (20, 58, 61) 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 (24), vests (21, 56) and evaporative shirts (56) 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 (21, 24) and body (56) temperature, as well as skin blood flow (56), 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 (61), cycling (6, 56, 58) and running (20, 60) performance (range 7.5 to 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 (79), ii) when environmental conditions are mild (58, 80, 103), 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 (67), iv) when cooling involves the sole use of a phase-change garment (24), v) when cooling involves the use of a alcohol- and menthol-based evaporative cooling solution (103), vi) prior to intermittent sprint cycling (59, 79) and running (67, 102) 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 (80). 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 (59) and non-active (54, 55, 57) 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 twenty 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 (54, 57), as well as running capacity (55) in hot environmental conditions (30-32˚C; 53% r.h.). 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 to when it was left on after losing its effectiveness (54), suggesting that there may be a limit to the extent of thermal deception.

2.5 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 (47, 52, 62, 63, 73). 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.

2.5.1 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 vaporisation (~2260 $\mathrm{kJ \cdot kg^{-1} \cdot {}^{\circ}C}$) is considerably greater than the specific heat of air (~1.0 $\mathrm{kJ \cdot kg^{-1} \cdot {}^{\circ}C}$), and collectively they contribute ~10% of the total body heat loss (104). Although cold air breathing has been reported in the literature (105-108), 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 nine-fold increase in respiratory heat exchange during submaximal cycling in hot humid conditions (38°C; 90-95% r.h.) (105). 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 (108). 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 (105, 107). However, the practical implementation of this strategy is not yet known.

2.5.2 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 (109) and fuel status (110). 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 summarised in Table 2.4. 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 (86, 87). As such, possible candidates have been identified, however contrary evidence exists (111, 112) and thus, the exact mechanism remains unclear.

Our discussion regarding this literature is intended to complement two literature reviews, which have summarised firstly the beneficial effects of beverage temperature on voluntary consumption of fluids around exercise (113) and secondly the mixed results of beverage temperature on exercise performance in the heat (114). Since this latter review (114), an additional study has been published (73), such that five studies (see Table 2.4) have investigated the effects of drink temperature on body temperature and its effect on subsequent endurance cycling performance in well trained subjects (27, 73, 75, 82, 115). 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 court-side during the intermittent rest breaks held during play.

As such, the general characteristics associated with many organised sports, which including 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 organised 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 (27), 60 min (115) and 90 min (73) 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 (73) induced a greater heat sink compared with the results of studies which used fluids of 10°C (27, 115), 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% r.h.). These findings are in agreement with the work of Lee et al. (75) who observed a reduction in thermoregulatory strain following the ingestion of a 4°C beverage before (3 x 300 ml ingested over 30 min) and every 10 min (100 ml) during sub-maximal exercise, compared to a 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^{-1}) upon the commencement of exercise, and a lower rise in skin temperature (Δ~0.96°C·h^{-1}) 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% r.h.). 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, Mündel et al. (82) demonstrated that a cold beverage (4°C) was more palatable and positively influenced fluid intake such that 23% (300 ml·h^{-1}) 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 (116) 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^{-1}) and heart rate (6 beats·min^{-1}·h^{-1}) that was associated with steady-state cycling in hot conditions, such that 6 out of 8 subjects cycled longer before exhaustion was reached, with a mean improvement of ~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 (116).

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. (117) 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 to 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^{-1} increase in ventilation and a 15%

reduction in cardiopulmonary rating of perceived effort (74). The authors attributed this improvement in performance to the stimulation of oropharangeal 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.

2.5.3 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 summarised in Table 2.5. Recently, the consumption of 6.8 - 7.5 $g \cdot kg^{-1}$ BM slushie, given in small boluses during seated rest in the 30 min prior to exercise, improved running capacity (47, 52) and cycling endurance performance (62). Indeed, Siegel et al. (47) showed that all ten subjects ran longer, with a mean improvement of 9.5 min (~23%) following slushie ingestion, when compared with a 4˚C beverage. Ice ingestion manifested in a moderate reduction in rectal (47, 52, 63), gastrointestinal (62) and skin temperatures (47), which allowed for a greater heat storage and level of thermal comfort during the respective exercise tasks. However, in a separate study, the authors (52) noted slightly different physiological responses to slushie ingestion despite similar applied methodologies to their previous study (47). 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) (47). 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 (52). 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. (73) 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 $g \cdot kg^{-1}$ slushie attenuated the reduction in repeated 2 min sustained maximal voluntary contraction torque development of the elbow flexors, compared to ingesting warm (40°C) fluid, following hyperthermia induced by running in hot conditions (34°C, 50% r.h.) (118). 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 (118) could also be observed during more dynamic, whole-body exercise performance.

2.6 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 acclimatised and untrained subjects when combining the effects of wearing an ice vest and drinking ~15°C water, compared to when either strategy was used in isolation. Ross et al., (65) showed greater effects of cooling using the combined strategy of ingesting a 14 $g \cdot kg^{-1}$ 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, which were applied singly. As such, the emergence of combination precooling strategies, which 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; 9 studies, involving 10 interventions) or the application of an external strategy with beverage ingestion (external and internal; 2 studies). Together, these studies are summarised in Table 2.6. 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).

2.6.1 External and External

Established strategies of combined external precooling have involved the sequential use of cold water immersion followed by the application of ice garments including iced towels (119), cooling jackets (24, 84), cooling vests (102) and gel-based packs (64). Although in some studies the application of the cooling garment has been to maintain the reduction in systemic (119) or local temperatures (64) 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 (24, 65, 102) and during simulated breaks in play (84, 102), offer greater ecological validity for athletes interested in optimising 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 (53, 66, 81). 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 (53) are considerably less than whole-body methods (53, 66, 81) that involve the combination of 3 - 4 individual strategies.

With the exception of the work by Hornery et al. (84), 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 (24, 53, 64-66, 81, 102, 119) (see table 2.6a). However, overall performance improvements were generally confined to protocols involving prolonged exercise (24, 64, 66), providing further evidence that precooling has smaller effects on brief protocols involving maximal sprint (81) or intermittent sprint performance (102, 119). Minett et al. (53) 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 precooling 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 (53). In contrast, Ross et al. (65) 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 to 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. (24), which involved 30-min water immersion in water (gradual reduction from 28.8 – 24.0°C) followed by 40 min 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 to the jacket only, although this improvement in performance did not reach statistical significance (P = 0.06). In summary, the effectiveness of combined precooling techniques on the performance of subsequent exercise may be determined by the type of exercise that is undertaken.

2.6.2 External and Internal

The current literature includes investigations of external and internal precooling techniques that have been employed sequentially (67) as well as concurrently (65). These studies are summarised in Table 2.6b. Although the focus of combined external and internal precooling interventions is the optimisation 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 (65, 67) and mental concentration (67). 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% (8W) in power output during the subsequent ~46 km time trial (65). 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 which allowed subjects to then run 1.2 $km \cdot h^{-1}$ (10.6%) faster in a self-selected speed test and 28 s (40%) longer during a running capacity test compared to a control condition (67). 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 (117, 120). Although the temperature of the beverage ingested in the recent study conducted by Clarke et al. (67) 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.

2.7 Limitations of the Current Literature Review

The goal of this review was to examine the available literature to investigate whether precooling 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.

Secondly, we acknowledge the difficulties associated in summarising 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 and 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 (77). 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.

2.8 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 to 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 $\dot{V}O_{2max}$ 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 precooling technique, an environment and performance test simulating a true competition scenario, and application to a specific competitive event involving elite athletes. In this study (19), 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 sec 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”, 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 2.8) 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 optimised 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 - 22˚C) water, or part-body immersion of non-active body parts to cooler (10 - 18˚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 have also been effective for localised cooling of the skin that is milder than ice, 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 (≤4°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 perceived as cold (i.e., methol 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 combinations 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.

2.9 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 optimise 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-caliber 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.

2.10 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 individualise 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.

CHAPTER 3 NOVEL PRECOOLING STRATEGY ENHANCES TIME TRIAL CYCLING IN THE HEAT

3.1 Abstract

Purpose: To develop and investigate the efficacy of a new precooling strategy combining external and internal techniques on the performance of a cycling time trial in a hot and humid environment. **Methods:** Eleven well-trained male cyclists undertook three trials of a laboratory-based cycling time trial simulating the course characteristics of the Beijing Olympic Games event in a controlled hot and humid environment (32-35˚C; 50-60% r.h.). The trials, separated by 3 - 7 d, were undertaken in a randomised crossover design, and consisted of the following: 1) CON – no treatment apart from the *ad libitum* consumption of cold water (4ºC); 2) STD COOL – whole-body immersion in cold (10ºC) water for 10 min followed by wearing a cooling jacket, or 3) NEW COOL – combination of consumption of 14 g ice slurry (‘slushie’) per kilogram body mass made from a commercial sports drink while applying iced towels. **Results**: There was an observable effect on rectal temperature (T_{re}) before the commencement of the time trial after both precooling techniques (STD COOL < NEW COOL< CON, $P < 0.05$), but pacing of the time trial resulted in similar T_{re}, heart rate and rate of perceived exertion throughout the cycling protocol in all trials. NEW COOL was associated with a 3.0% increase in power (~8 W) and 1.3% improvement in performance time (~1:06 min) compared with the CON trial, with the true likely effects ranging from a *trivial* to *large* benefit. The effect of the STD COOL compared with the CON trial was *unclear*.

Conclusions: This new precooling strategy represents a practical and effective technique that could be used by athletes in preparation for endurance events undertaken in hot and humid conditions.

3.2 Introduction

Preparations for the 2008 Beijing Olympic Games were dominated by concerns of coaches and athletes as to how to achieve optimal performance of sustained high-intensity exercise in hot and humid weather (21, 59). Thorough reviews of the literature show that techniques that reduce core temperature immediately before a prolonged endurance exercise carried out under high thermal stress can enhance exercise capacity and performance (14, 15). Effective techniques involving external cooling include immersion in cold water (69, 71), direct application of cold materials to the skin (19, 24), including the use of commercially available ice jackets (78, 79, 121), or combinations of these strategies (24).

Recently, the ingestion of large volumes of cold water has been investigated as a precooling strategy (27). This was based on calculations that ingestion of 1 L of water at 7°C by a 70-kg subject would reduce core temperature by ~0.5°C if negative heat load was equally distributed through the body and the specific heat of the body was assumed to be 0.85 (26). When tested, the actual reduction in core temperature was observed to be 0.61 ± 0.13°C at its maximum point, 20 - 25 min after ingestion, and remained 0.31 ± 0.13°C lower than a control trial 55 min after drinking the cold water (26). Furthermore, Lee and Shirreffs (27) reported that the consumption of 1 L of cold (10°C) fluid during exercise in mild conditions attenuated the rise in rectal temperature (T_{re}) during steady-state cycling compared with ingestion of equal volumes of warm (37°C) and hot (50°C) fluids. Of course, the ingestion of large volumes of fluid before or during exercise is impractical in many sports, particularly those involving high intensity exercise, because of the high risk of causing gastrointestinal upset or discomfort. A variation of this strategy, involving the ingestion of ice slurries, offers the potential for equal dissipation of heat from a smaller volume of ‘beverage’. On the basis of the theory of enthalpy of fusion, ice requires substantially larger heat energy to cause a phase change from a solid to a liquid state (at 0ºC) compared with the energy required to increase the temperature of liquid water (28).

Although there is a sound theoretical basis for using precooling strategies, “in the field” application during sporting competition requires identification of an ideal protocol for each unique event. Such a protocol not only needs to achieve the best outcomes for the event, which may include other physiological/nutritional benefits in addition to cooling, but also be practical to implement within the rules, logistics, and environment of the competition. The individual cycling time trial for men on the Beijing Olympic Games program involved two laps of a ~23 km course with prolonged hill climbing. A temperature pill was ingested by an Australian professional cyclist before the Good Luck Beijing time trial test event in August 2007. The test event was held over one lap of the Olympic course, and the core temperature revealed a rise in T_{re} up to 39°C over the hill climb, which persisted throughout the descent (L.A. Garvican, exercise physiologist, Australian Road Cycling Team, unpublished observations). These data support the concept that cyclists participating in this event could benefit from precooling strategies that would increase their capacity for heat storage over two laps of the course.

Established precooling practices of elite Australian cyclists (hereafter known as standard cooling practices or STD COOL) are based on the combined use of a cooling jacket with cold water immersion (24). However, the location and logistics of the Beijing Olympic Games event were likely to prevent these techniques from being used. Therefore, the aim of our work was to identify whether a new precooling strategy, incorporating an internal cooling technique, would be both practical and effective in enhancing cycling performance in the heat, when used to achieve a reduction in T_{re} prior to a cycling race (Study One). In particular, we wanted to test the effectiveness of a new strategy against the standard precooling technique in enhancing the performance of a cycling protocol simulating the Beijing individual time trial event. Our hypothesis was that, in comparison with a no-intervention trial, precooling techniques would reduce T_{re} before the start of exercise and enhance subsequent prolonged endurance performance (Study Two). As well as addressing the immediate needs of Australian cyclists who competed in the Beijing Olympic Games, the results of this study can provide a model for approaching thermoregulatory challenges in other sports or competitions.

3.3 Methods

Before commencement of the pilot (Study One) and main study (Study Two), ethical clearance was obtained from the appropriate human research ethics committee. All subjects were informed of the nature and risks of each study before providing written informed consent.

3.3.1 Pilot Testing to Identify Useful Precooling Strategies (Study One)

The cooling strategies used in this study were selected after an extensive pilot work, examining a variety of popular and novel approaches to precooling. Pilot work involved four subjects dressed only in cycling knicks and who completed eight different cooling strategies as well as a control condition (no cooling; (CONT)) in a counterbalanced experimental design. Trials were performed in a standardised hot environment (32-35°C and 50-60% relative humidity (r.h) as measured by a Kestrel 4000 Pocket Weather Tracker (Nielsen Kellerman, Boothwyn, PA)) and were conducted during a 90-min period that included 30 min of seated rest, 30 min of exposure to the experimental cooling strategy, and finally, a 30-min structured warm-up exercise on a cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands). This warm-up protocol was similar to that used by elite cyclists before the individual time trial and standardised for each individual (described below).

The pilot precooling strategies tested were as follows: 1) cooling jacket (24) - participants wore a waist-length cooling jacket with long sleeves and a hood, constructed with a polyester blend outer shell containing phase change material (RMIT University, Melbourne, Australia) directly applied to the skin for 30 min; 2) Arctic Heat vest (21) - participants wore a rechargeable, waist-length cooling vest constructed with a sportwool^{TM} outer shell containing a viscose gel (Arctic Heat Products, Burleigh Heads, Australia) directly applied to the skin, recharged every ~5 min, for 30 min; 3) iced towels (19) - participants wore bathroom towels dunked in icy water and wrung to extract liquid (three towels were constantly rotated to cover the skin of the torso and legs for 30 min; 4) large volume of cold fluid (27, 75) - participants ingested 1 L of cold (4ºC) sports drink (Gatorade, Pepsico Australia, NSW, Australia) in two boluses (at t = 30 and 45 min) and were given 15 min to consume each bolus; 5) small ‘slushie’ - participants ingested 500 g of an ice slurry made from sports drink (Gatorade, Pepsico Australia, Chatswood, Australia) using a commercial machine (Essential Slush Company, Burleigh Heads, Australia) and were given 30 min to consume the bolus with the aid of a straw and spoon to maximise the ingestion of ice; 6) large slushie - participants ingested 1 kg of a sports drink slushie in two boluses (at t = 30 and 45 min) and were given 15 min to consume each bolus; 7) plunge (69, 71) - participants were required to complete whole-body immersion in cold (10ºC) water to the level of the mesosternale in a 1.6-m-long × 0.6-m wide × 0.8-m high inflatable pool (Portacovery^{TM}, Canberra, Australia) for 10 min followed by 20 min of seated rest (temperature was maintained by the addition of ice and water); and 8) the combination of a large slushie and iced towels.

Figure 3.1 summarises T_{re} changes over the observation protocol relative to T_{re} at t = 30 min (end of the stabilisation phase), with Figure 3.1a summarising the trials involving internal and combination precooling techniques and Figure 3.1b showing results for trials involving external techniques. Changes in T_{re} (ΔT_{re}) at the end of the precooling phase (t = 60 min) were used to reflect the effectiveness of the various cooling treatments. We were also interested to note the ΔT_{re} at the end of the warm-up phase (t = 90 min), which represented the potential differential for heat storage at the commencement of a subsequent performance effort. On the basis of the observations on cooling achieved by various precooling methods, which are presented in the literature (14, 15), we categorised ΔT_{re} as either *small* (<0.3°C), *moderate* (0.3 to 0.6°C), *large* (0.6 to 0.8°C), or *very large* (>0.8°C). These results are summarised in Table 3.1 and demonstrate that the most successful cooling strategies were the plunge and the intake of a large slushie with and without the simultaneous application of iced towels.

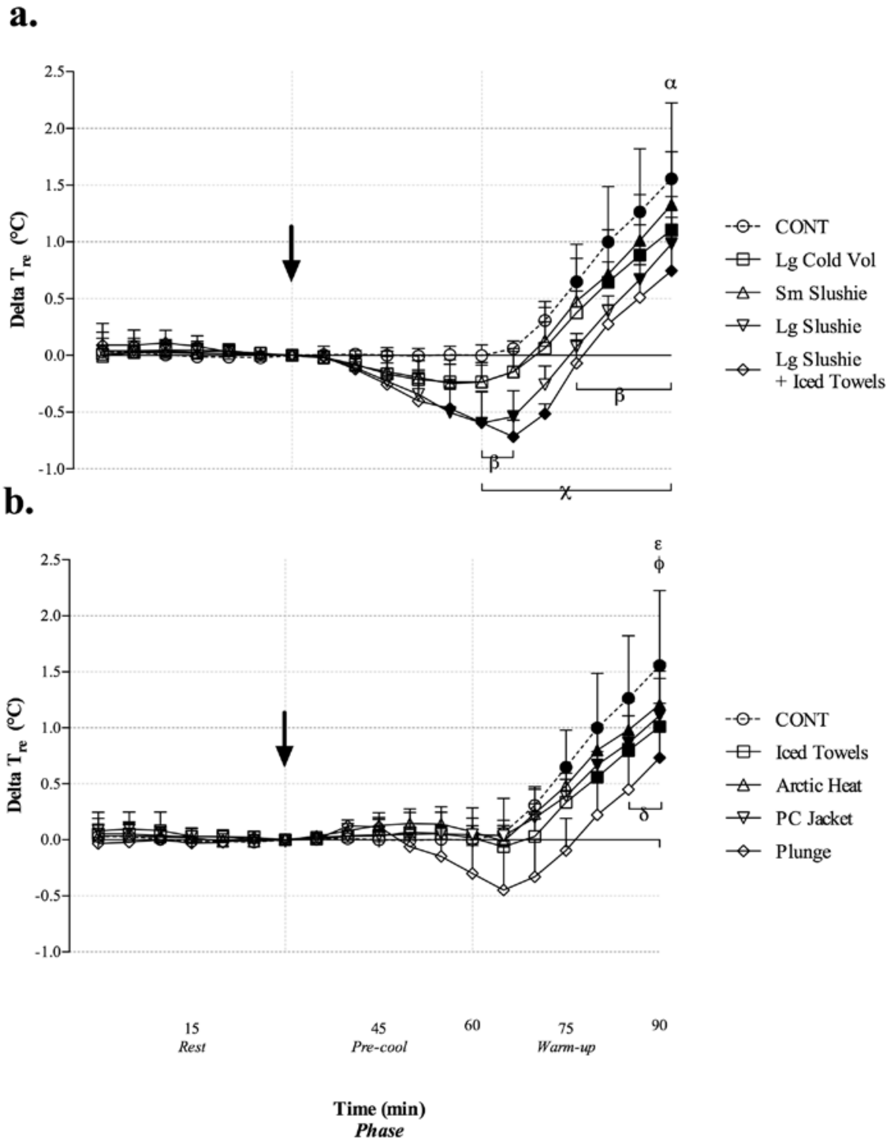

Figure 3.1 Pilot study’s relative change in rectal temperature. Internal and combination precooling (a) and external precooling (b) during 30 min of heat stabilisation phase, 30 min of precooling, and 30 min of warm-up. Significant time effects from t=30 min are denoted by dark symbols. Significant treatment effects between large cold volume are denoted by alpha (α), large slushie are denoted by beta (β), large slushie + iced towels are denoted by chi (χ), iced towels are denoted by delta (δ), Arctic Heat are denoted by epsilon (ε), and RMIT/AIS Jacket are denoted by phi (φ) when compared with CONT. Commencement of the precooling phase indicated with an *arrow* (↓). Statistical significance is set at the level of $P<0.05$. Data represented by mean ± SD.

Table 3.1 Relative change in rectal temperature in response to precooling and following a warm-up.

Effect	**Magnitude (°C)**	**Protocol**	**Effect of Cooling (ΔT_{re} t = 30 - 60 min)**	**Cooling + Warm-up (ΔT_{re} t = 60 - 90 min)**
Small	<0.3	Cooling Jacket	0.04 ± 0.05	1.11* ± 0.47
		No intervention (CONT)	-0.01 ± 0.07	1.56* ± 0.67
		Arctic Heat	-0.01 ± 0.38	1.21* ± 0.30
		Iced towels	-0.06 ± 0.16	1.01* ± 0.43
		Large Cold Volume	-0.24 ± 0.15	1.11* ± 0.29
		Small Slushie	-0.25 ± 0.17	1.33* ± 0.47
Moderate	0.3 - 0.6	Plunge	-0.45 ± 0.40	0.73* ± 0.49
		Large Slushie	-0.60* ± 0.28	0.98* ± 0.23
Large	0.6 - 0.8	Large Slushie + Iced Towels	-0.72* ± 0.15	0.75* ± 0.31

*Significant difference in ΔT_{re} (time effect), $P < 0.05$. Data are presented as mean ± SD.

The results of this pilot study identified iced towels and ingestion of a large slushie as a novel, practical and effective approach to precooling. The aim of the main study was then to investigate the effects of this new precooling strategy in comparison with the standard technique on thermoregulation and performance of an endurance cycling task in the heat.

3.3.2 Main Study (Study Two)

3.3.2.1 Study Overview

In a randomised crossover design, participants performed three experimental trials consisting of no intervention (CON), a standard cooling practice combining a cold water plunge followed by wearing a cooling jacket (STD COOL) and a new strategy combining the application of iced towels while ingesting a large slushie (NEW COOL). These experimental methods have been previously described (above) and were applied for a total for 30 min while dressed only in cycling knicks. All subjects were familiarised with the cycling protocol, and trials were separated by 3 - 7 d with a consistent recovery time between trials for each subject. The outcome variables were T_{re}, heart rate (HR), thermal comfort (122), gastrointestinal comfort (five-point Likert scale), perception of effort (123), cycling performance (time and power output), and blood lactate concentration.

3.3.2.2 Subjects

A total of 12 well-trained male A-grade cyclists aged 18-35 years were recruited from the local cycling community. All cyclists had no previous history of heat intolerance and were without injury or illness. One subject withdrew from the study following the acclimation phase and thus was removed from the analysis.

Characteristics of the subjects were as follows (mean ± SD): age = 33.0 ± 5.1 y; body mass (BM) = 72.1 ± 5.5 kg; maximum aerobic power (MAP) = 449 ± 26 W; peak oxygen uptake ($\dot{V}O_{2peak}$) = 71.6 ± 6.1 $ml \cdot kg^{-1} \cdot min^{-1}$.

3.3.2.3 Preparation for Trials

Before commencing the experimental phase, subjects visited the laboratory on at least nine occasions to heat acclimate and familiarise with the ergometer (Velotron, Racermate Inc., Seattle, WA, USA) and the experimental exercise protocol (simulated Beijing Olympic time trial course based on road altitude (Polar 725S HR monitor with altimeter (barometric pressure) and distance (speed pick-up) data collected at the Good Luck Beijing time trial test event (L.A. Garvican, unpublished observations)). Heat acclimation was completed during a 3-wk period and consisted of nine cycling sessions of at least 60 min in duration at a self-selected intensity. All acclimation sessions were conducted in a heat chamber set at the experimental climatic conditions (32 - 35°C, 50 - 60% r.h.). All subjects completed at least one familiarisation trial of the experimental cycling protocol in the heat chamber. Before the first experimental trial, subjects also performed a progressive maximal exercise test on a cycle ergometer (Lode Excalibur Sport) to determine peak oxygen consumption ($\dot{V}O_{2peak}$) and MAP output. After a 5-min warm-up at 150 W, the test protocol started at 175 W and increased 25 W every 60 s until volitional exhaustion. MAP was determined as the power output reached in the last completed stage. If the subject finished partway through a 60-s stage, MAP was calculated in a pro rata manner. Subjects' expired air was collected into a customised Douglas bag gas analysis system, which incorporated an automated piston that allowed the volume of air displaced to be quantified, with O_2 and CO_2 analysers (AEI Technologies, Pittsburgh, PA). The operation and calibration details of this equipment have been described previously (124).

Subjects followed a standardised diet and training protocol for up to 24 h before each experimental trial. Specifically, they were allowed to undertake a light exercise bout on the day prior to each trial (repeated for subsequent trials). In addition, they were required to consume a standardised diet, supplied in the form of prepackaged meals and snacks, providing 9 $g{\cdot}kg^{-1}$ BM carbohydrate (CHO); 1.5 $g{\cdot}kg^{-1}$ BM protein; 1.5 $g{\cdot}kg^{-1}$ BM fat, with a total energy goal of 230 $kJ{\cdot}kg^{-1}$ BM. Subjects refrained from any intake of caffeine and alcohol during this period. Compliance to the diet and exercise protocol was determined from a checklist kept by each subject and presented on arrival to the laboratory before each trial.

3.3.2.4 Experimental Trials

All testing was carried out in the afternoon to mimic the schedule of the Beijing cycling time trial. Approximately 2.5 h before a trial (-150 min before start of time trial), subjects reported to the laboratory, having just eaten their prerace meal from the packaged diet (providing 2 $g{\cdot}kg^{-1}$ BM CHO). Subjects brought with them a ‘first-waking’ urine sample to determine specific gravity, which was used to ensure cyclists attended the laboratory in a similar euhydrated state for each trial. At this time, their food and training diaries were checked for compliance to the standardisation protocols.

Subjects then voided their bladder, inserted a single-use thermal probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical Inc., St Louis, MO, USA) 12 cm beyond the anal sphincter, and fitted a chest strap for a Polar S810i HR monitor (Polar Electro OY, Kempele, Finland). Rating of thermal comfort, BM, T_{re} and HR were recorded before entering the heat chamber (-120 min before start of time trial). Cyclists were able to drink chilled (4˚C) water *ad libitum* through the period of stabilisation to heat (-120 to -60 min before the time trial) and throughout the warm-up period (-30 to 0 min before the time trial), with the volume chosen on their first trial being recorded and repeated in subsequent trials. Subjects were also allowed to void their bladder when required during the 2-h period before the time trial, with body mass being recorded before and after each toilet break. During this stabilisation to the hot environment, subjects were required to check the configuration of bike ergometer at a set time; otherwise subjects remained seated throughout this period.

The environmental conditions (temperature and r.h.) inside the chamber were measured every 10 min throughout the duration of the trial. During the heat stabilisation period (-120 to -60 min before the time trial), the subject’s HR, T_{re} and thermal comfort were recorded every 5 min. At the commencement of the precooling phase (-60 min before the time trial) subjects were exposed to one of the three experimental treatments lasting 30 min, which were as follows: 1) CON – no treatment apart from the *ad libitum* consumption of cold water (4ºC); 2) STD COOL – a combination protocol involving whole-body immersion in cold (10ºC) water to the level of the mesosternale for 10 min followed by wearing a cooling jacket for 20 min; or 3) NEW COOL – a combination protocol where subjects consumed a total of 14 $g{\cdot}kg^{-1}$ BM sports drink slushie given in two 7-$g{\cdot}kg^{-1}$ BM boluses and were given 15 min to consume each bolus while wearing iced towels as previously described.

During this time and in addition to the measurements previously outlined, subjects were asked to provide ratings of the effectiveness of cooling and stomach fullness.

Subjects then completed a standardised 20-min warm-up on the Velotron ergometer fitted with an SRM cycling power meter (Scientific Version, eight-strain gauge, Schoberer Rad Meβtechnik; Jülich, Germany) sampling power output (W) at 1-s intervals, which was calibrated before the commencement of the first time trial using a custom-built calibration rig previously described (125). This warm-up consisted of repetition of a protocol of 3 min at 25% MAP, 5 min at 60% MAP, 2 min at 80% MAP, and based on the actual protocols used by elite Australian time trial cyclists in similar conditions. The final 10 min before the start of the time trial allowed subjects to complete their own preparations, including toilet breaks and bicycle adjustments. During this time subjects were provided with standard race instructions for each time trial protocol, and the zero offset of the SRM crank was set according to manufacturer’s instructions. Drinks for subsequent intake during the time trial were removed from ice storage and left in the heat chamber to simulate drink temperatures that would be experienced in a race situation with high ambient temperatures.

Subjects completed the cycling time trial according to instructions, with HR and T_{re} being monitored continuously and manually recorded every 2 min, whereas self-reports of thermal sensation and stomach comfort were recorded at approximately 10-min intervals. A capillary blood sample was collected via a finger-pick to measure blood lactate concentration (Lactate Pro, Arkray KDK Corp., Kyoto, Japan) at the time trial start, ‘top of the climb’ (12.5 and 35.7 km), at half way, and at time trial completion (23.2 and 46.4 km).

The ergometer was placed in front of a large television screen that displayed the course profile on the accompanying computer software (Velotron 3D Software, RacerMate Inc., Seattle, WA, USA). The feedback provided to the subject was limited to distance covered (km), cycling gear ratio (12 – 27 / 48 - 54), road gradient (%), and instantaneous velocity (km·h^{-1}). There were two visual displays of the course: a topographical profile of the 46.4-km course, featuring an arrow to indicate the current course position of the cyclists, and a display of a road from the perspective of a rider. Subjects were provided with 350 ml of a 6% CHO-electrolyte drink (Gatorade, Pepsico Australia) at the 'top of each climb' (12.5 and 37.5 km), which simulated the ideal time to consume fluid on the Beijing time trial course, on the basis of the experience of professional cyclists during the Beijing test event. They were permitted to drink *ad libitum* for the next kilometer on the first trial. The volume that was consumed was measured and repeated for subsequent trials.

As a further strategy to mimic riding on a hilly course, the cyclist was positioned in front of a large industrial fan (750 mm, 240 V, 50 Hz, 380 W; model N11736; Trade Quip, Auckland, New Zealand). The speed of the fan was altered to simulate uphill or downhill wind speeds: specifically the fan was fixed on low speed (1130 ± 5 rpm) for 0 - 12.5 and 23.2 - 35.7 km and switched to high speed (1850 ± 5 rpm) for 12.5 - 23.2 and 35.7 - 46.4 km.

Split times, velocity and power output data were collected for each trial, with the periods of interest being time to top of first climb (12.5 km), end of first lap (23.2 km), time to top of second climb (35.7 km) and finish (46.4 km). On the completion of each time trial, subjects were asked a series of questions related to their effort ("How much of yourself did you give?") using a modified Borg scale where effort ≤100% is reported, motivation ("How motivated were you to race today?"), sensation ("How did you feel during the time trial?") and comfort ("How comfortable did you feel during the time trial?") presented as five-point Likert scales. This series of questions is a monitoring tool used routinely within the Australian road cycling team.

3.3.3 Statistical Analysis

Dependant variables including body mass, percent dehydration and postrace subjective ratings were analysed for significant effects using a one-way analysis of variance (ANOVA). A two-way (treatment × time) repeated-measures ANOVA was used to determine significant differences in dependant variables (T_{re}, HR, blood lactate, thermal comfort and stomach fullness) between treatment means at each time point. Pairwise comparisons were conducted to determine where the differences existed, using a Newman-Keuls *post hoc* test. These statistical tests were conducted using Statistica for Microsoft Windows (version 8; Statsoft, Tulsa, OK, USA), and the data are presented as means and SD. For analysis, significance was accepted at $P < 0.05$.

The performance data from the three trials were analysed using the magnitude-based inference approach recommended for studies in sports medicine and exercise science (126, 127). A mixed modeling procedure in the Statistical Analysis System (Version 9.1; SAS Institute, Cary NC) was used to estimate means (fixed effects) and within-subject and between-subject variations (random effects, modeled as variances). The fixed effects were 1) treatment (CON, STD COOL and NEW COOL) to adjust for a main effect, and 2) trial number (nos. 1-3) to adjust for learning and habituation. The random effects were 1) identity (subject 1-11) to control for the different abilities of the subjects and 2) extra variance on the first trial to allow for differences in familiarisation between subjects. We also investigated the extra variance of the NEW COOL treatment to account for the individual differences to this treatment; however the variance estimated was -0.5 (negative), and hence, this random effect was eliminated from the model. Performance data are represented by time trial time and power output during the various segments of the course and are reported as means ± SD. The magnitude of the change in time was interpreted by using values of 0.3, 0.9, 1.6, 2.5 and 4.0 of the within-athlete variation (coefficient of variation, CV) as thresholds for *small*, *moderate*, *large*, *very large*, and, *extremely large* differences in the change score between the trials (128). The typical variation (CV) for road cycling time trials in top athletes has been previously established as 1.3% by Paton and Hopkins (129), with the smallest worthwhile change in performance time established at 0.4% (130). Finally, these data are presented with inference about the true value of a precooling treatment effect on simulated cycling time trial performance. The practical interpretation of an effect is deemed *unclear* when the magnitude of change is substantial when the confidence interval (precision of estimation) could result in a positive and negative outcome (3, 17). Data for the incomplete trial were calculated by comparing the performance decrement of the athlete’s performance (time and power data) from trial 1 with the athlete’s best performance (trial 3).

3.4 Results

Monitoring of the subject’s compliance to pretrial standardisation requirements showed that all subjects consumed the standard diet as requested before each of their trials and refrained from strenuous training in the 24 h before the commencement of the time trial. Collection of ‘first-waking’ urine samples on the morning of each trial showed that subjects commenced each trial with similar within-subject and between-subject hydration status (data not shown). The mean changes in body mass from entrance to the heat chamber to the completion of the time trial were -2.43 ± 0.73 for CON, -2.30 ± 0.63 for STD COOL, and -1.67 ± 0.51 kg for NEW COOL, representing a mean loss of 3.3, 3.1, and 2.3% BM, respectively (CON, STD COOL > NEW COOL, $P < 0.05$). The volume of sports drink consumed during the time trial was 630 ± 70 g for all treatments, which provided a CHO intake of ~38 g (~0.5 $g{\cdot}kg^{-1}$ BM).

Monitoring of the heat chamber showed that all trials were carried out in similar conditions (mean conditions across the ~3.5 h of heat exposure in each trial were 34.1 ± 0.3ºC and 52.8 ± 3.5% r.h. for CON, 33.8 ± 0.5º C and 53.4 ± 4.1% r.h. for STD COOL, and 33.9 ± 0.5º C and 53.4 ± 3.6% r.h. for NEW COOL (all $P > 0.05$). Ten cyclists completed the three trials according to our protocol. One subject was instructed to cease cycling in one trial at the 38.8 km point of the 46.4 km course due to ethical obligations (T_{re} exceed 41ºC and his self-reported thermal sensation was 7 = *very hot*). This situation occurred during his first trial (STD COOL). This subject was able to complete the two other trials without incident.

The T_{re} at the end of stabilization phase (t = -120 min before the time trial) was considered to be the baseline value for each trial. Figure 3.2 shows the relative changes in T_{re} during each trial. There was an observable treatment effect on T_{re} during the period before the time trial, with T_{re} being lower at the completion of the cooling phase and throughout the warm-up after both precooling techniques (STD COOL < NEW COOL< CON, $P < 0.05$). The warm-up was associated with a rise in T_{re} in all trials so that it had moved above baseline values by the start of the time trial. T_{re} continued to rise during the time trial in all trials, such that there were no differences in T_{re} between treatments during this phase ($P > 0.05$).

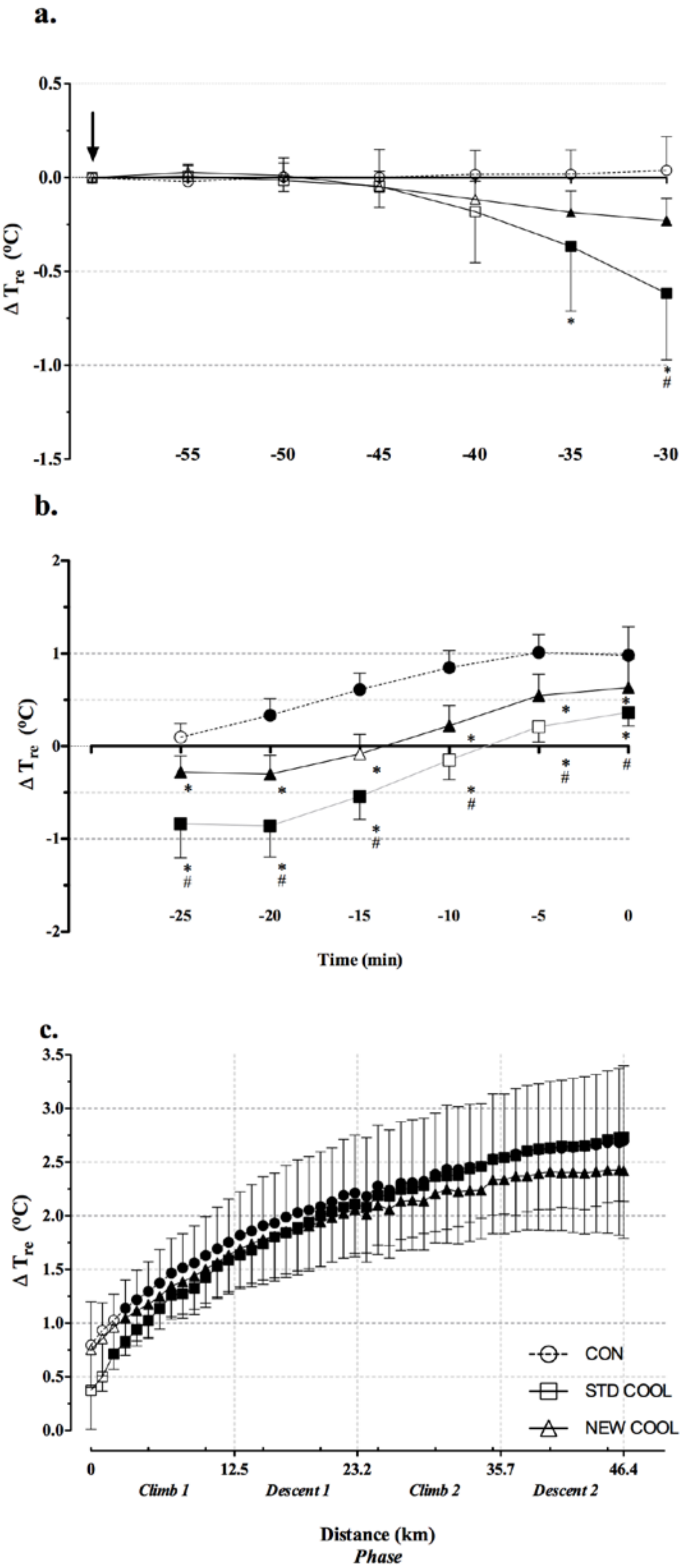

Figure 3.2 Relative change in rectal temperature during precooling (a), a warm-up (b), and, a 46.4 km simulated time trial (c). Significant time effects from t = -120 min before the time trial are denoted by *dark symbols*. Significant treatment effects between STD COOL and NEW COOL when compared with CON are denoted by an *asterisk* (*). Significant interaction effects between STD COOL and NEW COOL are denoted by a *hash* (#). Commencement of the precooling phase indicated with an *arrow* (↓). Statistical significance is set at the level of $P < 0.05$. Data represented by mean ± SD.

Figure 3.3 shows the changes in HR as a percentage of maximal HR (% HR_{max}) during each trial. Figure 3.3a shows no change in relative HR during the cooling phase. However, with the onset of the warm-up (Figure 3.3b), there was a concomitant increase in relative HR with an observable treatment effect: NEW COOL, STD COOL < CON at -25, -20, -10 min before the time trial ($P < 0.05$). There was a significant difference in HR between trials at -5 min before the time trial; however, HR was not significantly different at the time trial start. HR rose quickly above baseline values at the start of the time trial and continued to rise throughout. There were no differences in relative HR profiles between trials.

Performance information from each of the time trials is presented in Table 4.2 and includes time (h:min:sec) and power output (W) for the entire time trial, for each of the laps, and for each of the four segments (climbs 1 and 2, and descents 1 and 2). The error of measurement across all trials in the current study was established as 1.7%. Overall, NEW COOL was associated with a 3.0% increase in power output (~8 W; $P = 0.04$) and a 1.3% improvement in performance time (~1:06 min; $P = 0.08$) compared with the CON trial, with the true likely effects ranging from a *trivial* to *large* benefit. The effect of the STD COOL trial compared with that of the CON trial was *unclear* for power output (1.1 ± 2.4%, $P = 0.43$) and performance time (-0.5 ± 1.2%, $P = 0.53$).

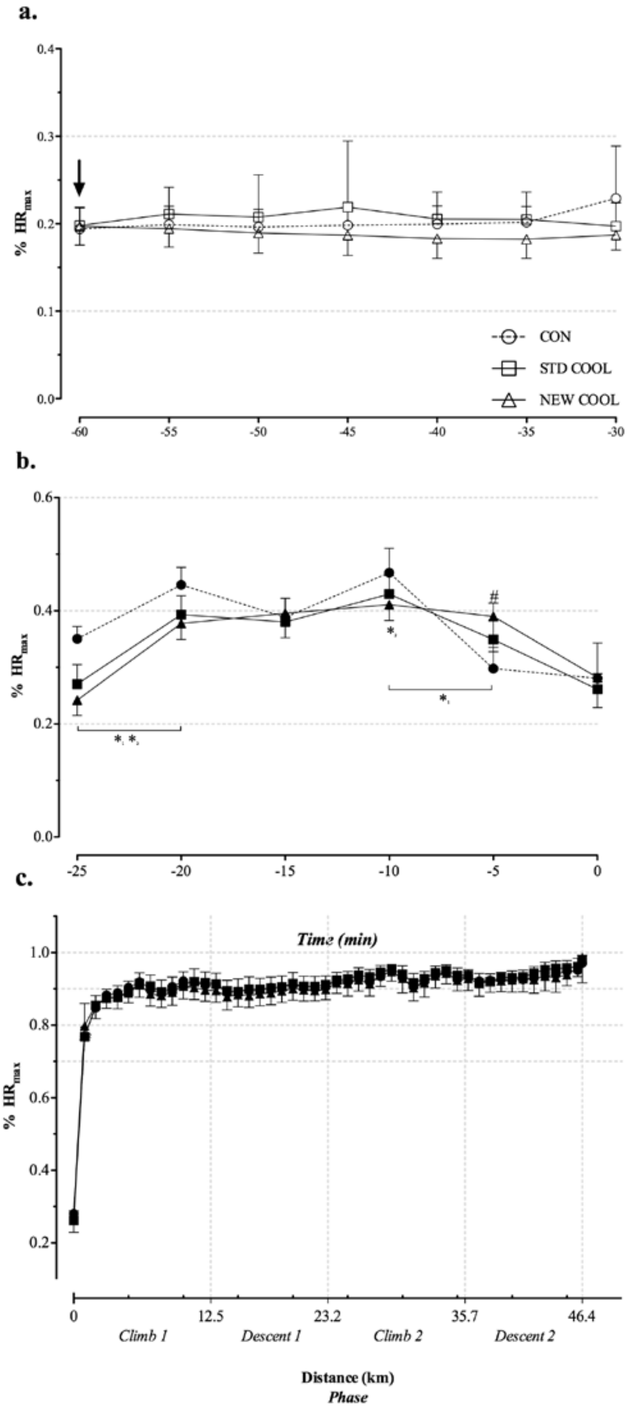

Figure 3.3 Percentage of maximal heart rate during precooling (a), a warm-up (b), and, a 46.4-km simulated time trial (c). Significant time effects from t= -120 min before the time trial are denoted by *dark symbols*. Significant treatment effects between STD COOL and NEW COOL are denoted by an *asterisk* ($*_1$ and $*_2$, respectively). Significant interaction effects between STD COOL and NEW COOL are denoted by a *hash* (#). Commencement of precooling phase is indicated with an *arrow* (↓). Statistical significance is set at the level of $P < 0.05$. Data are presented as mean ± SD.

Table 3.2 Summary of cycling time trial performance data (performance time and power putput).

Course Profile		Treatment	Performance Time			Power Output			Effect magnitude / Practical outcome
Phase	**Distance** (km)	**Intervention**	**mean ± SD** (h:min:sec)	**mean; ±90% CL** (%)	**P**	**mean ± SD** (W)	**mean; ±90% CL** (%)	**P**	Effect of intervention compared with CON
Total	0 - 46.4	CON	1:20:12 ± 3:19	-	-	276 ± 27	-	-	-
		STD COOL	1:19:42 ± 2:22	-0.5; ±1.2	0.53	279 ± 22	1.1; ±2.4	0.43	Unclear
		NEW COOL	1:19:06 ± 2:50	-1.3; ±1.2	0.08	284 ± 24	3.0; ±2.4	0.04	Trivial to large benefit (faster/ greater power)
Lap 1	0 – 23.2	CON	39:35 ± 1:34	-	-	280 ± 26	-	-	-
		STD COOL	39:15 ± 1:09	-0.6; ±1.1	0.34	285 ± 21	1.5; ±2.2	0.25	Unclear
		NEW COOL	39:13 ± 1:21	-0.9; ±1.1	0.19	285 ± 24	1.7; ±2.2	0.19	Trivial to moderate benefit
Lap 2	23.2 – 46.4	CON	40:38 ± 2:01	-	-	272 ± 29	-	-	-
		STD COOL	40:27 ± 1:29	-0.3; ±1.6	0.74	274 ± 27	0.7; ±3.2	0.72	Unclear
		NEW COOL	39:54 ± 1:38	-1.8; ±1.6	0.07	282 ± 27	3.6; ±3.2	0.06	Trivial to large benefit
Climb 1	0 – 12.5	CON	26:14.3 ± 1:12.3	-	-	292 ± 24	-	-	-
		STD COOL	25:52.2 ± 56.6	-1.2; ±1.2	0.11	298 ± 21	1.8; ±1.9	0.10	Trivial to large benefit
		NEW COOL	25:56.5 ± 1:00.3	-1.0; ±1.2	0.16	297 ± 22	1.6; ±1.9	0.15	Trivial to large benefit
Climb 2	23.2 – 35.7	CON	27:43.9 ± 2:09.3	-	-	275 ± 30	-	-	-
		STD COOL	27:11.2 ± 1:03.9	-1.7; ±2.4	0.26	278 ± 25	1.0; ±3.2	0.60	Unclear
		NEW COOL	26:49.8 ± 1:14.5	-3.2; ±2.4	0.04	284 ± 26	3.2; ±3.2	0.09	Small to extremely large benefit
Descent 1	12.5 – 23.2	CON	13:00.9 ± 44.2	-	-	257 ± 32	-	-	-
		STD COOL	13:23.4 ± 27.1	2.8; ±2.6	0.07	259 ± 24	0.5; ±3.8	0.80	Trivial to extremely large harm (slower / less power)
		NEW COOL	13:17.0 ± 30.3	2.2; ±2.6	0.16	263 ± 29	2.1; ±3.8	0.34	Unclear
Descent 2	37.5 – 46.4	CON	13:14.4 ± 31.9	-	-	264 ± 31	-	-	-
		STD COOL	13:16.1 ± 28.6	0.3; ±0.7	0.47	263 ± 33	-0.6; ±3.6	0.79	Unclear
		NEW COOL	13:03.9 ± 28.5	-1.3; ±0.7	0.01	277 ± 30	4.4; ±3.6	0.05	Small to moderate benefit

Outcomes were assessed by using the following criteria: *trivial* <0.4%, *small* 0.4 – 1.1%, *moderate* 1.2-2.0%, *large* 2.1-3.2%, *very large* 3.3 – 5.1%, and *extremely large* >5.2% change in performance time. CL = Confidence Limits; P = Probability.

There was an interaction between the two experimental treatments on Descent 2, with NEW COOL achieving a *small* to *very large* benefit in power output (4.9%; likely range = 1.3 to 8.5%; ~14 W; P = 0.03) and a *small* to *large* benefit in performance time (-1.6%; likely range = -0.9 to -2.3%; ~12.2 s; P = 0.009) than STD COOL. There was no evidence of any extra variance (an individual response) on the NEW COOL treatment under the conditions of this study.

Blood lactate results were similar across all experimental conditions. There was a trend for lactate concentrations to mirror the course profile, being slightly higher at the top of each climb and lower at the end of climb 1. There was an effect of time, whereby blood lactate concentration was greater than baseline values (3.2 ± 1.3, 3.1 ± 1.4, and 3.4 ± 1.4 $mmol \cdot L^{-1}$ for CON, STD COOL, and NEW COOL; P > 0.05) at the top of climb 1 following STD COOL (5.1 ± 1.8, P < 0.05) and at the completion of the time trial (5.4 ± 1.5, 5.5 ± 1.6, and 6.7 ± 1.4 for CON, STD COOL, and NEW COOL, respectively, P < 0.05).

Figure 3.4 shows changes in the subjects' thermal comfort (Figure 3.4a) and stomach fullness (3.4b) during each trial. There was no significant change in the rating of thermal comfort after athletes entered the chamber to stabilise to the hot and humid conditions for 60 min. However, once precooling commenced at t = -60 min before the time trial, the rating of thermal comfort was significantly reduced (from a rating of ~4.6 to 0), such that subjects reported feeling cooler when treated with STD COOL (-55 to – 27 min before the time trial, P < 0.05) and NEW COOL (-60 to -30 min before the time trial, P < 0.05) treatments compared with CON. The warm-up caused an increase in ratings of thermal comfort so that, in all treatments, subjects rated their thermal comfort as being warmer than baseline levels ($P < 0.05$). Once the time trial had commenced, thermal comfort deteriorated such that subjects progressively felt warmer, and there were no differences detected between trials. There was no significant change in the ratings of perceived stomach fullness across the three trials.

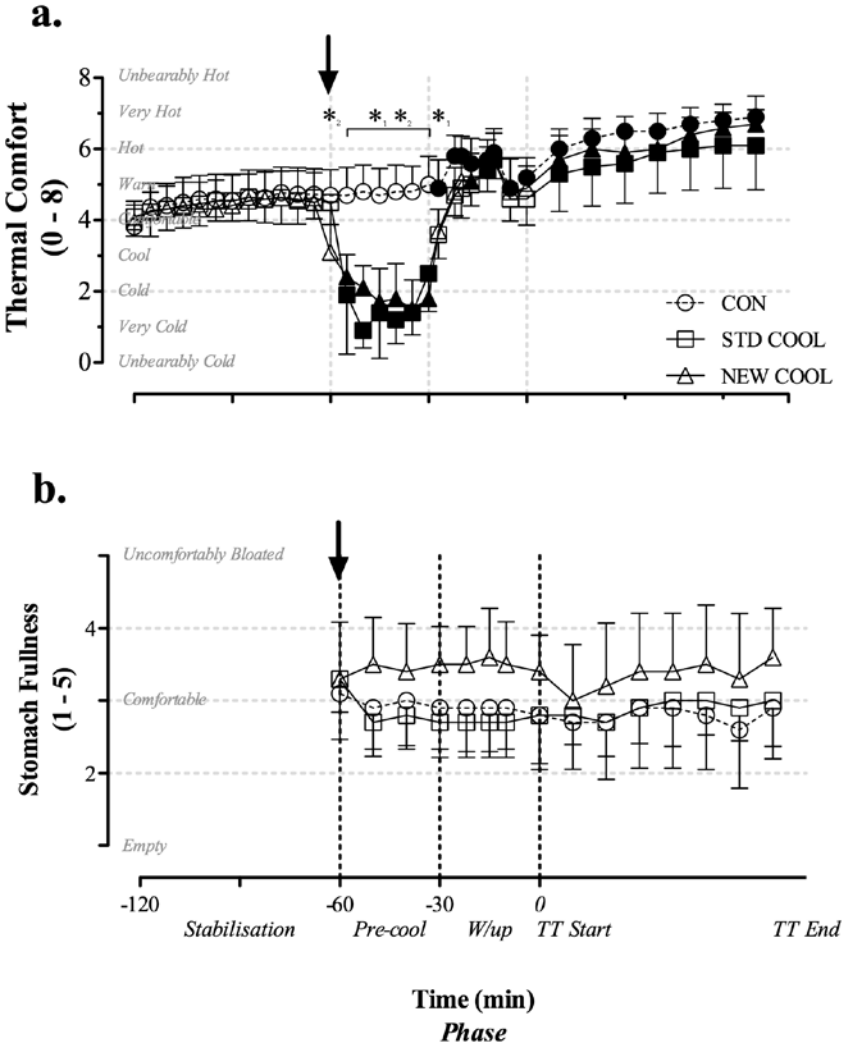

Figure 3.4 Subjective ratings of comfort. Thermal comfort (a) and stomach fullness (b). Significant time effects from t = -120 min before the time trial are denoted by *dark symbols*. Significant treatment effects between STD COOL and NEW COOL are denoted by an *asterisk* ($*_1$ and $*_2$, respectively). Commencement of precooling phase indicated with an *arrow* (↓). Statistical significance is set at the level of $P < 0.05$. Data represented by mean ± SD.

Subjective information provided by each subject at the completion of each trial suggested that there was no effect of any treatment on their ratings of effort given (98.0 ± 6.0%, 98.2 ± 3.4%, 96.8 ± 7.5% for CON, STD COOL, and NEW COOL, respecvtively, $P > 0.05$), where 100% equals *I gave everything I had*, their sensation (3.1 ± 0.8, 3.3 ± 0.6, 3.1 ± 1.1 for CON, STD COOL, and NEW COOL, respectively, $P < 0.05$), where a score of 3 indicates *felt okay*, motivation (4.0 ± 0.9, 3.8 ± 0.8, 4.2 ± 0.8 for CON, STD COOL, and NEW COOL, respectively, $P > 0.05$), where a score of 4 indicates *motivated*, and comfort (2.3 ± 0.9, 3.0 ± 0.9, 2.6 ± 1.0 for CON, STD COOL, and NEW COOL, respectively, $P > 0.05$), where a score of 2 indicates *uncomfortable*.

3.5 Discussion

The purposes of the current study were to identify a practical cooling strategy that was effective in achieving a reduction in T_{re} before a simulated cycling time trial in hot and humid conditions and to compare the effectiveness of this new strategy against standard precooling practices in enhancing cycling endurance performance. Our study showed that a new precooling strategy, combining the external application of iced towels with the internal consumption of a slushie made from sports drink, enhanced the performance of a laboratory cycling protocol simulating the Beijing Olympic Games time trial in hot and humid conditions. In contrast, a precooling protocol based on the previously established strategy of a cold water plunge followed by the use of a cooling jacket failed to provide clear benefits. The benefits to cycling performance achieved by the new precooling strategy were most evident in the second half of the time trial, in both the *climb* and *descent* portions of the laboratory protocol. This new precooling strategy represents a practical and effective technique that could be used by cyclists in preparation for races of similar characteristics to the Beijing Olympic time trial course that are undertaken in hot and humid conditions.

In the present study, both NEW COOL and STD COOL achieved a noticeable (*moderate* and *very large*, respectively) cooling effect on subjects who had been exposed to a hot and humid environment for 60 min. There were differences in the characteristics of these cooling methodologies, however, which might explain why only the NEW COOL protocol achieved a clear performance benefit over the CON trial. The timing of the peak cooling effectiveness (time of the lowest T_{re}) was similar in both treatments, occurring 5 min after the completion of the cooling protocol (i.e., after 5 min of active warming via the time trial warm-up). However, the magnitude of cooling achieved *before* the time trial was ~0.6ºC greater with the STD COOL trial, where we were able to replicate a similar magnitude to standard precooling practices on the basis of the work of Quod et al., (24). Unlike previous studies (27, 75, 82, 131, 132), we cannot directly compare the effects of each treatment on changes in T_{re} *during* the time trial because the workload was self-paced. Indeed, the HR and T_{re} recorded during the time trial were similar between trials, but the important finding was that, overall, a higher mean power output and faster performance were achieved with the NEW COOL treatment. This is a common finding amongst the literature during self-paced trials, whereby a successful intervention is associated with faster times or higher power outputs for the similar perturbations in physiological responses such as HR, rating of perceived exertion (RPE) and core temperature (24, 69, 71, 133). Such findings give support to the model of teleoanticipation proposed by Ulmer (134), whereby efferent feedback during an intensive close-looped exercise task allows an individual to choose an exercise pace that will allow them to finish the task at a common metabolic endpoint.

It is of interest to speculate why the NEW COOL treatment achieved a beneficial effect on time trial performance, whereas the effects of the STD COOL treatment, which produced a larger cooling response were *unclear*. The statistical treatment and our observations of subject behavior suggest that the larger cooling effect may introduce a poorer pacing strategy on the basis of *feeling better* at the start of the time trial. Performance benefits were seen in climb 1 after STD COOL, with an increase in concentrations of blood lactate above resting values. In fact, by the end of the first climb, the pre-time trial differences in T_{re} were abolished. This pacing strategy could not be sustained during descent 1, with cyclists experiencing a *trivial* to *large* reduction in performance in STD COOL compared with that in CON. It is possible that with greater practice or education, subjects might be able to learn how to better pace efforts after whole-body cooling using a plunge so that the there is better coupling between thermal sensations and potential for heat storage.

Another recently conducted study has also demonstrated the utility of the ingestion of ice on running endurance in a comparably hot environment (131). In that study, subjects consumed 7.5 $g \cdot kg^{-1}$ of an energy-containing drink presented as an icy slurry (-1˚C) or as a cold beverage (4˚C) immediately before undertaking a sustained high-intensity treadmill run. The slushie drink was associated with a reduced T_{re} and an increased running time to exhaustion (50.2 ± 8.5 min vs. 40.7 ± 7.2 min, $P = 0.001$). However, there was an increased T_{re} at the point of fatigue with the slushie treatment, suggesting a surprising uncoupling of T_{re} and the reaching of fatigue. It was speculated that the oral ingestion of the icy drink may have cooled the brain or produced greater cooling sensations that allowed additional work to be undertaken before volitional fatigue. There is the potential for negative effects from such a strategy if exercise continues beyond the ‘healthy’ limits of the body’s thermal load. Clearly, further investigations of the use of internal cooling strategies are merited.

Although the focus of these interventions was the optimisation of thermoregulation via precooling, we acknowledge that the slushie consumption associated with the NEW COOL strategy involved intake of additional amounts of fluid and CHO; nutritional factors that might enhance performance *per se*. In fact, there were modest but significant differences in pretrial fluid intake between treatments so that the mean ‘fluid deficit’ (change in BM) incurred from entry to the heat chamber to the completion of the time trial was 2.3% in NEW COOL vs. ~3.2% in the other trials. Thus it is possible that a small enhancement in hydration status will have contributed to better cycling performance with the NEW COOL strategy. Unfortunately, the literature on the effects of small gradations in fluid levels on cycling *performance* is limited to two studies. In one investigation, Dugas et al. (135) measured performance of six male cyclists during repeat 80-km time trials in hot conditions in which subjects consumed different volumes of fluid to incur fluid deficits equivalent to ~0.5, 2, 3 and 4% BM. Their study failed to detect differences in performance between trials using traditional probability statistics; however, data pooling to counter the risk of a type II error associated with low sample size, showed that the higher fluid trials (0.5-2% BM loss) showed greater power outputs and a strong trend to faster performance times particularly in the second half of the time trial than the lower fluid intake trials (3 - 4% BM loss). The other study conducted in temperate conditions failed to detect any differences in performance of a 1-h cycling time trial when cyclists consumed low, medium and high volumes of fluid to incur 1275, 1025 and 538 g BM loss, respectively, during the protocol (136). However, other studies that have investigated subtle differences in fluid deficits on physiological variables during steady cycling (132) and on basketball skills (137) have shown a progressive decline in variables, with the progressive increases in the degree of dehydration between 1 and 4% BM.

It is possible that the structured fluid regimen associated with the slushie ingestion may be better for cycling performance than the 'voluntary dehydration' typically associated with *ad libitum* drinking patterns in real-life sporting situations and also seen in our study. This is a contentious issue (138), and there is contradictory evidence from the sparse literature comparing performance outcomes associated with *ad libitum* versus structured fluid intake during exercise in a hot environment. One study (139) found that a structured drinking plan involving a larger volume of fluid intake did not enhance time to fatigue after 90 min of running in the heat compared to *ad libitum;* in fact, several subjects incurred severe gastrointestinal discomfort associated with the higher fluid intake. Meanwhile, Dugas et al. (135) concluded from the previously discussed investigation that there were no detectable differences in performance between an *ad libitum* fluid intake (associated with a 2% BM loss) and trials that incurred either higher or lower fluid deficits.

The NEW COOL protocol provided subjects with an additional CHO intake (0.8 $g \cdot kg^{-1}$) compared with the other trials. Although failure to match fuel availability represents another potential explanation of performance differences between trials, we think that this is unlikely. The CHO content of the slushie is small in comparison with the other strategies, on the basis of current sports nutrition guidelines (140) used to promote CHO availability in the other trials (9 $g \cdot kg^{-1}$ in the 24 h before the trial, including 2 $g \cdot kg^{-1}$ in the pre-event meal, and an additional 0.5 $g \cdot kg^{-1}$ during the time trial). Furthermore, the time trial protocol used in our study is unlikely to be limited by CHO availability (141-143).

On this basis, we feel confident that the main effect of the NEW COOL treatment on cycling performance was achieved via its cooling effect. There is a small literature concerning the benefits of ingesting cold water before and/or during exercise in hot conditions to provide a heat sink. Lee et al. (75) found that the ingestion of 1500 ml of cold fluids (4ºC) before and during steady-state cycling in hot and humid conditions reduced heat accumulation and increased time to exhaustion by 23% (~64 vs. ~52 min, $P < 0.001$) compared with a trial in which an equal volume of warm fluids (37ºC) was consumed. Similarly, the consumption of cold fluids (4ºC) was more palatable and was associated with an attenuated rise in rectal temperature and heart rate, and an 11% increase in endurance during steady-state cycling in the heat (~62 vs. ~55 min, $P < 0.05$) compared with the intake of a more neutral temperature drink (19ºC) (82).

The combination of applying of iced towels and ingesting a large slushie provides a practical solution for sport scientists to precool athletes in the field. The logistical ease of preparing iced towels in a portable icebox allows for minimal demand on equipment, storage, transport, cost and personnel. A sports drink slushie can be prepared using a portable commercial machine and can further be simplified by freezing and part-thawing ready-to-drink commercially available beverages. For instance, when precooling with this strategy at an event with similar logistical limitations as the Beijing Olympic Games, athletes are able to use standard hotel towels prepared in an icy slurry of water and shaved ice while ingesting a slushie. In contrast, logistical difficulties associated with employing other popular cooling strategies (i.e., cold water immersion, ice jackets and ice vests) can be limited by equipment, access to sufficient water and/or electricity, freezer space and transport demands. Therefore, the NEW COOL strategy provides a practically and logistically simpler strategy to pre-cool athletes ‘in the field’.

In summary, we developed a novel precooling strategy combining internal and external cooling techniques, which may also offer benefits of better fuel and fluid status over the currently self-chosen patterns of cyclists and which can be practically applied in field settings. Moreover, this study demonstrated that this technique was more effective than the precooling technique, previously established and commonly used in the sport of cycling, in enhancing the performance of a time trial simulating the event included in the Beijing Olympic Games. The benefits of the new technique were most evident in the second half of the time trial. Further studies should be undertaken to elucidate the mechanisms associated with the performance benefits seen with our strategy and to determine the range of sports in which this protocol might be useful.

CHAPTER 4 EFFECTS OF COMBINED HYPERHYDRATION, WITH AND WITHOUT GLYCEROL INGESTION, AND PRACTICAL PRECOOLING ON CYCLING TIME TRIAL PERFORMANCE IN HOT AND HUMID CONDITIONS

4.1 Abstract

Purpose: To investigate the effectiveness of combining glycerol hyperhydration and an established precooling technique on cycling time trial performance in hot environmental conditions. **Methods:** Twelve well-trained male cyclists performed three 46.4 km laboratory-based cycling trials that included two climbs, under hot and humid environmental conditions (33.3 ± 1.1˚C; 50 ± 6% r.h.). Subjects were required to hyperhydrate with 25 $g \cdot kg^{-1}$ body mass (BM) of a 4˚C beverage containing 6% carbohydrate (CON) 2.5 h prior to the time trial. On two occasions, subjects were also exposed to an established precooling technique (PC) 60 min prior to the time trial, involving 14 $g \cdot kg^{-1}$ BM ice slurry ingestion and applied iced towels over 30 min. During one PC trial, 1.2 $g \cdot kg^{-1}$ BM glycerol was added to the hyperhydration beverage in a double-blind fashion (PC+G). Statistics used in this study involve the combination of traditional probability statistics and a magnitude-based inference approach. **Results:** Glycerol hyperhydration resulted in a lower urine output (330 ml, 10%) and also large reductions in rectal temperature (-0.6 to -0.7˚C). Precooling induced further *small* (-0.3˚C) to *moderate* (-0.4˚C) reductions in rectal temperature with PC and PC+G treatments, respectively, when compared with CON (0.0˚C, $P<0.05$). Overall, PC+G failed to achieve a *clear* change in cycling performance over

CON, but PC showed a *possible* 2% (30 s, P = 0.02) improvement in performance time on climb 2 compared to CON. This improvement was attributed to subjects' lower perception of effort reported over the first 10 km of the trial, despite no *clear* performance change during this time. No differences were detected in any other physiological measurements throughout the time trial. **Conclusion:** The addition of glycerol to a hyperhyration strategy followed by precooling did not result in any additional performance benefit to the same strategy that was used without glycerol and precooling. Further research is warranted to further refine preparation strategies for athletes competing in thermally stressful events to optimise health and maximise performance outcomes.

4.2 Introduction

During strenuous exercise performed in hot and/or humid conditions, the combined effects of a high metabolic heat production combined with insufficient heat dissipation lead to the development of hyperthermia (2, 3). These high body temperatures (i.e., >39°C) reduce exercise performance (9, 44), as evidenced by the inability to sustain a constant exercise intensity (5, 144) or through alterations in self-selected pace (2, 4). Fortunately, there are established strategies that can be applied prior to an event that can lessen the impact of heat gain and facilitate heat loss from the body. For instance, precooling through the application or ingestion of cold air, water and ice have been demonstrated to be effective in lowering deep body temperatures and enhancing heat storage capacity (for review, see (14, 15, 145)). We have recently established that a combination of external (application of iced towels) and internal (consumption of an ice slurry) cooling is a practical and effective strategy for reducing body temperature and enhancing cycling time trial performance in hot conditions (65, 146).

Pre-exercise hyperhydration involves the deliberate intake of large fluid volumes prior to performing an exercise task. This strategy has been proposed to attenuate possible reductions in performance that may occur with dehydration in a hot environment (34). However, both pre-hydrating (38) and acute cold exposure (147, 148) are accompanied by concomitant increases in diuresis, which may limit their usefulness prior to a prolonged event. When compared with water ingestion alone however, fluid retention is increased (~8 $ml \cdot kg^{-1}$ body mass) when osmotically active agents such as sodium or glycerol are consumed with the fluid (34). Furthermore, the addition of glucose to a solution containing glycerol may further enhance fluid absorption and be of further benefit from a metabolic perspective (149). A recent meta-analysis concluded that the use of glycerol hyperhydration in hot conditions provides a *small* (3%, Effect Size = 0.35) but worthwhile enhancement to prolonged exercise performance above hyperhydration with water (34). However, some studies involving glycerol hyperhydration have failed to show performance benefits (150-154) and furthermore, it appears that the beneficial effects may not be simply explained in terms of an attenuated body fluid deficit. Rather, improved exercise performance may be the result of a reduction in body temperature with glycerol hyperhydration (150, 155, 156).

In light of the unknown but potentially interrelated effects of precooling and pre-exercise hyperhydration, with and without glycerol, on endurance performance, the present study aimed to investigate the effectiveness of combining glycerol hyperhydration and an established precooling technique on cycling time trial performance in hot environmental conditions. In addition, a sub-purpose was to examine this objective using high levels of construct validity, by using as many real-life competition circumstances as possible, such as a high pre-exercise environmental heat load and a simulated performance trial with hills and appropriate levels of convective cooling.

4.3 Methods

4.3.1 Subjects

Twelve competitive well-trained male cyclists (mean ± SD; age 31.0 ± 8.0 y, body mass (BM) 75.2 ± 9.2 kg, maximal aerobic power (MAP) 444 ± 33 W, peak oxygen consumption ($\dot{V}$O2peak) 68.7 ± 8.8 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were recruited from the local cycling community to participate in this study. Prior to commencement of the study, ethical clearance was obtained from the appropriate human research ethics committees. Subjects were informed of the nature and risks of the study before providing written informed consent. Prior to the study, subjects completed a medical questionnaire and had no prior history of heat intolerance, current injury or illness.

4.3.2 Study Overview

On separate days following heat acclimation and an incremental exercise test to exhaustion, participants performed a total of three hilly 46.4-km experimental cycling time trials (described below) in hot environmental conditions (33.3 ± 1.1°C; 50 ± 6% r.h.). Trials were conducted in a randomised counterbalanced order. Prior to the commencement of each performance trial (t = -180 min), subjects were required to ingest 25 g·kg^{-1} BM of a cold (4°C) beverage containing 6% carbohydrate (CHO; Gatorade, Pepsico, Australia, NSW, Australia). On two occasions, subjects were also exposed to an established combined external and internal precooling technique, whereby iced towels were applied to the subject's skin while ingesting additional fluid in the form of an ice slurry (slushie) made from sports drink (PC). The precooling method used in this study, as previously described (65), commenced 60 min prior to the start of the trial (t = -60 min) and was applied for a period of 30 min. During one of the precooling trials, the recommended dose (157) of 1.2 g·kg^{-1} BM glycerol (PC+G) was added to the large fluid bolus in a double blind fashion. PC and PC+G trials were compared to a control trial, which consisted of the large beverage ingestion without glycerol and received no precooling (CON). A schematic representation of the test protocol is given in Figure 4.1. Experimental trials were separated by 3 - 7 d with a consistent recovery time between trials for each subject.

4.3.2.1 Heat Acclimation

Prior to the first experimental trial, subjects visited the laboratory on at least nine occasions to heat acclimate and familiarise with the cycle ergometer (Velotron, Racermate Inc., Seattle, WA, USA) and the experimental exercise protocol (simulated Beijing Olympic time trial course, as previously described (65)). Heat acclimation was completed over a three-week period and consisted of prolonged (>60 min) sub-maximal self-paced cycling, which was performed on at least nine occasions. All acclimation sessions were conducted in a heat chamber under climatic conditions (32-35°C, 50% r.h.) similar to the experimental trials (described below). In addition to the heat acclimation trials, all subjects completed at least one familiarisation trial of the experimental cycling protocol in the heat chamber.

4.3.2.2 Incremental Cycle Test

Prior to the first experimental trial subjects also performed a progressive maximal exercise test on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). After a 5-min warm-up at 150 W, the test protocol started at 175 W and increased 25 W every 60 s until volitional exhaustion. Maximal aerobic power (MAP) was determined as the power output of the highest stage completed. If the participant finished partway through a 60 s stage, MAP was calculated in a pro-rata manner. Expired gases were collected into a calibrated and customised Douglas bag gas analysis system, which incorporated an automated piston that allowed the concentrations of O_2 and CO_2 (AEI Technologies, Pittsburgh, PA) and the volume of air displaced to be quantified. The operation and calibration of this equipment have been described previously (124). Peak oxygen consumption was calculated as the highest oxygen consumption recorded over a 60 s average.

4.3.2.3 Experimental Time Trials

Subjects followed a standardised pre-packaged diet and training schedule for 24 h prior to each experimental trial. The standardised diet was supplied in the form of pre-packaged meals and snacks, providing 9 $g \cdot kg^{-1}$ BM CHO; 1.5 $g \cdot kg^{-1}$ BM protein; 1.5 $g \cdot kg^{-1}$ BM fat, with a total energy goal of 230 $kJ \cdot kg^{-1}$ BM. Subjects refrained from any intake of caffeine and alcohol over this period. Individualised menus were prepared accounting for food preferences using FoodWorks Professional Edition (Version 6.0, Xyris Software, Brisbane, Australia), as described previously (158). Subjects were provided with all foods and drinks in portion controlled packages for the first 20 h of the standardised period and were given verbal and written instructions on how to follow the diet. Subjects were allowed to undertake light

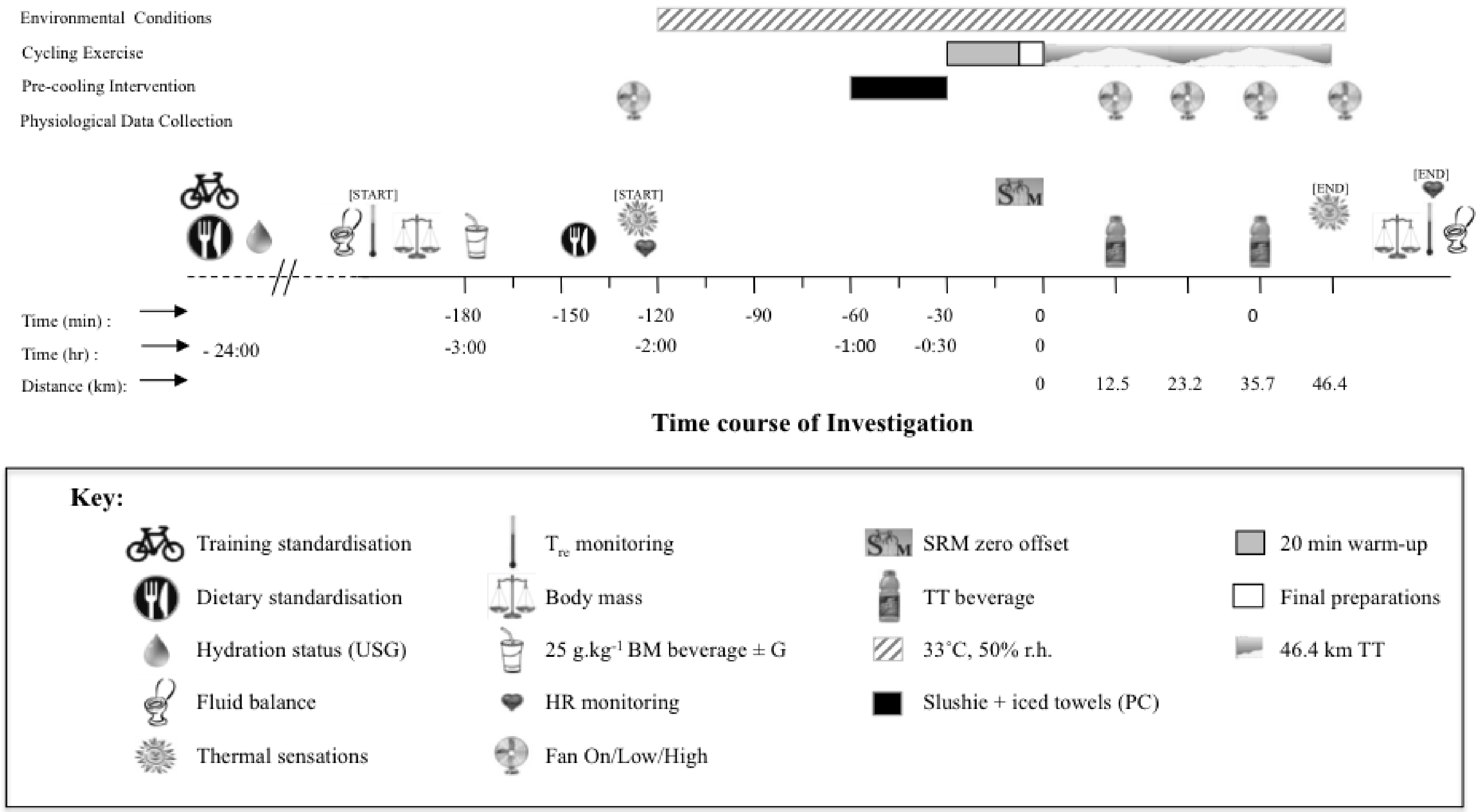

Figure 4.1 Diagram of test protocol.

exercise on the day prior to each trial and were asked to repeat this for subsequent trials. Compliance to the diet and exercise protocol was determined from a checklist kept by each subject and presented on arrival to the laboratory prior to each trial. Subjects' 'first-waking' urine sample was also analysed for the determination of specific gravity to ensure the cyclist attended the laboratory for each trial in a similar hydration state.

For each experimental trial subjects were required to cycle a 46.4-km time trial on a Velotron cycle ergometer, (Velotron 3D Software, RacerMate Inc., Seattle, WA, USA) which was fitted with a calibrated (125) SRM cycling power meter (scientific version, 8 strain gauge, Schoberer Rad Meβtechnik; Jülich, Germany), which was set to sample at 1-s intervals. The measurement error for cycling time trials during laboratory protocols such as this has been established as 1.7%, as described previously (65). The course profile for this time trial was a simulation of the 2008 Beijing Olympic Games time trial course, as described previously (65). All experimental trials were carried out in the afternoon, to mimic the schedule of the 2008 Olympic Games cycling time trial. On arrival to the laboratory, three hours prior each trial (t = -180 min), subjects voided their bladder (not for collection) and inserted a single use thermal probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical Inc., St Louis, MO, USA) 12 cm beyond the anal sphincter for determination of rectal temperature (T_{re}). Changes in rectal temperature at the end of the precooling phase (t = -30 min) and at the end of the warm-up phase (t = 0 min) were used to reflect the effectiveness of the precooling treatment and the potential differential for heat storage at the commencement of the time trial. Reduction in rectal temperature as a result of precooling were categorised as either *small* (<0.3˚C), *moderate* (0.3 - 0.6˚C), *large* (0.6 - 0.8˚C) or *very large* (>0.8˚C) based on our previous work (65).

On arrival at the laboratory, subjects were immediately given a large cold beverage (given as two boluses of 12.5 $g \cdot kg^{-1}$ BM at t = -180 and -165 min) to consume within 30 min. At t = -150 min and every 30 min leading up to the commencement of the time trial, and immediately afterwards, subjects were required to void their bladder. Urine was weighed and analysed for specific gravity. At this time, subjects consumed the last of their standardised diet as a "pre-race meal" which provided 2 $g \cdot kg^{-1}$ BM CHO.

Rating of thermal comfort, T_{re} and heart rate (HR; Polar S810i HR monitor, Polar Electro OY, Kempele, Finland) were recorded before entering the heat chamber, and every 5 min during 60 min of passive rest in the heat chamber (heat stabilisation; t = -120 to -60 min). The environmental conditions inside the chamber were measured and corrected every 5 min throughout the duration of the trial. On two occasions (PC and PC+G trials), following the completion of the stabilisation phase, subjects consumed 1,024 ± 122 g slushie containing 6% CHO, which was equivalent to 13.6 $g \cdot kg^{-1}$ BM, providing a CHO intake of 61 g (0.8 $g \cdot kg^{-1}$ BM). The slushie was given in two ~7 $g \cdot kg^{-1}$ BM boluses and subjects were given 15 min to consume each bolus while wearing iced towels, as previously described (65). During the control trial subjects received no cooling intervention (CON). During this time subjects were also asked to provide ratings of stomach fullness.

Following stabilisation and precooling, subjects completed a standardised 20-min warm-up on the Velotron ergometer. The warm-up consisted of two bouts of 3 min at 25% MAP, 5 min at 60% MAP and 2 min at 80% MAP, which is a protocol used by some elite time trial cyclists prior to competition. The final 10 min before the start of the time trial allowed subjects to complete their own preparations. During this time subjects were provided with standard pre-race instructions and the zero offset of the SRM crank was set according to manufacturer's instructions.

Feedback provided to the subject was limited to distance covered (km), cycling gear-ratio (12 – 27 / 42 - 54), road gradient (%) and instantaneous velocity ($km \cdot h^{-1}$). Subjects were provided with 314 ± 207 g fluid containing 6% carbohydrate (Gatorade, Pepsico Australia, Chatswood, Australia), which provided a further CHO intake of 19 g (0.25 $g \cdot kg^{-1}$ BM) at the "top of each climb" (12.5 and 37.5 km), which simulated the ideal time to consume fluid on the Beijing time trial course based on the experience of professional cyclists during training and racing on the actual course. On the first trial, subjects were given a total of 325 ml at each of these points and were permitted to drink *ad libitum* for the next kilometer on the first trial. The volume that was consumed was measured and repeated for subsequent trials. Drinks were removed from ice storage at the commencement of the time trial and left in the heat chamber to simulate drink temperatures that would be experienced in race conditions. To further replicate competition, the cyclist was positioned in front of a large industrial fan (750 mm, 240 V, 50 Hz, 380 W, model Number: N11736, TQ Professional), which was adjusted to simulate uphill or downhill wind speeds. Specifically, the fan was fixed on low speed to simulate 12 $km \cdot h^{-1}$ wind speed for 0 -

12.5; 23.2 - 35.7 km and switched to high speed to simulate 32 km·h^{-1} wind speed for 12.5 -23.2 and 35.7 - 46.4 km.

Split times, velocity and power output data were collected for each trial, with the periods of interest being time to top of first climb (12.5 km), end of first lap (23.2 km), time to top of second climb (35.7 km) and finish (46.4 km). Throughout the trials, HR and T_{re} was recorded every 2 min, while self-reports of perception of effort (RPE) (123), thermal sensation (122), and gastrointestinal comfort (5-point Likert scale), were recorded at approximately 5-km intervals. On the completion of each time trial, subjects were asked a series of questions related to their effort, motivation, sensation and comfort, as reported previously (65).

4.3.3 Statistical Analysis

Pre-trial body mass, percentage dehydration, and post-trial subjective ratings were compared between trials (i.e., CON, PC, PC+G) using a one-way analysis of variance (ANOVA). A two-way (trial × time) repeated measures ANOVA was used to examine differences in dependant variables (i.e., rectal temperature, heart rate, urine specific gravity and volume, thermal comfort, stomach fullness and RPE) between trial means at each time point. If a significant main effect was observed, pairwise comparisons were conducted using Newman-Keuls *post hoc* analysis. These statistical tests were conducted using Statistica for Microsoft Windows (Version 10; StatSoft, Tulsa, OK) and the data are presented as means and standard deviations (SD). For these analyses, significance was accepted at $P < 0.05$.

The performance data from the three trials were analysed using the magnitude-based inference approach recommended for studies in sports medicine and exercise sciences (128). A spreadsheet (Microsoft Excel), designed to examine post-only crossover trials, was used to determine the clinical significance of each treatment (available at newstats.org/xPostOnlyCrossover.xls), as based on guidelines outlined by Hopkins (159). Performance data are represented by time trial time and power output during the various segments of the course, and are represented as means ± SD. The magnitude of the percentage change in time was interpreted by using values of 0.3, 0.9, 1.6, 2.5 and 4.0 of the within-athlete variation (coefficient of variation) as thresholds for *small*, *moderate*, *large*, *very large* and *extremely large* differences in the change in performance time between the trials (128). These threshold values were also multiplied by an established factor of -2.5 for cycling (160), in order to interpret magnitudes for changes in mean power output. The typical variation (coefficient of variation) for road cycling time trials has been previously established as 1.3% by Paton and Hopkins (129), with the smallest worthwhile change in performance time established at 0.4% (130), which is equivalent to 1.0% in power output. These data are presented with inference about the true value of a precooling treatment effect on simulated cycling time trial performance. In circumstances where the chance (%) of the true value of the statistic being >25% *likely* to be beneficial (i.e., faster performance time, greater power output), a practical interpretation of risk (benefit:harm) is given. An odds ratio (OR) of >66 was used to establish that the benefit to performance time gained by using one strategy outweighed any potential harm (in performance time) that could result.

4.4 Results

Performance time (h:min:s) and power output (W) for the entire time trial, for each of two laps and for each of four segments (climb 1 and 2, and descent 1 and 2) of each time trial are presented in Table 4.1 (Appendix I). Overall performance time and average power output were not significantly different between any of the three performance trials ($P > 0.05$). However, there was a possibility of performance benefits on selected parts of the course. On Lap 2 of the PC condition, there was a 1.2% reduction in performance time (30 s; $P = 0.07$) and a 1.4% increase in power output (3 W, $P = 0.34$) compared with CON. This improvement was brought about by the 1.8% faster performance time (30 s; $P = 0.02$) and greater power output (6 W, $P = 0.07$) that was achieved predominantly on the climbing section (Climb 2). Moreover, the likelihood of a detrimental performance outcome was sufficiently outweighed by the chance of benefit (OR = 8,369).

Rectal temperature towards the end of the stabilisation phase (t = -65 min before the time trial) was considered to be the baseline value for each trial. At this time point, there were no differences in rectal temperature between trials ($P > 0.05$, Figure 4.2a). There was a *large* (-0.6 to -0.7°C) reduction in rectal temperature from when subjects' arrived at the laboratory and following hyperhydration beverage ingestion, which was consistent across all trials ($P < 0.05$). Relative change in rectal temperature at the end of the warm-up and just prior to the time trial was significantly lower in the PC+G compared with the CON trial ($P < 0.05$). Relative change in rectal temperature continued to rise during the time trial in all trials, such that there was no difference in relative change in rectal temperature between treatments during this phase (CON, 1.33 ± 0.27°C·h^{-1}; PC, 1.45 ± 0.32°C·h^{-1}; PC+G, 1.39 ± 0.26°C·h^{-1}; $P > 0.05$). In all trials, heart rate remained similar to baseline levels throughout the stabilisation and precooling phases, but increased at onset of the warm-up and remained above baseline until the completion of the time trial (Figure 4.2b). Heart rate was lower in the CON, compared with PC and PC+G trials 5 min prior to the time trial ($P < 0.01$), however these differences were not apparent at the time trial start ($t = 0$ min) or throughout the duration of the time trial.

Collection of 'first waking' urine samples on the morning of each trial, mean changes in body mass, fluid consumed and urine volume produced during the trials is presented in Table 4.2. Urine specific gravity results showed that subjects commenced each trial with similar within-subject and between-subject hydration status ($P > 0.05$). The time course of urine production represented in Figure 4.3a shows that the volume was elevated following the ingestion of the large fluid bolus, but returned to baseline values prior to the commencement of the time trial. In the CON and PC trials, the volume of urine produced was greater than baseline values at $t= -90$ min to -30 min ($P < 0.05$). However, when glycerol was co-ingested with the fluid (PC+G), the elevated urine volume was limited to one time point ($t = -90$ min; $P < 0.001$) and was significantly lower than volumes produced in CON and PC trials at $t = -60$ and -30 min ($P < 0.01$). During the CON ($P < 0.01$) and PC ($P < 0.001$) trials, urine specific gravity was significantly lower than baseline values at all time points (Figure 4.3b). The urine specific gravity of samples collected during the PC+G trial were significantly lower than baseline ($P < 0.01$) at $t = –120$ min and -90 min and returned to baseline levels for the remainder of the trial. There was an interaction between treatments, such that urine specific gravity was greater in the

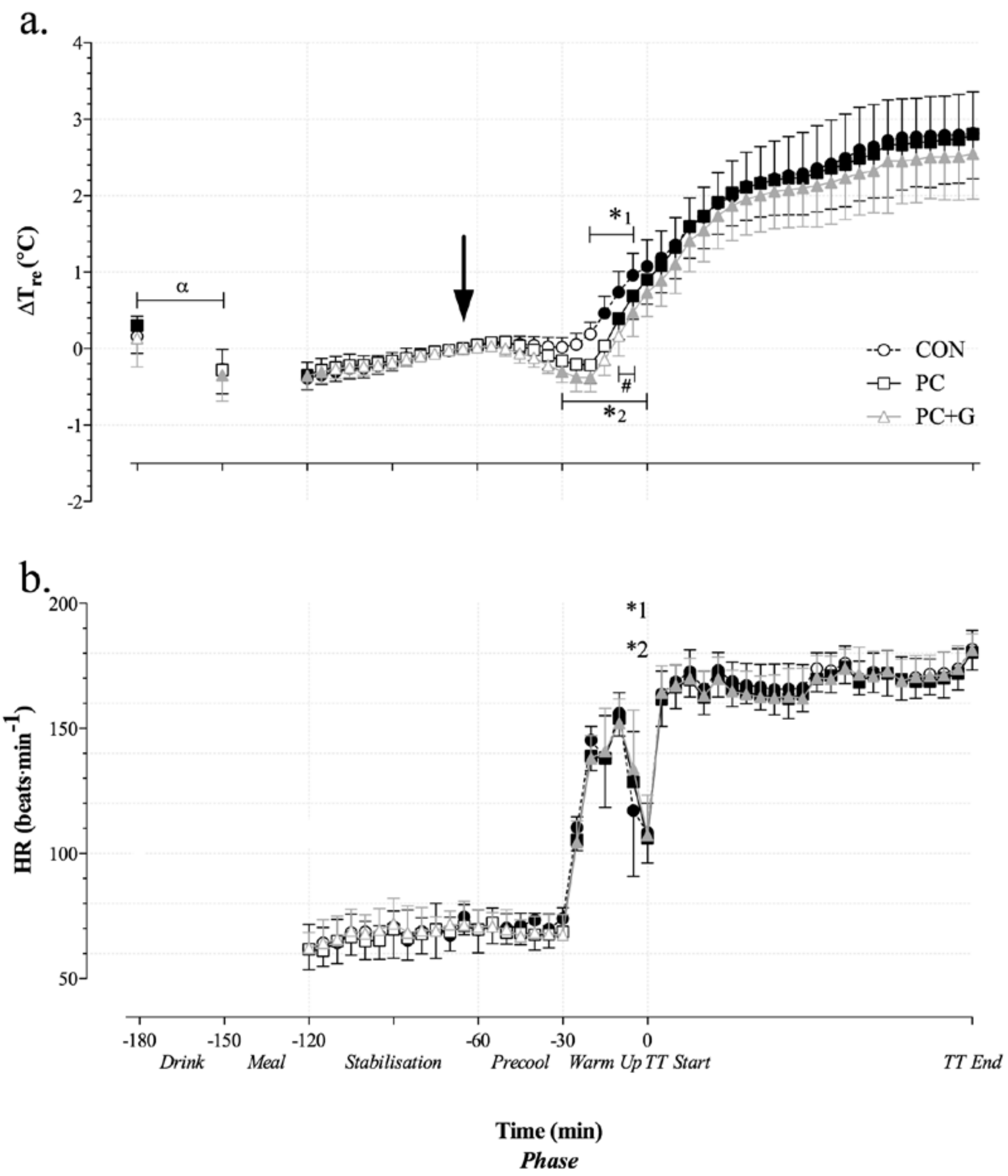

Figure 4.2 Relative change in rectal temperature (a) and heart rate (b) throughout the experimental trial. Significant time effects from t = -65 min before time trial (arrow) are denoted by *dark symbols*. Significant time effect from t = -180 min to t = -150 min following drink ingestion with and without glycerol ingestion denoted by alpha (α). Significant effects of precooling treatment (1; PC and 2; PC+G) compared with CON are denoted by a star symbol ($*_1$,$*_2$, respectively). Significant interaction between PC and PC+G treatments are denoted by a hash (#) symbol. Data are presented as mean ± SD.

Table 4.2 Fluid balance.

	CON	**PC**	**PC+G**
'First waking' Urine Specific Gravity	1.015 ± 0.005	1.015 ± 0.005	1.016 ± 0.004
Δ BM^{A} (kg)	-2.56 ± 0.60	-2.50 ± 0.61	-2.52 ± 0.60
Δ BM^{A} (%)	-3.19 ± 0.83	-3.13 ± 0.90	-3.14 ± 0.85
Sweat rate ^{A} (L.h^{-1})	1.94 ± 0.48	1.91 ± 0.48	1.92 ± 0.47
Total fluid consumed ^{B} (L)	2.18 ± 0.74	3.22 ± 1.24*	3.24 ± 1.25*
Total urine volume ^{C} (L)	1.71 ± 0.34	1.51 ± 0.30	1.20 ± 0.36 *$^{\#}$

^{A} represents n=11; pre to post time trial, ^{B} represents fluids consumed from -180 min prior to the time trial until the end of the time trial, ^{C} represents urine volume collected from -150 min prior to the time trial until immediately after the time trial, * represents substantial difference to CON (P<0.05), $^{\#}$ represents substantial difference between PC and PC+G treatments (P=0.03). Data are presented as mean ± SD.

PC+G than CON and PC trials at t = -60 min and -30 min prior to the commencement of the time trial (all P < 0.001). Due to the inclusion of slushie ingestion being part of the precooling intervention, the amount of sports drink ingested by subjects inside the heat chamber (t = -120 min to end of the time trial or ~3.5 h) was greater in PC (1,335 ± 211 ml) and PC+G (1,356 ± 206 ml) trials, compared with the CON (299 ± 214 ml, P < 0.001) trial, which provided a further ~80 g of carbohydrate.

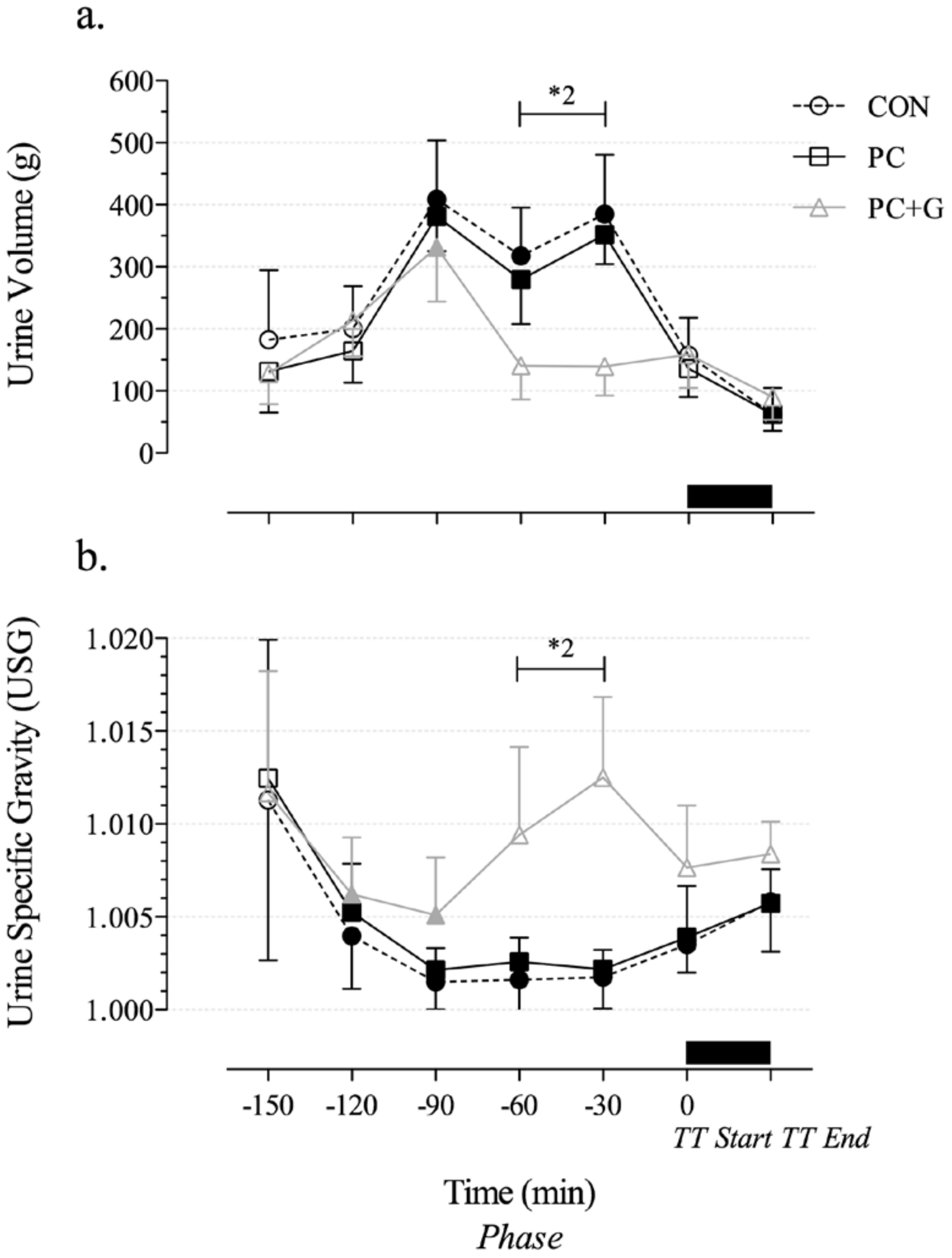

Figure 4.3. Volume of urine output (a) and urine specific gravity (b) throughout the experimental trial. Significant time effects from t = -150 min before the time trial are denoted by *dark symbols*. Significant treatment effect of PC+G compared with CON denoted with star symbol ($*_2$). Time trial denoted by black bar. Data are presented as mean ± SD.

There was no significant change in the rating of thermal comfort after subjects had entered the heat chamber to stabilise to the hot and humid conditions for 60 min (t = -120 to -60 min before the time trial, Figure 4.4a). However, once precooling commenced (t = -60 min before the time trial), the rating of thermal comfort was significantly reduced, such that subjects reported feeling cooler when treated with PC and PC+G (t = -55 to -25 min before time trial, $P < 0.05$). There was no significant change in ratings of perceived stomach fullness (Figure 4.4b) across the three trials, however, there were significant interactions ($P < 0.05$, Figure 4.4c) detected in RPE throughout the first 17 km of the time trial (Climb 1 and the first 4.5 km of descent 1). Subjects reported a lower RPE following PC compared with PC+G at 5 and 10 km, and in PC compared with CON at 10 km, and CON compared with PC+G at 17 km.

Subjective information provided by each subject at the completion of each trial is presented in Table 4.3. These data suggest that subjects' perceived level of effort, sensations, motivation and comfort experienced, were similar across all trials.

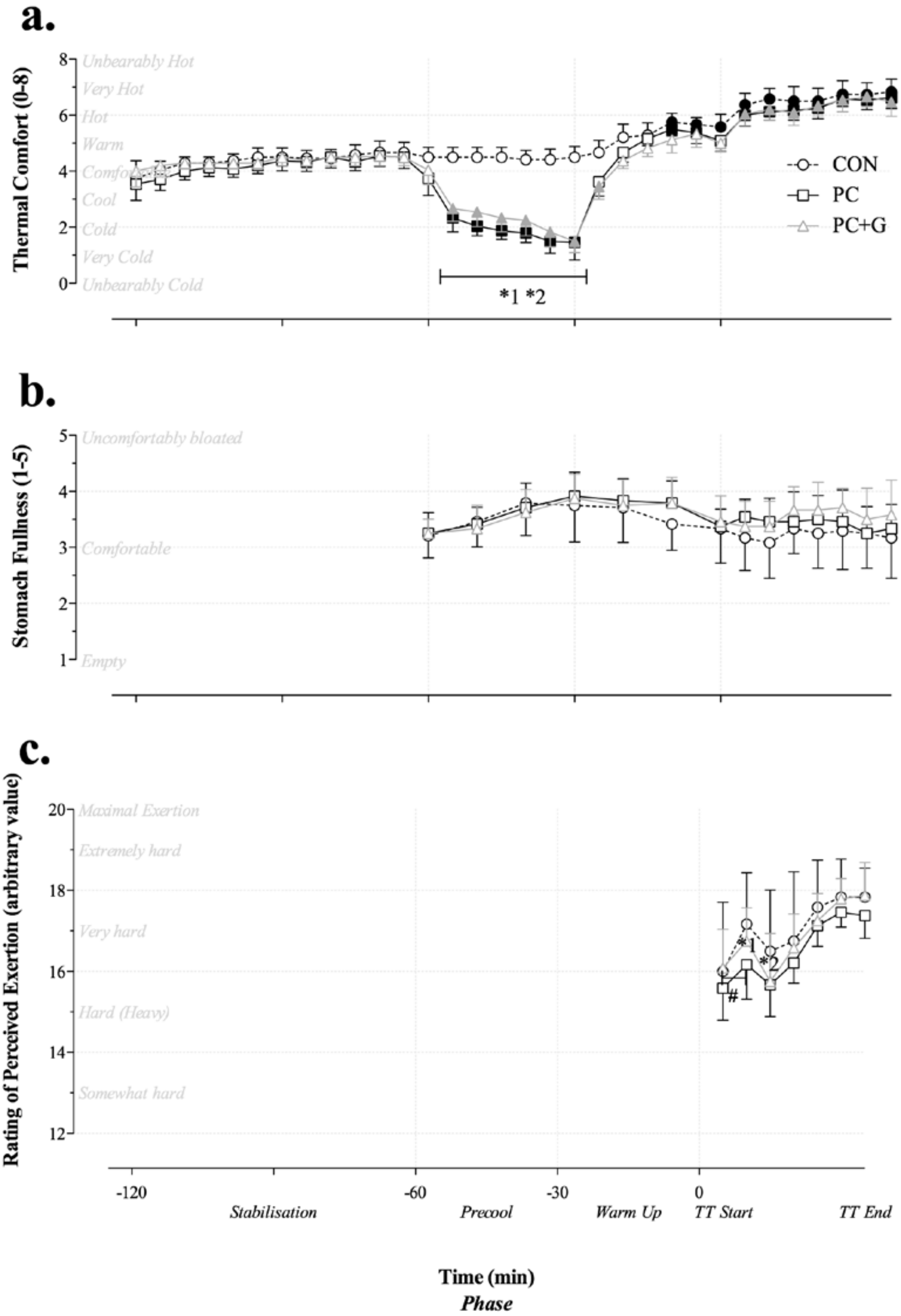

Figure 4.4. Subjective ratings of comfort. Thermal comfort (a), stomach fullness (b). and rating of perceived exertion (c). Significant time effects from t = -65 min before the time trial are denoted by *dark symbols*. Significant effects of precooling treatment (1; PC and 2; PC+G) compared with CON are denoted by a star symbol ($*_1$,$*_2$, respectively). Data are presented as mean ± SD.

Table 4.3 Subjective information on completion of time trials

Theme		**CON**	**PC**	**PC+G**
Effort given	(%)	94 ± 10	95 ± 6	98 ± 4
Sensation	(Arbitrary value)	4.0 ± 0.9	3.8 ± 1.1	3.8 ± 0.8
Motivation	(Arbitrary value)	4.6 ± 1.4	4.9 ± 1.2	5.2 ± 0.7
Comfort	(Arbitrary value)	2.4 ± 1.2	2.5 ± 0.9	2.9 ± 0.7

Data presented are mean ± SD. All comparisons P > 0.05.

4.5 Discussion

The purpose of the current study was to investigate the effectiveness of combining glycerol hyperhydration and a practical precooling strategy on performance during a cycling time trial that simulated a real-life event in hot and humid environmental conditions. The main findings of this study were that: i) a hyperhydration strategy, with or without the addition of glycerol, in addition to an established precooling technique, failed to achieve a *clear* enhancement of cycling time trial performance in hot humid conditions, ii) the ingestion of a large volume of chilled (4°C) fluid prior to the time trial (CON) induced a *clear* and sustained *large* reduction in body temperature, and iii) when precooling, involving the application of iced towels and the ingestion of a slushie, was performed after consumption of a hyperhydration solution without, but not with glycerol, a further *small* reduction in deep body temperature, reduced perceived exertion and improved performance on the second half of the time trial (i.e., climb 2) occurred.

Our original hypotheses were that our precooling strategy would result in lower body temperatures compared with the control condition and the prior ingestion of a hyperhydration strategy would be further enhanced with the addition of glycerol. While glycerol hyperhydration resulted in an increased fluid balance of ~330 ml (10%) and the precooling technique caused a further *small* to *moderate* reduction in deep body temperature, together these alterations did not lead to a *clear* improvement in overall performance. In fact, on further inspection of performance data, a *possible* (49% chance) performance benefit (2%) was observed on climb 2 following hyperhydration, without glycerol, plus precooling (PC intervention) over the control trial. This improved performance was associated with subjects reporting a lower perception of effort over the first 10 km of the time trial (2.5 km short of the top of the climb), despite similar pacing strategies and physiological perturbations (i.e., rectal temperature, heart rate, thermal comfort and stomach fullness) across all trials. As such, it appears that benefits associated with hyperhydration plus precooling offered some advantage in attenuating the perception of effort during the initial portion of the trial, allowing for improved performance in the later stages of the trial when thermal load was greatest. These results may be partially explained by the pre-trial brief, in which subjects were instructed “if feeling *good*, to save the *big* effort for the second lap”.

Despite hyperhydrating with the co-ingestion of glycerol plus precooling (PC+G intervention) resulting in a significant reduction in thermal comfort and core body temperature, performance was not significantly different to the control trial over any part of the course. Moreover, although subjects received the same precooling intervention, the magnitude of cooling was greater in the PC+G trial compared with the PC trial (a *moderate* versus *small* reduction in rectal temperature, respectively). We are unable to provide a clear explanation into the potential mechanism of this enhanced effect. However, the differences in performance among trials in the present study, despite differing core body temperatures are commensurate with those from our previous work (146), whereby a greater reduction in rectal temperature did not lead to greater performance effects. These results thus provide further data to refute the existence of a direct relationship between magnitude of cooling and the functional outcome (15, 24). In fact, we may have induced a magnitude of cooling that surpassed a threshold temperature, in which performance may be impaired during self-paced endurance exercise, as we have recently proposed (146).

While results of the present study may indicate that the precooling and hyperhydration interventions used are ineffective in enhancing real life sporting performance, an unexpected finding from this study was that the ingestion of the pre-event fluid in the control trial, also induced a *clear* and sustained *large* reduction in body temperature. A chilled beverage was selected as the control condition for hyperhydrating subjects to mask the flavor characteristics of the glycerol in the sports drink in PC+G trial, to standardise total fluid intake, and to simulate the conditions of a real-life event. Indeed, when performing in hot and humid conditions, participants are usually exposed to the environmental conditions for more than 2 hr prior to the event and in most circumstances would preferentially ingest a cool beverage. It is possible that the *large* reduction in rectal temperature observed in the control trial may have provided a benefit to performance and thus reduced the likelihood of observing clear physiological or performance effects. Indeed, this protocol and magnitude of cooling observed is similar to studies that have shown improvements in endurance capacity following cold fluid ingestion precooling (73, 75, 82). These studies used ~20.5 to 22.5 $ml \cdot kg^{-1}$ fluid served at 4˚C in the 90 min before (73) and/or during (75, 82) an exercise task performed in hot and humid conditions. Interestingly, we observed a sustained cooling effect with mean baseline rectal temperature (t = -65 pre time trial) remaining below pre-hydration levels, despite subjects being exposed to the hot and humid conditions for ~60 min following consumption. Although we cannot determine whether the reduction in core body temperature improved performance in the present study, we have previously shown that the same precooling strategy resulted in a 3% increase in average cycling power output of similar calibre cyclists over the same course (65), when compared to a control trial without any fluid intake. Collectively these results indicate that hyperhydration with or without glycerol, plus precooling through the application of iced towels and the ingestion of a slushie, may provide minimal performance benefit, over the ingestion of a large cool beverage.

Although the focus of precooling was the optimisation of thermoregulation, we acknowledge the composition of the slushie, in the current study, provided additional fluid and carbohydrate; nutritional components that may also enhance performance. However, as we have previously discussed (65, 146), it is unlikely that performance of our cycling protocol would be influenced by providing euhydrated subjects with further fluid or having greater carbohydrate availability associated with this strategy, at least within the limits of detection of our protocol and under the control conditions of nutritional preparation (i.e., following a carbohydrate rich meal, well hydrated). Furthermore, this study design was representative of real-life circumstances, whereby cyclists simply added the precooling strategy to a hyperhydration strategy.

In summary, the current study does not support the hypothesis that hyperhydration, with or without the addition of glycerol, plus an established precooling strategy is superior to hyperhydration, in reducing thermoregulatory strain and improving exercise performance. Despite increasing fluid intake and reducing core body temperature, hyperhydration plus precooling failed to improve performance when compared with the consumption of a large cool beverage prior to the trial. These results indicate that a combined precooling technique (i.e., ice towel application and slushie ingestion) results in minimal performance benefit over and above the typical real-life pre-race preparations (i.e., consumption of a cold fluid). Further research is warranted in order to examine the influence of fluid temperature and volume on the success of glycerol hyperhydration and precooling strategies, presumably because the control condition, chosen to standardise total fluid intake, also involved a substantial precooling effect. Specifically, further studies could be undertaken to compare glycerol hyperhydration using a tepid beverage to distinguish the effects of this strategy on fluid status from its thermoregulatory impact and allow separation of the different elements that may underpin a performance change.

CHAPTER 5 FLUID BALANCE, CARBOHYDRATE INGESTION AND BODY TEMPERATURE DURING MEN'S STAGE-RACE CYCLING IN TEMPERATE CONDITIONS

5.1 Abstract

Purpose: To observe fluid balance, voluntary carbohydrate intake and thermoregulatory characteristics of highly competitive road cyclists during a multiday stage race in temperate conditions**. Methods:** Ten internationally competitive male cyclists competed in two stage-races (2009 Tour of Gippsland; n=5, and 2010 Tour of Geelong; n=5) in temperate conditions (13.2-15.8°C; 54-80% r.h.). Body mass (BM) was recorded immediately before and after each stage. Peak gastrointestinal temperature ($T_{GI\ peak}$) was recorded throughout each stage. Cyclists recalled the types and volumes of fluid and food consumed throughout each stage. **Results:** Although fluid intake varied according to the race format, there were strong correlations between fluid intake and distance across all formats of racing, in both tours (r = 0.82, r = 0.92). Within a stage, the relationship between finishing time and fluid intake was trivial. Mean BM change over a stage was 1.3%, with losses >2% BM occurring on 5 out of 43 measured occasions. Most subjects consumed carbohydrate at rates, which met the new guidelines (30 - 60g·h^{-1} for 2 - 3 h; ~90g·h^{-1} for >3 h), based on event duration. There was a consistent observation of a $T_{GI\ peak}$ >39°C during stages of the Tour of Gippsland (67%) and the Tour of Geelong (73%) despite temperate environmental conditions. **Conclusion:** This study captured novel effects of high intensity stage racing in temperate environmental conditions. In these conditions, cyclists were generally able to find opportunities to consume fluid and

carbohydrate to meet current guidelines. We consistently observed high $T_{GI\ peak}$ which merit further investigation.

5.2 Introduction

Hyperthermia, dehydration and reductions in carbohydrate content are all considered as contributors to fatigue during prolonged exercise, especially when performed in high ambient temperatures (161, 162). For example, it has been shown that cycling performance is compromised when athletes reach body temperatures in the range of 39 - 41°C (2, 10, 163). The primary mechanism for heat loss during intense exercise is the evaporation of sweat. However, an increase in sweat rate causes a decrease in total body water and may compromise exercise capacity. Indeed, fluid deficits of as little as 2% body mass (BM) have been shown to impair high intensity cycling performance in hot laboratory settings (164). Despite this, there is currently little information available with regards to the incidence of hyperthermic induced fatigue and the real-life drinking practices of athletes in the field, especially during competitions in cooler environmental conditions.

In order to maintain exercise performance, an athlete's race nutrition plan should deliver sufficient fluid to limit body mass losses to 2 - 3% BM during exercise (161). In addition, the plan should also provide carbohydrate for the brain and working muscle at rates that are dependent on the absolute exercise intensity and duration of the event, with suggested targets for carbohydrate intake being 30 - 60 $g \cdot h^{-1}$ for events of up to 2 - 3 h and up to 90 $g \cdot h^{-1}$ for ultra-endurance events of >3 h (110). The individual race nutrition practices of endurance athletes during competition are therefore likely to be a balance of their specific physiological requirements and their opportunities to consume fluids and carbohydrate during the event. As such, a consensus on guidelines for fluid and fuel intake during sport might be assisted by having better information on the real-life practices of athletes during a range of sporting activities and varying environmental conditions (165).

Road cycling tours involve multiple (typically 5 - 21) days of prolonged high-intensity racing over unique courses, resulting in considerable nutritional challenges (166). Intake during each day's racing is important in addressing acute requirements for fuel and fluid to support performance during each stage and also contributing to the cyclist's total (often extreme) nutritional requirements over the multiple days of racing. Indeed, during the grand tours, energy intake during racing must contribute a substantial proportion of the day's total energy requirements in order to allow the cyclist to meet the extreme demands of this style of racing. For example, in order to remain in approximate energy balance over the three weeks of the Tour de France it has been reported that cyclists consume 49% of the total daily intake (~25 $MJ \cdot d^{-1}$) during racing (167). Further, ~60% of the day's total fluid and carbohydrate intake was consumed during the race. While the consumption of carbohydrate (~94 $g \cdot h^{-1}$) met current guidelines for fuelling during ultra-endurance sports, there were insufficient data to address how well the ~4 L of fluid consumed during each stage matched immediate sweat losses or contributed to daily hydration status.

Cycling tours differ according to their total duration, as well as the number, length and style of race performed on each day. This variation may affect the acute nutritional requirements of each race, but also the total daily nutritional demands and the importance of race nutrition in meeting these needs. Therefore, it is of interest to focus more closely on the acute hydration and refueling practices of athletes within stages of a cycling tour, and their effect on fluid balance within the stage and across multi-day racing. Furthermore, we are currently unaware of any research examining core temperature during stage race cycling in cool weather or involving multiple races on the same day. Therefore the purpose of this study was to observe the voluntary fluid and carbohydrate intakes, along with the hydration, fluid balance and thermal stress, of highly competitive cyclists during a multiday stage race performed in temperate conditions.

5.3 Methods

5.3.1 Subjects

Ten internationally competitive male cyclists (mean ± SD; age 19.7 ± 0.8 y, BM 72.0 ± 6.1 kg, and height 180 ± 5 cm) of the Australian Institute of Sport Road Cycling squad were recruited to participate in this study. Prior to the study, subjects provided written informed consent and the experimental procedures were approved by the appropriate human research ethics committee. Subjects included two World Champions, a World Cup winner, two World Junior Champions, two UCI Continental Circuit stage winners (2.2 UCI Europe tour; 2.2 UCI Asia Tour), a representative at World Junior Road Championships and one Australian National Road Series race winner. Furthermore, one cyclist went on to win his first World Championship title six-weeks after the study. Only one rider featured in both races, however because the investigated tours were separated by >1 y, this athlete’s data are independently reported in acknowledgement of further growth, physical development and cycle racing experience. Both stage-races (described below) featured as part of the Australian National Road Series, and in each case the five cyclists represented all members of a single team.

5.3.2 Procedures and Protocol

5.3.2.1 Tour Details

Five cyclists competed in the 2009 Tour of Gippsland (Victoria, Australia), which involved 9 stages (55 ± 21 km; 71 sprints, 20 hill climbs) over 5 d. The stage race involved 5 road races and 4 criterium stages. One hundred and thirty eight cyclists started the tour, with 109 completing all stages. Five cyclists also participated in the 2010 Tour of Geelong (Victoria, Australia), involving 6 stages (66 ± 42 km; 49 sprints, 15 hill climbs) over 5 d and included 3 criteriums, 2 road races and 1 individual time trial. One hundred and six cyclists started the tour, with 44 completing all stages of racing.

5.3.2.2 Performance and Environmental Conditions

Cycling power output was recorded via a calibrated SRM power meter (Schoberer Rad Meβtechnik; Jülich, Germany) fitted to the subject's bicycle. Prior to the commencement of each stage, the zero offset of the SRM crank was set according to the manufacturer's instructions. Following the event, individual finish place and stage time were accessed via official race results. Both stage races were held during the Australian winter months of July and August during each respective year. Environmental conditions (ambient temperature and relative humidity) were recorded at the start and finish of each stage, using a Kestrel® 4000 Pocket Weather Tracker (Nielsen Kellerman, Boothwyn PA).

5.3.2.3 Body Temperature and Thermal Comfort

Cyclist's peak gastrointestinal temperature ($T_{GI\ peak}$) was monitored via wireless transmission from an ingestible sensor (CorTemp; HQInc, Palmetto, Florida, USA) to a data recorder within a neoprene pouch in each rider's jersey pocket. Preliminary field trials with these athletes indicated that passing of the sensor from the gut occurred in as few as 7.5 h. Therefore, sensors were ingested before breakfast on each race-day morning, allowing 4.5 - 9.5 h for the sensor to pass sufficiently through gastrointestinal tract. Races contested within 4.5 – 6.0 h of ingesting the temperature sensor were all criterium events, which are typically fast and dynamic with limited opportunities for cyclists to drink. On this basis we feel confident that beverage ingestion would have minimal influence on T_{GI} readings as has been noted as a limitation of this technique (168). Prior to each tour, all sensors were calibrated in a water bath across the expected physiological range (36 - 42°C). Subjective ratings of thermal sensation (122) were recorded immediately before and after each stage.

5.3.2.4 Hydration and Body Mass

On all race days, a 'first-waking' sample of urine was analysed for the determination of specific gravity (USG) using a portable refractometer (UG-α, Atago, Tokyo, Japan). USG greater than 1.020 were regarded as being one sign of hypohydration (169). Body mass was measured immediately before and after each stage using portable scales that were placed on a standard base and sensitive to 50 g (UC-321, AND Australasia, Adelaide, Australia). Subjects were weighed fully clothed in race attire (e.g., cycling knicks, jersey, undershirt, socks, shoes, gloves, helmet, cap, vest, food, core temperature data recorder). Estimations were made regarding the amount of moisture trapped in shoes and clothing during racing on dry weather stages, based on measured changes in clothing weighed before and after stages on multiple occasions. Appropriate care was undertaken to ensure that each cyclist was re-weighed after the race with the same clothing that had been worn pre-race.

5.3.2.5 Fluid Balance and Carbohydrate Intake

Immediately after each stage, cyclists recalled volumes and types of fluid and food consumed throughout the race, which were notated according to a field protocol established by Ebert, Martin, Stephens, McDonald & Withers (170). Race nutrition consisted of bidons (drink bottles) filled to a standard volume (650 ml) with either a commercially available sports drink (Gatorade; Pepsico Australia, NSW, Australia) or water, as well as sports bars (PowerBar® Performance Bar, PowerBar®, Berkeley, California, USA), gels (PowerBar® Gel), bananas and pre-packaged cakes. Carbohydrate content of foods and fluids was determined via nutritional information contained on packaging or FoodWorks Professional software (Xyris Software, Queensland, Australia). Fluid loss and percentage change in body mass was determined from the reduction in BM during each stage, after correction for the volume of fluid ingested, as previously detailed by Ebert et al. (170). Due to heavy rainfall during several stages of the Tour of Geelong which created large errors associated with accounting for additional water and/or mud stored in clothing, the data were deemed inaccurate and excluded from analysis.

5.3.3 Statistical Analysis

These data are field observations, which were compared with contemporary guidelines. They are reported as mean ± SD to describe group characteristics, and the prevalence of individual observations that met or failed to meet recommendations. Pearson product-moment correlation coefficients were used to determine relationships between selected variables of interest. Changes in BM from pre- to post-race, and day 1 to day 5 of each tour were calculated and differences were determined using a Student’s T-test. For analysis, significance was accepted at the level where $P < 0.05$.

5.4 Results

5.4.1.1 Environmental Conditions

The mean ambient temperature and relative humidity was 15.8 ± 1.4°C and 54 ± 12% r.h. during the stages of the Tour of Gippsland, and 13.2 ± 2.1°C and 80 ± 8% r.h. during the Tour of Geelong.

5.4.1.2 Performance

The stage-race characteristics of the Tour of Gippsland can be found in Table 5.1. Cyclists completed all stages of the race with performance outcomes including overall General Classification results (accumulated time for each stage) ranged from 1st – 97th placing, with wins in Criterium and Young Rider classifications, and 5 stage wins by two cyclists. The mean power output of one rider was 359 W during criterium racing and 292 W during road racing inclusive of stages 2 - 8. Table 5.2 summarises the race characteristics of the Tour of Geelong. Cyclists completed all stages of the race and performance outcomes including overall General Classification results ranging from 1st – 17th placing, including 3 stage wins by two cyclists.

5.4.1.3 Body Temperature

Due to technical malfunctions and passing of core temperature sensors, T_{GI} data were recorded on 39 out of 45 stages during the Tour of Gippsland with $T_{GI\ peak}$ during racing being 38.9 ± 0.7°C, and 67% of observations being >39°C (Figure 5.1a). During the Tour of Geelong, gastrointestinal data were collected on only 15 out of 30

Table 5.1 Stage-race characteristics: Tour of Gippsland

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**Stage 7**	**Stage 8**	**Stage 9**
Distance (km)	51.5	57.7	28.5	75.3	36.0	88.3	33.0	76.8	44.0
Winner's time (h:min:s)	1:18:00	1:28:36	0:37:34	1:52:17	0:49:04	2:20:38	0:47:50	1:48:44	0:58:57
Course profile	Flat	Rolling	Flat	Rolling	Flat	Rolling	Flat	Rolling	Flat
Race type[A,B]	Road Race	Road Race	Criterium	Road Race	Criterium	Road Race	Criterium	Road Race	Criterium
Ambient temperature (°C)	16.2	15.4	15.2	14.9	15.9	16.6	13.0	16.4	18.3
Relative humidity (%)	56.1	62.4	62	53.9	49.8	39	77	46	42
Mean power output (W)*	-	293	365	272	338	310	373	291	-

*Mean power was taken from one cyclist's SRM. [A]Road Races involved competing riders, who started simultaneously from a predetermined start point, to cycle over a set course of roads to a predetermined end point (not necessarily the same location) with winner being the first rider to cross the finish line. [B]Criterium races involved competing riders, who started simultaneously, to cycle over a set number of laps of a closed short circuit (public roads closed to normal traffic), with the winner being the first to cross the start/finish line without having been 'lapped'.

Table 5.2 Stage-race characteristics: Tour of Geelong

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Distance (km)	48.0	79.6	63.0	20.0	143.1	45.0
Winner's time (h:min:s)	1:04:50	1:57:17	1:26:44	0:24:48	3:43:02	1:04:17
Course profile	Flat	Rolling	Flat	Flat	Rolling	Flat
Race type[C]	Criterium	Road Race	Criterium	Individual Time Trial	Road Race	Criterium
Ambient temperature (°C)	10.6	11.0	14.4	13.4	13.5	16.2
Relative humidity (%)	83	90	79	79	65	82

[C] Individual time trial races involved competing riders to race alone (drafting not permitted) over a set course with individual start times at equal time intervals, with the winner being the rider with the fastest time.

possible occasions. Data were collected on 4 of the 5 cyclists, with one only recording one data trace (Cyclist 9). $T_{GI\ peak}$ during racing was 39.3 ± 0.4°C, with 73% of observations being >39°C (Figure 5.2). Subjective ratings of thermal comfort during each stage were 4.7 ± 0.9 (where a score of 5 = *warm*) during the Tour of Gippsland, and 3.4 ± 1.5 (where a score of 3 = *cool* and 4 = *comfortable*) during each stage of the Tour of Geelong.

5.4.1.4 Hydration and Body Mass

USG from first-waking samples on Days 1 - 4 of the Tour of Gippsland was 1.023 ± 0.006, with 12 of 20 samples, including 3 from Day 1, recording values >1.020. On race days 1 - 5 of the Tour of Geelong, cyclists presented in the morning with USG readings of 1.017 ± 0.005. No samples >1.020 were reported on day 1, but 6 of the 20 samples from days 2 - 5 recorded values >1.020. When all stages of the Tour of Gippsland were combined, the change in body mass from pre- to post-race was -1.3

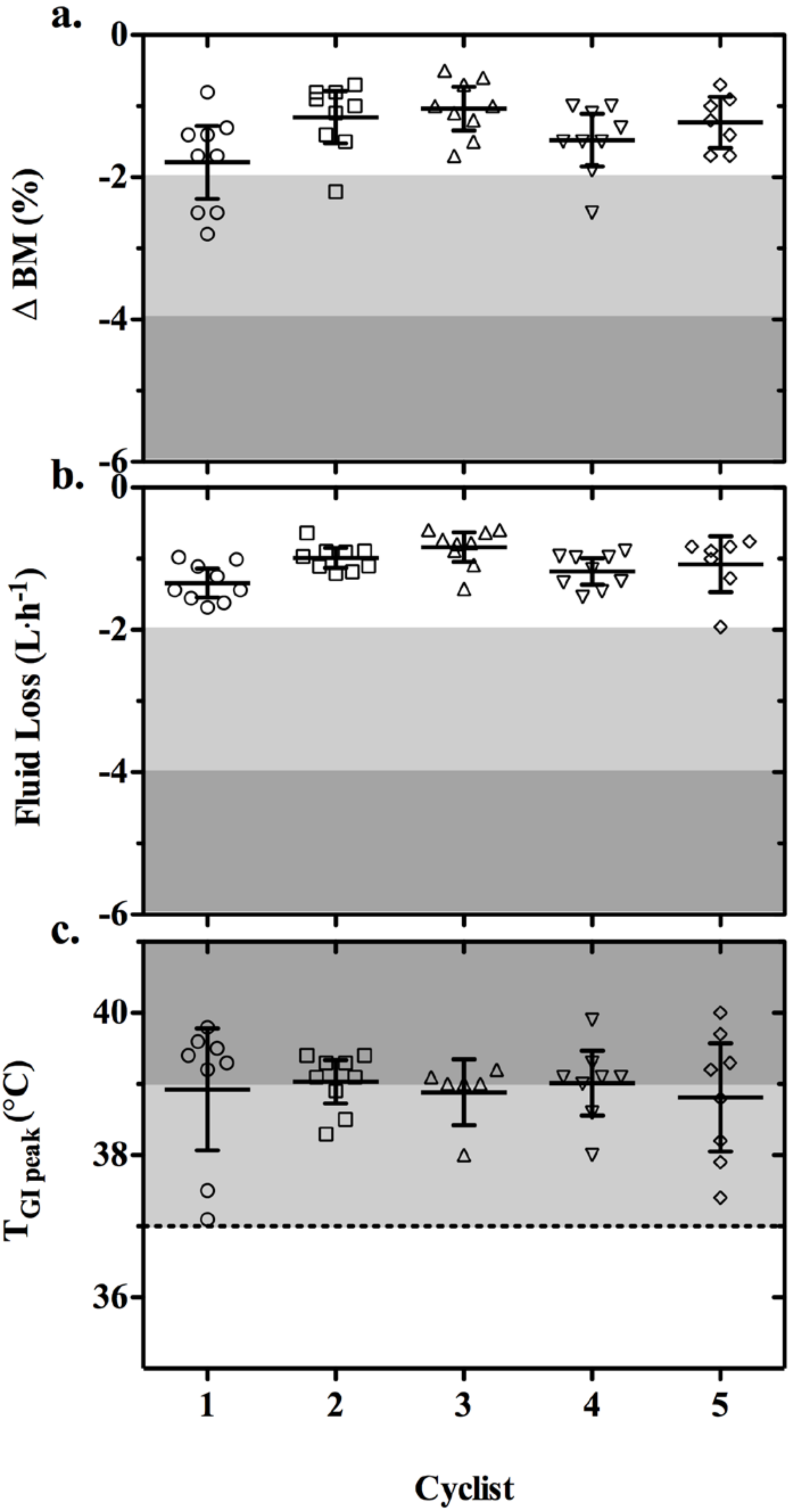

Figure 5.1 Percentage changes in body mass (a), fluid loss (b), and peak gastrointestinal temperature (c) during the 2009 Tour of Gippsland.

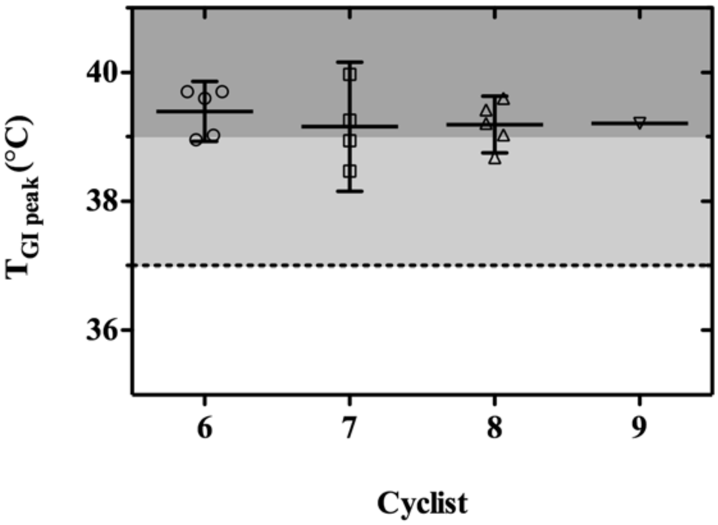

Figure 5.2 Peak gastrointestinal temperatures during the 2010 Tour of Geelong.

± 0.2% BM (range: -0.5 to -2.8%, $P < 0.001$; Figure 5.1b), with an estimated fluid loss of 1.1 ± 0.3 $L \cdot h^{-1}$ (range: -0.6 to -2.0 $L \cdot h^{-1}$; Figure 5.1c). The change in BM was -1.5 ± 0.3% ($P < 0.001$; $n = 19$) for road stages and -1.1 ± 0.2% BM ($P < 0.001$; $n = 24$) for criterium stages. Change in pre-race BM from day 1 to day 5 was -1.1 ± 1.0% ($P = 0.06$) for the Tour of Gippsland and -0.4 ± 1.2% ($P = 0.49$) for the Tour of Geelong.

5.4.1.5 Fluid Balance and Carbohydrate Intake

Table 5.3 summarises intake of fluid and carbohydrate during stages of both tours, differentiating between the types of races and noting mean values across all cyclists as well as the subgroup of cyclists who consumed fluid or food during a stage. During the Tour of Gippsland ($n = 45$), there were positive correlations between the absolute volume of fluid consumed during each stage and stage distance ($r = 0.82$,

Table 5.3 Nutrient consumption rate during racing

	Tour of Gippsland		**Tour of Geelong**	
	Mean of all cyclists	**Mean of cyclists who consumed nutrients during stage**	**Mean of all cyclists**	**Mean of cyclists who consumed nutrients during stage**
Fluid Consumption				
Road Race	410 ± 189 ml·h^{-1} (n=25)	410 ± 189 ml·h^{-1} (n=25)	558 ± 145 ml·h^{-1} (n=10)	558 ± 145 ml·h^{-1} (n=10)
Criterium	181 ± 198 ml·h^{-1} (n=20)	241 ± 195 ml·h^{-1} (n=15)	237 ± 220 ml·h^{-1} (n=15)	274 ± 214 ml·h^{-1} (n=13)
Individual time trial	-	-	360 ± 501 ml·h^{-1} (n=5)	899 ± 188 ml·h^{-1} (n=2)
CHO Consumption				
Road Race	40.5 ± 24.2 g·h^{-1} (n=25)	44.0 ± 21.9 g·h^{-1} (n=23); 60%	64.2 ± 23.7 g·h^{-1} (n=10)	64.2 ± 23.7 g·h^{-1} (n=10); 58%
Criterium	11.1 ± 14.9 g·h^{-1} (n=20)	27.7 ± 8.6 g·h^{-1} (n=8); 48%	27.5 ± 25.0 g·h^{-1} (n=15)	29.4 ± 24.7 g·h^{-1} (n=14); 48%
Individual time trial	-	-	46.0 ± 46.5 g·h^{-1} (n=5)	76.7 ± 28.2 g·h^{-1} (n=3); 86%

CHO = carbohydrate. Data presented as mean ± SD (n); % CHO as solid.

very large) and the hourly rate of fluid intake and stage distance (r = 0.55, *moderate*). On all but five occasions, during criteriums (n = 15) cyclists consumed fluid during racing with an estimated fluid intake of 0.24 ± 0.19 $L\cdot h^{-1}$. Mean fluid intake during road stages (n = 25) was 0.41 ± 0.19 $L\cdot h^{-1}$, which correlated with cyclists' individual race time (r = 0.64, *large*). There was also a positive correlation (r = 0.72, *very large*) between the estimated fluid deficit and individual race time. During the Tour of Geelong (n = 30), there were also positive correlations between stage distance and fluid volume (r = 0.92, *almost perfect*) and rate of fluid intake (r = 0.42, *small*). On all but two occasions during criterium stages (n = 13), cyclists consumed fluid during racing with an estimated fluid intake of 0.27 ± 0.21 $L\cdot h^{-1}$. Mean fluid intake during road stages (n = 10) was 0.56 ± 0.14 $L\cdot h^{-1}$, which correlated with individual race time (r = 0.90, *almost perfect*). Only two cyclists, ranked 2nd and 3rd in the team during the individual time trial, consumed fluid during stage 4, with volumes of 325 ml and 490 ml respectively.

On 14 occasions (12 during criteriums and 2 during road stages) during the Tour of Gippsland, no carbohydrate was ingested during racing. However, when consumed, mean carbohydrate intake during criterium racing was 24 ± 7 g, equivalent to 28 ± 9 $g\cdot h^{-1}$, with results for road racing being 85 ± 47 g, equivalent to 44 ± 22 $g\cdot h^{-1}$. When cyclists consumed carbohydrate in the form of food or fluid during racing in the Tour of Geelong, the mean estimated carbohydrate intake was 29 ± 25 $g\cdot h^{-1}$ during criterium stages (n = 14), and 64 ± 24 $g\cdot h^{-1}$ during road races (n = 10). Stage 5 was the only road race stage where riders raced >3 hr, with all riders consuming a mean rate of 80 ± 15 $g\cdot h^{-1}$. Only the top three team-ranked cyclists in the individual time trial ingested energy from fluid and/or food during stage 4, which was estimated to contain 27, 46 and 27 g carbohydrate respectively. When carbohydrate was consumed during racing in both tours, the percentage that was ingested in the form of solid food was ~59% for road races, 48% for criteriums and 85% for the individual time trial.

5.5 Discussion

This study collected novel data on fluid balance, voluntary ingestion of fluid and carbohydrate and thermoregulatory characteristics of highly competitive cyclists during two multi-day stage races undertaken in temperate conditions. The major findings from this study are: i) mean changes in body mass, from pre- to post-race during stages were *small* (1.3%), with deficits greater than 2% BM occurring on only five out of 43 measured occasions, ii) some cyclists chose to consume no fluids during stages involving criterium or individual time trial formats, but fluid intake always occurred during road racing, iii) there were strong correlations between fluid intake and distance across all formats of racing (r = 0.82, *very large* and r = 0.92, *almost perfect*), iv) although cyclists did not consume carbohydrate during some race formats (23% of all stages, predominately criterium formats), during most races, subjects consumed carbohydrate at rates which met the new guidelines (110) based on event duration, and v) there was consistent observation of a $T_{GI\ peak}$ >39˚C during stages of the Tour of Gippsland (67%) and Tour of Geelong (73%) despite temperate environmental conditions.

This study is the first to report T_{GI} of cyclists during stage race cycling, and during races held in temperate environmental conditions. Our findings report a high percentage of observations of $T_{GI\ peak}$ >39°C, which are generally associated with hyperthermic fatigue (2, 10, 163). Despite this, subject's perceived thermal comfort was comfortable to warm during the various stages of the two tours. The incidence of such high body temperatures are likely to be related to exercise intensity and tactics which dictate which riders need to achieve sustained or repeated high-intensity efforts during a race. It was noted however that due to the temperate environment cyclists tended to start each stage wearing several layers of clothing. It is possible that this clothing may have reduced heat dissipation and contributed to the high $T_{GI\ peak}$ readings observed. However, these suggestions are speculative and require further investigation, as does the effect of such body temperatures on cycling performance in cooler conditions.

Guidelines for fluid intake during sport are highly topical, with various opinions on requirements needed to achieve a benefit to performance, and whether this should be achieved via a race nutrition plan (109) or dictated by thirst (171). What is not well appreciated in this debate, however, is that voluntary fluid intake is not only determined by desire or perceived need/benefit, but by the opportunity to consume fluid within the rules and logistics of a sport and the culture of drinking. Furthermore, the appropriateness of fluid intake should be judged against the specific needs of the individuals and situations under investigation rather than generic quantitative guidelines. In our study, which involved temperate environmental conditions and short- to moderate-length stages (~40 - 140 min), we observed that cyclists, who consumed fluid at mean intakes of 400 - 600 $ml \cdot h^{-1}$, were generally able to match fluid intake to sweat losses, as evidenced by few (~10%) stages resulting in a change in body mass greater than -2%.

Previous studies have observed fluid intake during stage race cycling of 4.1 L per stage (~500 to 1000 ml·h^{-1}) of the Tour de France (167), and 1.0 L·h^{-1} during the 2005 Tour Down Under (170). These stage races are typically performed in warm weather and despite the observation of higher rates of fluid intake, there is still evidence of larger fluid deficits being incurred across each stage, compared with the present study. Indeed, Ebert et al. (170) reported a mean change in body mass of -2 kg (-2.8% BM) during stages of the Tour Down Under, while others have reported that professional cyclists can lose 2.1 - 4.5 kg BM during a typical stage (172). Observations of stage races scheduled in more temperate environmental conditions report lower volumes of fluid ingestion, which are similar to those observed in this study. For instance, total fluid intakes of 1.26 ± 0.55 L (300 - 350 ml·h^{-1} over stages lasting 3.5 - 4.5 h) have been observed during the 1994 Vuelta Ciclista a España (Tour of Spain) (173) while rates of 0.4 L·h^{-1} have been observed by female cyclists during the 2005 Tour De L'Aude (France)(170).

While it is not possible to determine if the drinking behaviors of cyclists in the present study aided or impaired performance or if maintaining body mass within 2% BM was beneficial, data from this study provides some insight into strategies that are valued and practical to achieve during cycling. In the current study, we observed that an increased race distance was associated with a greater total fluid intake, and to a smaller extent, rate of intake while riding. The type of race format may have partially dictated nutritional behaviors, with overall intakes being lower and a greater number of cyclists choosing not to consume any fluids during criterium stages. This is understandable given the greater technical requirement and more aggressive tactical approach to criterium style racing, which would directly interfere with the cyclist's ability to consume fluids. Moreover, assuming cyclists begin in a euhydrated condition, any fluid consumption during such short events would be unlikely to improve performance. Likewise, opportunities to consume fluids during time trial cycling may be limited by the necessity to maintain a high intensity and the requirement to move from a streamline position in order to ingest fluids.

In contrast, fluid and food consumption is more easily achieved during road racing than other racing formats, with specific feed zones supplemented by regulations and a culture that allow riders to collect nutrition supplies from team cars. Nevertheless, studies often find that the fastest athletes in prolonged running and cycling races are often the most dehydrated or have drunk the least (170, 174). This is intuitive because these athletes are working at the highest intensities and are less inclined to sacrifice time or risks of gut upset to drinking from these feed zones or aid station. Contradictory to this, a relationship between fluid intake and finishing place was not observed within any given stage of the present study. In fact, in the Tour of Gippsland, where body mass changes over each stage were accurately determined, we found that the fastest finishers in each road stage incurred the *smallest* fluid deficits. It is likely that different characteristics are at play in some stage races, like those in our study. Here, team tactics allow cyclists who are deemed to have the best chance of winning, to ride within the slipstream of the *peloton* or their teammates for much of the race. This effect both reduces the relative power output for the same speed and allows them to receive race nutrition supplies from the team *domestiques*, thus meeting their fuel intake goals and better maintaining fluid balance. However, this represents the ideal opportunity and may be overturned by specific conditions (e.g., when the intensity is higher or while descending), or tactical issues (e.g., when the lead cyclist is vulnerable to attack, or is in a breakaway and has lost their support riders). Indeed, Garcia-Roves et al. (173) suggested that low fluid intakes in their study of three out of twenty Vuelta stages may have been partially explained by aggressive riding tactics.

As a final comment on hydration issues, we noted that despite generally matching fluid needs across each stage, cyclists found it challenging to maintain day-to-day hydration status, with about half of the morning urine samples showing a specific gravity consistent with *mild-moderate* dehydration (1.020 – 1.030) (175), particularly on the morning after a race day involving 2 stages. Given that subjects consumed meals and fluids between undertaking these morning measurements and racing, or between finishing one stage and undertaking the next on a single day, it is unlikely that cyclists commenced any stage with a concerning level of fluid deficit.

Cyclists in the current study ingested carbohydrate at a rate equivalent to ~30 $g \cdot h^{-1}$ during 50 - 65 min stages (predominantly criteriums). Contemporary guidelines suggest that the acute ingestion of carbohydrate is unlikely to provide additional muscle substrate during high intensity exercise lasting less than 1 h in duration, when subjects are in a fed state (161). However, It is likely that such carbohydrate ingestion would have been important in contributing to the high total energy intake required for multiple days of stage racing and possibly improving individual stage performance. Indeed frequent mouth contact with carbohydrate (periodic 10 s mouth-rinse every ~10 min) has been shown to enhance performance of a 1-h laboratory cycling time trial in well-trained cyclists, even when a pre-event meal high in carbohydrate had been consumed (176). In these circumstances, central mechanisms, involving stimulation of brain reward centers, may be responsible for enhanced pacing (177).

A pragmatic approach on strategies to promote high carbohydrate availability during exercise of longer duration (>1 h) is that the rate of ingestion should be scaled to the characteristics of the event and further guided by convenience and individual choice (110). During road race stages, our highly competitive cyclists consumed carbohydrate at a mean rate of 44 - 64 $g \cdot h^{-1}$, meeting the current recommendations of 30 - 60 $g \cdot h^{-1}$ (110). Furthermore, during the longest stage (Stage 5, 143 km) of the Tour of Geelong, they sustained a mean rate of intake of ~80 $g \cdot h^{-1}$ for ~4 h, which is also in line with the new recommendations that higher rates of intake are possible and beneficial for ultra-endurance exercise (110). These rates of carbohydrate ingestion are greater than have been previously reported during relatively long stage-races (170, 173). Nevertheless, they are in agreement with the reports of high rates of carbohydrate intake during the Tour de France (167), which incidentally formed part of the rationale for re-examining optimal carbohydrate intakes during sport (110).

In summary, this investigation provides novel information on voluntary ingestion of fluid and carbohydrate, and thermoregulatory characteristics of internationally competitive cyclists during a multiday stage race in temperate conditions. Cyclists in this study typically experienced only mild mismatches between fluid intakes and sweat rates, while achieving recommended rates of carbohydrate consumption during racing. However, there were differences in feeding strategies according to the format and tactics of racing. In the present study we consistently observed high peak gastrointestinal temperatures at magnitudes typically associated with hyperthermic-induced fatigue. Further research is required to determine the impact of elevated body temperature on cycling performance in temperature conditions.

CHAPTER 6 EFFECTS OF AMBIENT TEMPERATURE WITH AND WITHOUT PRACTICAL PRECOOLING AND CYCLING TIME TRIAL PERFORMANCE

6.1 Abstract

Purpose: To investigate whether precooling, using the combination of ice slurry ingestion and iced towel application, would be successful in enhancing high-intensity cycling time trial performance in temperate and hot conditions. **Methods:** Twelve well-trained male cyclists undertook four trials of a laboratory-based cycling time trial simulating the characteristics of the 2010 World Championship road cycling individual time trial event (45.6 km) in temperate (Temp; 21.2 ± 0.6°C, 54 ± 11% r.h.) or hot (Hot; 31.9 ± 0.7°C, 35 ± 7% r.h.) environmental conditions following precooling (PC) or seated rest (CON). The trials, separated by 3 - 7 d, were conducted in a randomised counterbalanced order. **Results**: CON_{Hot} was associated with a 7.8% reduction in power output (-23 W) and a 3.3% increase in performance time (+2:19 min) compared to CON_{Temp}. There was an observable effect on rectal temperature (T_{re}) before the commencement of the time trial following PC in both hot and temperate conditions. PC_{Hot} was associated with a 3.1% greater power output (7 W) and a faster performance time (52 s) compared to CON_{Hot}. The effect of PC_{Temp} compared with that of CON_{Temp} was unclear. **Conclusion:** Practical precooling was effective at reducing body temperature prior to exercise, which translated into a performance enhancement in hot, but not temperate conditions.

6.2 Introduction

The influence of ambient temperature on endurance cycling performance has been well documented (3, 10). Exercise performance may be compromised by increased thermoregulatory strain when exercising in warm conditions (i.e., >30°C) and reduced mechanical efficiency when exercising in cooler conditions (<4°C) (3). While optimal endurance cycling performance is typically observed in temperate environmental conditions (i.e., 11 to 23°C), high thermal strain may still occur, as evidenced by elevated rectal temperatures (~39°C) (2). Such laboratory-based observations have recently been validated in the field, whereby highly-trained cyclists were reported to consistently (>67% of observations) record peak gastrointestinal temperatures in excess of 39°C during competitive road cycling races held in temperate (13 to 16°C) conditions (Chapter Five). Despite these high core temperatures, the design of this observational study did not reveal the influence of high core temperatures on cycling performance.

Precooling prior to exercise resulting in hyperthermia has been shown to reduce deep body and/or skin temperatures, and subsequently increase the athlete’s capacity to store metabolic and environmental heat (14, 15, 145). Indeed, a number of studies in hot and/or humid laboratory conditions (30 - 40˚C, 20 - 80% r.h.) have shown improvements in exercise capacity (5, 52, 55, 56, 82) and sports performance (20, 24, 54, 59, 65, 69, 71) resulting from various external and internal precooling strategies. Furthermore, there is evidence to suggest that cycling performance is influenced by the degree to which a precooling protocol reduces body temperature (24). To date, the influence of precooling on exercise capacity in temperate conditions is unclear, with studies showing either enhanced (18, 23, 68) or no change in exercise capacity (22, 27, 58, 78, 80, 83, 84, 96, 97, 103, 115). However, a unifying theme in these latter studies is that it is unlikely that exercise protocols used generated sufficient thermal strain in order to effect performance. Furthermore, the majority of these studies (27, 58, 78, 80, 84, 103, 115) employed mild precooling treatment interventions, which had limited effect on deep body temperatures. A number of these studies (83, 84, 96, 97) involved intermittent sprint protocols, which often do not benefit from precooling interventions, even when exercising in warm conditions (145). By contrast, studies that have shown precooling to be effective in improving performance in temperate conditions have used exercise protocols that created hyperthermic conditions, but with impractical precooling strategies that would be unachievable in the field (i.e., intermittent cold air exposure; 0 - 5˚C, (18, 23, 68)). We have recently shown that a practical and logistically simple precooling strategy involving both internal and external cooling methods is effective in reducing core body temperature and improving exercise performance in the heat (Chapter 3). However, the influence of such cooling on performance in temperate conditions is currently unclear.

Therefore, the purpose of the present study was to examine the influence of a practical and logistically simple precooling strategy on simulated high-intensity cycling performance in hot and temperate environmental conditions. The warmer conditions were included in the study design to confirm that our unique cycling protocol, designed to simulate a real-life road cycling course, was sufficiently robust to allow expected performance differences to be detected in a reliable subject group.

Furthermore, the direct comparison of results under different environmental conditions and following exposure to precooling strategies was required to fully examine the effects of thermoregulatory challenges on pacing and performance of a cycling protocol involving variable work efforts as occurs in real life events. We hypothesized that i) performance of the cycling time trial would be impaired in hot compared to temperate conditions, ii) our precooling strategy would enhance time trial performance in hot conditions, and iii) precooling would also enhance time trial performance in temperate conditions since hyperthermia would be limiting to performance in the corresponding control trial.

6.3 Methods

6.3.1 Subjects

Twelve well-trained male A-grade cyclists (mean ± SD; age 31.9 ± 7.0 y, body mass (BM) 74.4 ± 5.1 kg, maximal aerobic power (MAP) 477 ± 34 W, peak oxygen consumption ($\dot{V}O_{2peak}$) 72.4 ± 6.4 $ml\cdot kg^{-1}\cdot min^{-1}$) were recruited from the local cycling community to participate in this study. Prior to commencement of the study, ethical clearance was obtained from the appropriate human research ethics committees. Subjects were informed of the nature and risks of the study before providing written informed consent. Prior to the study, subjects completed a medical questionnaire and had no prior history of heat intolerance or current injury or illness.

6.3.2 Study Overview

On separate days following an incremental exercise test to exhaustion, subjects performed a total of four 45.6-km experimental cycling time trials (described below) in hot (31.9 ± 0.7°C, 35 ± 7% r.h.) or temperate (21.2 ± 0.6°C, 54 ± 11% r.h.) environmental conditions, following precooling (PC) or seated rest (CON). Trials were conducted in a randomized counterbalanced order. Subjects were exposed to the respective ambient conditions for 90 min prior to and throughout the entire 45.6-km simulated cycling time trial.

On two occasions prior to the cycling time trial (i.e., at 21°C and 32°C), subjects were exposed to an established combined external and internal precooling technique, whereby iced towels were applied to the subject's skin while ingesting fluid in the form of an ice slushie made from sports drink. The precooling method used in this study, as previously described (65), commenced 60 min prior to the start of the trial (t = -60 min) and was applied for a period of 30 min. On the other two occasions, subjects remained seated in the respective ambient conditions and received no precooling. Experimental trials were separated by 3 - 7 d with a consistent recovery time between trials for each subject.

Before commencing the experimental trials, subjects visited the laboratory on a number of occasions to perform an incremental test (see below) and familiarisation time trials. Subjects performed familiarisation of the 46.5-km cycling time trial on a magnetically braked ergometer (Velotron, Racermate Inc., Seattle, WA, USA) in 21°C and 32°C ambient conditions. Commencement of the experimental phase took place toward the end of the Australian Summer (January to April), such that all subjects were naturally acclimatized to, and experienced at cycling in hot conditions.

6.3.2.1 Incremental Cycling Test

Prior to the first experimental trial, subjects performed a progressive maximal exercise test on a cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). After a 5-min warm-up at 150 W, the test protocol started at 175 W and increased 25 W every 60 s until volitional exhaustion. Maximal aerobic power (MAP) was determined as the power output of the highest stage completed. If the subject finished partway through a 60 s stage, MAP was calculated in a pro-rata manner. Expired gases were collected into a calibrated and customized Douglas bag gas analysis system, which incorporated and automated piston that allowed the concentrations of O_2 and CO_2 (AEI Technologies, Pittsburgh, PA) and the volume of air displaced, to be quantified. The operation and calibration of this equipment have been described previously (124). Peak oxygen consumption ($\dot{V}O_{2peak}$) was calculated as the highest oxygen consumption recorded over a 60 s average.

6.3.2.2 Experimental Time Trials

Subjects followed a standardised pre-packaged diet and training schedule for 24 h prior to each experimental trial. The standardised diet was supplied in the form of pre-packaged meals and snacks, providing 8.0 ± 0.3 $g \cdot kg^{-1}$ BM carbohydrate (CHO); 1.5 ± 0.0 $g \cdot kg^{-1}$ BM protein; 1.5 ± 0.1 $g \cdot kg^{-1}$ BM fat, with a total energy content of 222 ± 7 $kJ \cdot kg^{-1}$ BM. Subjects refrained from any intake of caffeine and alcohol over this period. Individualised menus were prepared accounting for food preferences using FoodWorks Professional Edition (Version 6.0, Xyris Software, Brisbane, Australia), as described previously (158). Subjects were provided with all foods and drinks in portion-controlled packages for the first 20 h of the standardisation period and were given verbal and written instructions on how to follow the diet. Subjects were allowed to undertake light exercise on the day prior to each trial and were asked to repeat this for subsequent trials. Compliance to the diet and exercise protocol was determined from a checklist kept by each subject and presented on arrival to the laboratory prior to each trial. The subject's 'first-waking' urine sample was also analyzed for the determination of specific gravity to ensure the cyclist attended the laboratory for each trial in a similar state of hydration.

For each experimental trial subjects were required to cycle a 45.6-km time trial on the Velotron cycle ergometer. The measurement error for cycling time trials during laboratory protocols such as this has been established as 1.7%, as described previously (65). The course profile for this time trial was a simulation of the 2010 Melbourne World Championship time trial course and was based on global positioning system (GPS) mapping data (road altitude and distance) provided by the official event profiler (Figure 6.1). All experimental trials were carried out in the afternoon, to mimic the schedule of the 2010 World Championships cycling time trial. Approximately 2 h prior to a trial (t = -120 min) subjects consumed the last of their standardised 'pre-race meal' which provided 1.5 $g \cdot kg^{-1}$ BM CHO. Subjects then voided their bladder, after which BM was recorded, and then inserted a single-use thermal probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical Inc., St Louis, MO, USA) 12 cm beyond the anal sphincter, and fitted a chest strap for a Polar S810i heart rate (HR) monitor (Polar Electro OY, Kempele, Finland) and skin thermistors. Changes in rectal temperature (ΔT_{re}) at the end of the precooling phase (t = -30 min) and at the end of the warm up phase (t = 0 min) were used to reflect the effectiveness of the precooling treatment and the potential differential for heat storage at the commencement of the time trial. Changes in rectal temperature were categorized as either *small* (<0.3˚C), *moderate* (0.3-0.6˚C), *large* (0.6-0.8˚C) or *very large* (>0.8˚C) based on our previous work (65).

6.3.2.3 Data Collection

Skin temperature (T_{sk}) was sampled and logged via dynamically calibrated wireless iButtons® (DS1922L Thermochron iButton®, Maxim Integrated Products, Inc., Sunnyvale, CA, USA). The operation and calibration of these devices have been described elsewhere (178). The iButtons® were programmed before their application on the subject's skin, as outlined by the manufacturer, with resolution set at 0.0625°C, sampling rate at 30-s intervals, and time-clock synchronised with that of a laptop computer. Four iButtons® were attached directly onto the skin with breathable adhesive tape in the same anatomical locations (chest; T_{chest}, forearm; $T_{forearm}$, thigh; T_{thigh}, and calf; T_{calf}) for each trial. Caution was taken to ensure a similar amount of tape was used to affix the iButton® to the skin each time. Mean skin temperature was calculated according to the equation established by Ramanathan (179), where mean $T_{sk} = 0.3 \times (T_{chest} + T_{forearm}) + 0.2 \times (T_{thigh} + T_{calf})$. Rectal temperature was used as a surrogate measure of core temperature (T_c) and together with, mean body temperature (T_b) was calculated according to the equation established by Schmidt and Bruck (22), where mean $T_b = 0.87\ T_c + 0.13$ mean T_{sk}.

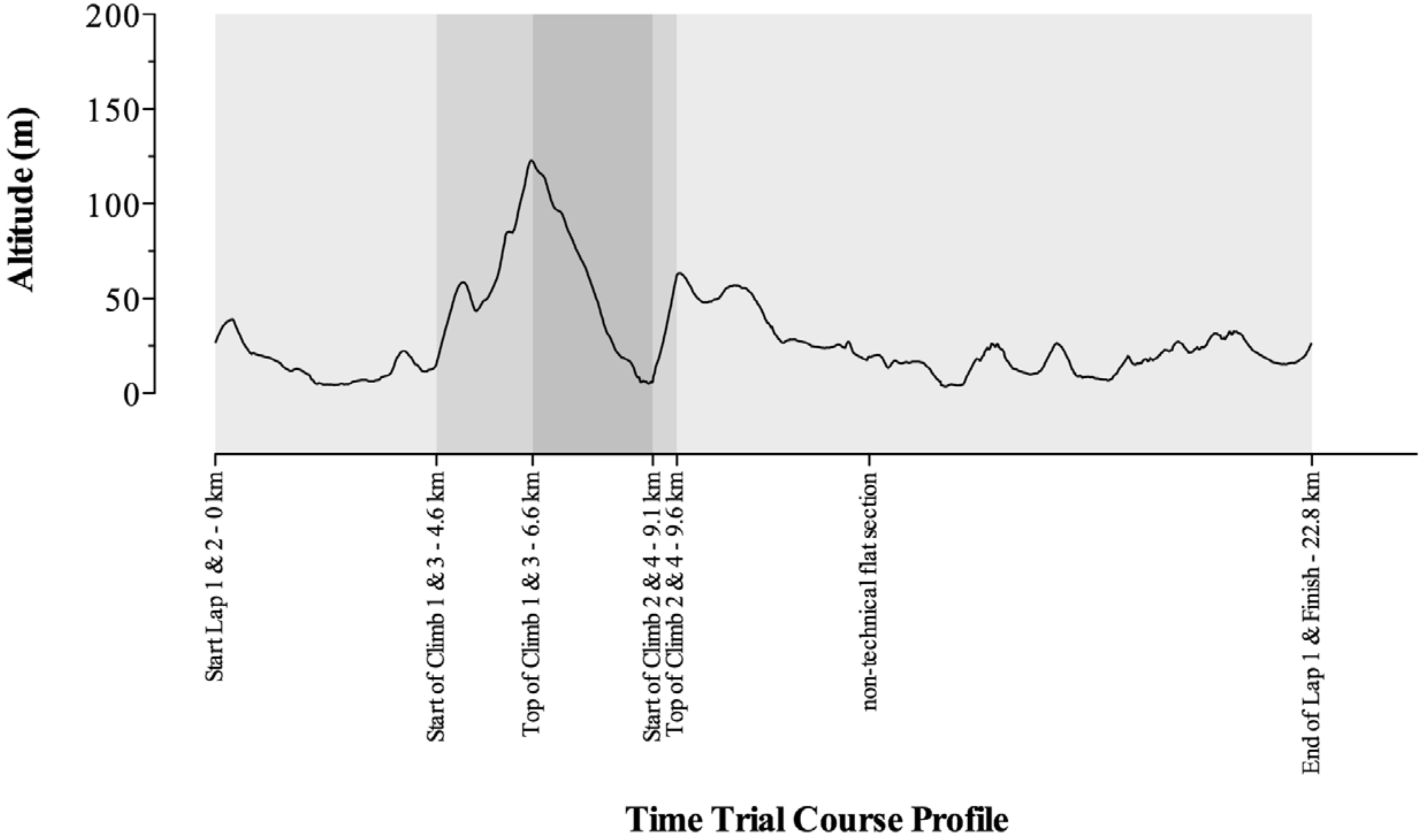

Figure 6.1. 2010 World Road Cycling Championships individual time trial course profile. Points of interest on the course are identified on the X-axis. Shading is used to denote different sections of the course, and include flat (light gray), uphill (moderate gray), and downhill (dark gray) terrain types.

Ratings of thermal comfort, gastrointestinal comfort, T_{re} and HR were recorded before entering the environmental chamber and every 5 min during 30 min of passive rest in the environmental chamber (heat stabilisation; t = -90 to -60 min). At t = -60 min, t = 30 min, immediately prior to, and immediately following the trials, subjects were required to void their bladder. Urine was weighed and analysed for specific gravity. Cyclists consumed 560 ± 343 g water throughout the stabilisation and warm-up period (t = -90 to 0 min). On two occasions (PC_{Temp} and PC_{Hot} trials), following the completion of the stabilisation phase, subjects also consumed 926 ± 116 g of an ice slurry (slushie) containing 6% CHO, which was equivalent to 12.5 $g \cdot kg^{-1}$ BM, providing a CHO intake of 56 g (0.75 $g \cdot kg^{-1}$ BM). The slushie was given in two ~7 $g \cdot kg^{-1}$ BM boluses and subjects were given 15 min to consume each bolus while wearing iced towels, as previously described (65). During the control trials (CON_{Temp} and CON_{Hot} trials) subjects received no cooling intervention. Throughout the stabilisation and intervention period, subjects were asked to provide ratings of stomach fullness, as previously described (65).

Following stabilisation and precooling, subjects completed a standardised 20-min warm-up on the Velotron ergometer. The cycle ergometer was fitted with a calibrated (125) SRM cycling power meter (scientific version, 8 strain gauge, Schoberer Rad Meβtechnik; Jülich, Germany), which was set to sample at 1-s intervals. The warm-up consisted of 3 min at 25% MAP, 5 min at 60% MAP and 2 min at 80% MAP, which was performed twice, and based on the protocol used by elite time trial cyclists prior to competition. The final 10 min before the start of the time trial allowed subjects to complete their own preparations. During this time, subjects were provided with standard pre-race instructions and the zero offset of the SRM crank was set according to manufacturer's instructions.

Feedback provided to the subject was limited to distance covered (km), cycling gear-ratio (12 – 27 / 48 - 54), road gradient (%) and instantaneous velocity ($km \cdot h^{-1}$; Velotron 3D Software, RacerMate Inc., Seattle, WA, USA). Subjects were provided with 497 ± 119 g fluid containing 6% CHO (Gatorade, Pepsico Australia, Chatswood, Australia), which provided a further CHO intake of 30 g, at 6.6 and 29.4 km (the top of the first climb on each lap) and at 13.6 and 36.4 km (non-technical flat section; Figure 6.1). These sections of the course simulated the ideal time to consume fluid, based on the experience of professional cyclists while training on the actual course. On the first trial, subjects were given a total of 165 ml fluid at each of the points of interest, and were permitted to drink *ad libitum* for one kilometer at each of these distances. The volume that was consumed on the first trial was measured and repeated for subsequent trials. Drinks were removed from ice storage at the commencement of the time trial and left in the heat chamber to simulate drink temperatures that would be experienced in race conditions. To further replicate competition, the cyclist was positioned in front of a large industrial fan (750 mm, 240 V, 50 Hz, 380 W, model Number: N11736, TQ Professional), which was adjusted to simulate flat, uphill or downhill wind speeds. Specifically, the fan was fixed on *low* to simulate 25 $km \cdot h^{-1}$ wind speed for climbing sections (4.6 to 6.6 km, 9.1 to 9.6 km, 27.4 to 29.4 and 31.9 to 32.4 km), *moderate* to simulate 40 $km \cdot h^{-1}$ wind speed for flat sections (0 to 4.6 km, 9.6 to 27.4 km and 32.4 to 45.6 km), and *high* to simulate 65 $km \cdot h^{-1}$ wind speed for descending sections of the course (6.6 to 9.1 km and 29.4 to 31.9 km).

Throughout the trials, heart rate and rectal temperature were recorded every 2 min, while self reports of rating thermal sensation (122), stomach fullness (five-point Likert scale) and perceived exertion (RPE) (123) were recorded at approximately 5-10 km intervals. Split times, velocity and power output data were collected for each trial, with periods of interest indicated in Figure 6.1. Specifically, each lap was broken into two flat segments, two uphill segments and one downhill segment. On the completion of the time trial, subjects were asked to report their effort, motivation, sensation and comfort, as reported previously (65).

6.3.3 Statistical Analysis

Urine specific gravity, body mass changes, urine volume and post-trial subjective ratings were compared between trials (i.e., CON_{Temp} PC_{Temp}, CON_{Hot} and PC_{Hot}) using a one-way analysis of variance (ANOVA). A two-way (trial × time) repeated measures ANOVA was used to determine significant differences in dependent variables (i.e., rectal temperature, mean skin temperature, mean body temperature, heart rate, thermal comfort and stomach fullness) between trial means at each time point. If a significant main effect was observed, pairwise comparisons were conducted using Newman-Keuls *post hoc* analysis. These statistical tests were conducted using Statistica for Microsoft Windows (Version 10; StatSoft, Tulsa, OK) and the data are presented as means and SD. For analysis, significance was accepted at $P < 0.05$.

The performance data from the four trials were analysed using the magnitude-based inference approach recommended for studies in sports medicine and exercise sciences (128). A spreadsheet (Microsoft Excel), designed to examine post-only crossover trials, was used to determine the clinical significance of each treatment (available at newstats.org/xPostOnlyCrossover.xls), as based on guidelines outlined by Hopkins (159). Performance data are represented by time trial time and power output during the various segments of the course, and are represented as means ± SD. The magnitude of the percentage change in time was interpreted by using values of 0.3, 0.9, 1.6, 2.5 and 4.0 of the within-athlete variation (coefficient of variation) as thresholds for *small*, *moderate*, *large*, *very large* and *extremely large* differences in the change in performance time between the trials (128). These threshold values were also multiplied by an established factor of -2.5 for cycling (160), in order to interpret magnitudes for changes in mean power output. The typical variation (coefficient of variation) for road cycling time trials has been previously established as 1.3% by Paton and Hopkins (129), with the smallest worthwhile change in performance time established at 0.4% (130), which is equivalent to 1.0% in power output. These data are presented with inference to the true value of a precooling treatment effect on simulated cycling time trial performance. In circumstances where the chance (%) of the true value of the statistic is >25% *likely* to be beneficial (i.e., faster performance time, greater power output), a practical interpretation of risk (benefit:harm) is given. An odds ratio (OR) of >66 was used to establish that the benefit to performance time gained by using one strategy outweighed any potential harm (in performance time) that could result.

6.4 Results

6.4.1.1 Performance

Performance time (h:min:s) and power output (W) for the entire time trial, for each of the two laps and for each of three terrain types (i.e., flat, climb and descent sections) of each time trial is presented in Table 6.1 (Appendix J). Overall, CON_{Hot} was associated with a 7.8% reduction in power output (-23 W, $P < 0.01$) and a 3.3% increase in the time taken to complete the time trial (+2:19 min, $P < 0.01$) compared with CON_{Temp}, with true likely effects ranging from *large* to *very large* performance impairments (Table 6.1). This impairment was associated with lower power outputs (-1.7 to -14.7%) and slower performance times (+1.1 to 5.6%) that were accumulated over all sections of the course. The chance of impairment to performance time and power output was *almost certain* (>99%).

Overall, PC_{Hot} was associated with a 3.1% greater power output (9 W, $P = 0.07$) and a 1.2% faster performance time (52 s, $P = 0.13$) compared to CON_{Hot}. Although these differences failed to reach the traditional level of statistical significance, our interpretation using a magnitude-based inference approach revealed *trivial* to *large* improvements in performance (Table 6.1). The chance of a performance time benefit was quantified as 85% *likely*, with an acceptable level of risk (OR=191) as the chance of impairment was <5%. Indeed, on lap 2, PC_{HOT} was associated with a 4.8% higher power output (14 W, $P = 0.01$) and a 1.8% faster performance time (40 s, $P = 0.04$) compared with CON_{Hot}, with true likely effects ranging from *small* to *large* benefits. The chance of performance time benefit on lap two was *likely*, with <1% chance of impairment.

The overall effect of PC_{Temp} compared with CON_{Temp} was *unclear* for a change in power output (0.9 ± 1.4%, $P = 0.27$) and performance time (0.2 ± 0.8%, $P = 0.73$). There was, however, a 2.3% lower power output (8 W, $P = 0.04$) and a 1.5% slower performance time (6 s, $P = 0.03$) following PC_{Temp} on the first flat section of the course, with true likely effects ranging from *small* to *large* impairments, when compared to CON_{Temp}. The chance of performance time impairment was *likely*, with a <1% chance of performance time improvement.

6.4.1.2 Hydration Markers

Results of the analyses of ‘first waking’ urine samples on the morning of each trial, mean changes in body mass and urine volume produced during the trials are presented in Table 6.2. Although there were changes in body mass between trials when subjects received precooling treatments (i.e., PC_{Temp} and PC_{Hot}) when compared with corresponding control treatments (i.e., CON_{Temp} and CON_{Hot}, $P < 0.001$), there were no differences between trials in the volume of urine produced from -90 min before the start until immediately after completion of the time trial in all trials.

6.4.1.3 Temperature and Heart Rate

Temperature (rectal, mean skin and mean body) towards the end of the stabilisation phase (t = -65 min) was considered to be the baseline value for each trial. At this time point, there were no differences in respective temperatures between trials ($P > 0.05$). Figure 6.2 shows the relative change in rectal temperature, the change in mean skin and mean body temperature from baseline, during each trial.

Table 6.2 Measures of hydration status.

	$\mathbf{CON_{Temp}}$	$\mathbf{PC_{Temp}}$	$\mathbf{CON_{Hot}}$	$\mathbf{PC_{Hot}}$
Urine Specific Gravity	1.016 ± 0.004	1.017 ± 0.003	1.016 ± 0.004	1.016 ± 0.004
Δ BM^{A} (kg)	-1.12 ± 0.70	0.87 ± 0.51*	-1.65 ± 0.83	0.76 ± 0.66*
Δ BM^{A} (%)	-1.48 ± 0.82	1.18 ± 0.70*	-2.16 ± 0.95	1.03 ± 0.86*
Total urine volume^{B} (ml)	790 ± 257	646 ± 333	571 ± 275	470 ± 303

^{A} represents n=10; from entrance to the heat chamber to the completion of the time trial, ^{B} represents urine volume collected from -90 min prior to the time trial until immediately after the time trial, *represents effect of precooling (i.e., PC_{Temp} and PC_{Hot}) to corresponding controls (i.e., CON_{Temp} and CON_{Hot}, $P<0.001$). All data presented as means ± SD.

Relative change in rectal temperature towards the end of precooling and during the warm up was greater in the precooling trials (-0.70 ± 0.20˚C for PC_{Temp}; *Large,* -0.54 ± 0.22˚C for PC_{Hot}; *Moderate*), such that the relative rectal temperature was lower compared with the corresponding control trial (-0.19 ± 0.14˚C for CON_{Temp} and 0.02 ± 0.13˚C for CON_{Hot}, $P < 0.05$). There was also an interaction between ambient conditions (i.e., CON_{Temp} and CON_{Hot}, $P < 0.05$), however, this was only evident at 3 to 13 min of the warm up (Figure 6.2a). The warm up was associated

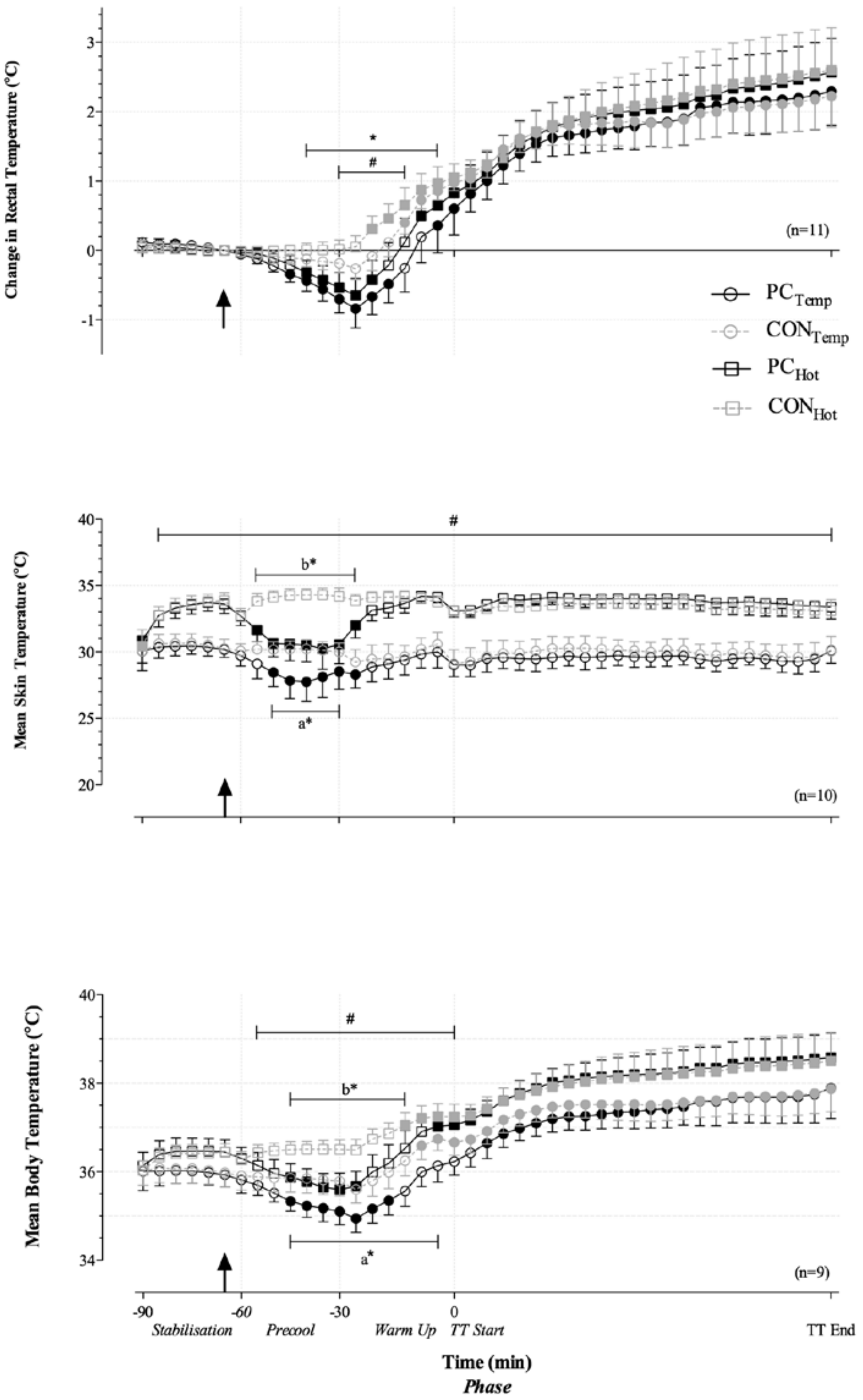

Figure 6.2 Relative change in rectal temperature (a), mean skin temperature (b) and mean body temperature (c) throughout the experimental trial. Statistically significant ($P < 0.05$) time effects from t = -65 min before time trial (arrow) are denoted by *dark symbols*. Significant effects of temperature (CON_{Temp} v CON_{Hot}) are denoted by a hash (#) symbol. Significant effects of precooling (a; PC_{Temp}, and b; PC_{Hot}) compared to respective control (CON_{Temp} and CON_{Hot}) are denoted by star (*) symbol. Data are presented as mean ± SD.

with a rise in rectal temperature in all trials so that it had moved above baseline by the start of the time trial (1.04 ± 0.14 ˚C, 0.81 ± 0.26˚C, 1.12 ± 0.19˚C and 0.95 ± 0.28 ˚C for $\mathrm{CON}_{\mathrm{Temp}}$, $\mathrm{PC}_{\mathrm{Temp}}$, $\mathrm{CON}_{\mathrm{Hot}}$ and $\mathrm{PC}_{\mathrm{Hot}}$, respectively). Relative change in rectal temperature continued to rise during the time trial in all trials, but there were no differences in rectal temperature between treatments during this phase ($P > 0.05$).

There was a noticeable interaction between ambient conditions (i.e., $\mathrm{CON}_{\mathrm{Temp}}$ and $\mathrm{CON}_{\mathrm{Hot}}$) for mean skin temperature from climate chamber entrance until completion of the time trial ($P < 0.05$, Figure 6.2b). When comparing mean skin temperature between precooling and control treatments, substantial differences were observed after the commencement of the treatment period, but returned to control values within 5 min of the warm-up. Mean skin temperature remained stable throughout the time trial, with no differences detected between the precooling or control trials in either environmental condition.

Mean body temperature in precooling trials was significantly lower towards the end of the precooling phase and during the warm-up, when compared to control trials. There was also an interaction during this time with respect to ambient temperature such that $\mathrm{CON}_{\mathrm{Temp}}$ was significantly lower than $\mathrm{CON}_{\mathrm{Hot}}$ ($P < 0.05$). The warm-up was associated with a rise in mean body temperature in all trials, but had moved above baseline by the start of the time trial in all except the $\mathrm{PC}_{\mathrm{Temp}}$ trial. Mean body temperature continued to rise during the time trial in all trials and there were no differences detected during this phase ($P > 0.05$, Figure 6.2c).

In all trials heart rate remained similar to baseline levels throughout the stabilisation and precooling phases. Heart rate increased at onset of the warm-up, and although there were a few interactions between treatment conditions, the differences had subsided well before the commencement of the time trial. Heart rate remained elevated above baseline and no differences were apparent throughout the duration of the time trial (Figure 6.3).

6.4.1.4 Subjective ratings

Figure 6.4 shows the changes in the subjects' thermal comfort (Figure 6.4a), stomach fullness (Figure 6.4b) and RPE (Figure 6.4c) during each trial. There was no significant change in the rating of thermal comfort after the subjects had entered the heat chamber to stabilise to 21˚C and 32˚C temperatures for 30 min (t =-90 to -60 min). However, once precooling commenced (t = -60 min), the rating of thermal comfort was significantly reduced, such that subjects reported feeling cooler when treated in the PC versus the CON condition (t = -60 to -30 min, $P < 0.05$). There was no significant change in ratings of perceived stomach fullness or RPE across the four trials.

Subjective information provided by each subject at the completion of the time trial is presented in Table 6.3. These data suggest that subjects' perceived ratings of effort given, and sensations, motivation, and comfort experienced, were similar across all trials.

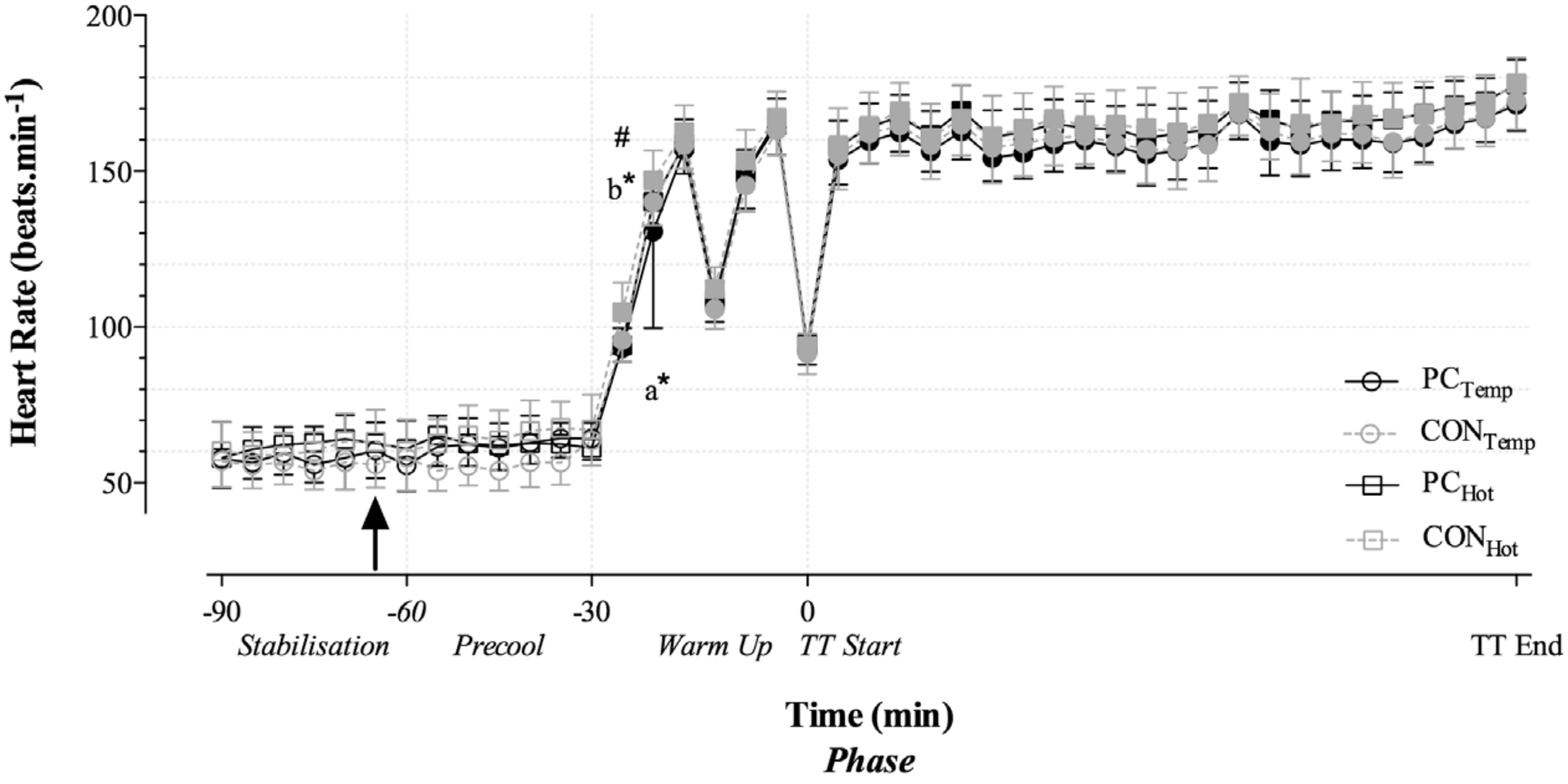

Figure 6.3 Heart rate throughout the experimental trial. Significant time effects from t = -65 min before time trial (arrow) are denoted by *dark symbols*. Statistically significant ($P < 0.05$) effects of temperature (CON$_{Temp}$ v CON$_{Hot}$) are denoted by a hash (#) symbol. Significant effects of precooling (a; PC$_{Temp}$, and b; PC$_{Hot}$) compared to respective control (CON$_{Temp}$ and CON$_{Hot}$) are denoted by a star (*) symbol. Data are presented as mean ± SD.

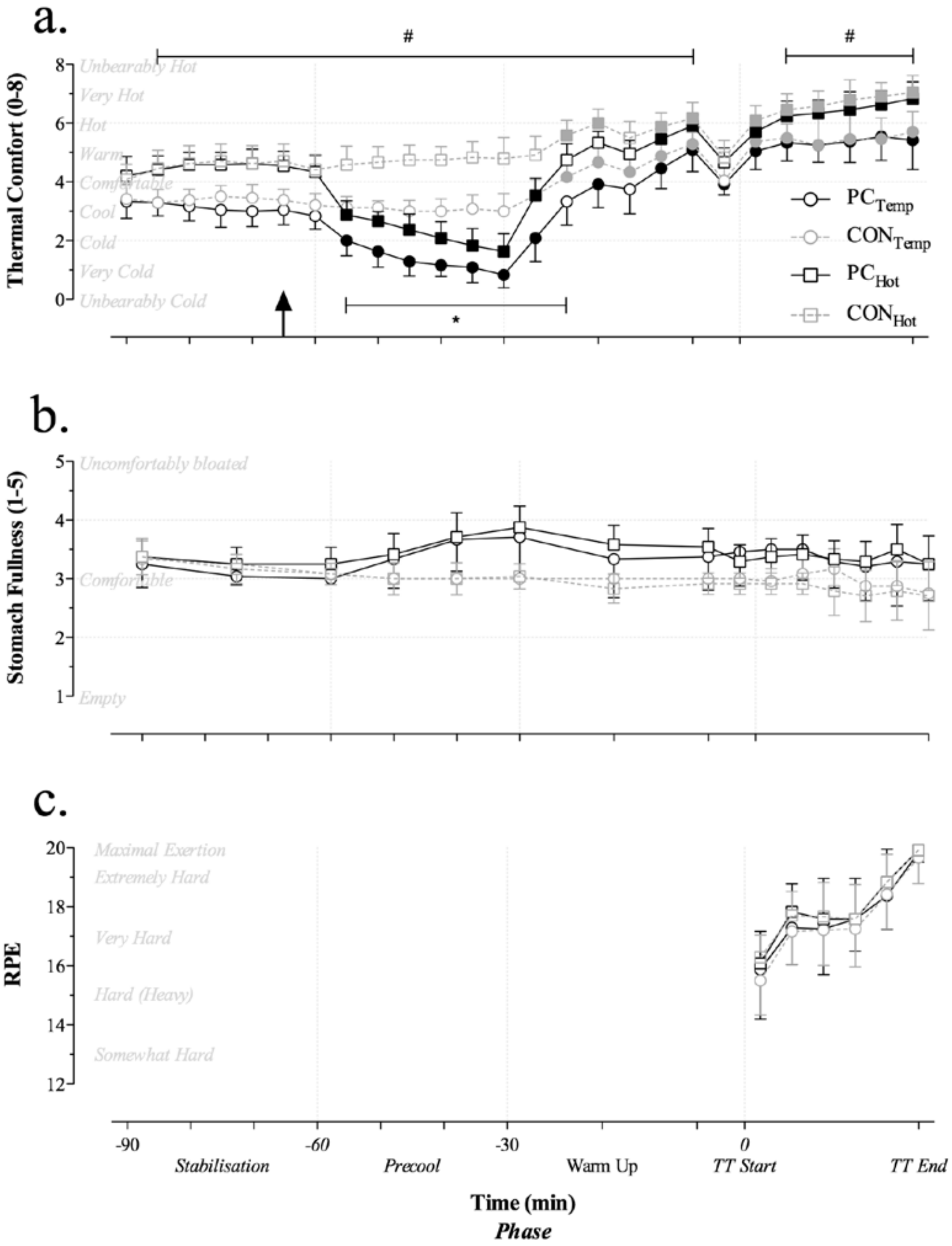

Figure 6.4 Subjective ratings of thermal comfort (a), stomach fullness (b) and rating of perceived exertion (c). Statistically significant ($P < 0.05$) time effects from t = -65 min before time trial (arrow) are denoted by *dark symbols*. Significant effects of temperature (CON_{Temp} v CON_{Hot}) are denoted by a hash (#) symbol. Significant effects of precooling (PC_{Temp} and PC_{Hot}) compared to respective control (CON_{Temp} and CON_{Hot}) are denoted by a star (*) symbol. Data are presented as mean ± SD.

Table 6.3. Subjective information on completion of time trials.

Theme	**CON_{Temp}**	**PC_{Temp}**	**CON_{Hot}**	**PC_{Hot}**
Effort given (%)	97 ± 4	98 ± 3	97 ± 5	98 ± 4
Sensation (arbitrary value)	4.3 ± 0.8	4.7 ± 0.7	3.8 ± 0.8	4.0 ± 1.0
Motivation (arbitrary value)	5.0 ± 0.9	5.0 ± 0.6	4.9 ± 0.9	5.0 ± 0.8
Comfort (arbitrary value)	3.3 ± 0.9	3.0 ± 0.9	2.7 ± 0.9	2.8 ± 1.0

Data presented as mean ± SD. All comparisons P > 0.05.

6.5 Discussion

To the best of our knowledge, this is the first study to examine the effects of precooling on laboratory cycling time trial performance in hot (32˚C) and temperate (21˚C) environmental conditions. Our findings support two of the original hypotheses. Cycling time trial performance was impaired in hot compared with temperate conditions, which was evident on all sections of the course. Furthermore, precooling enhanced cycling time trial performance when performed in hot conditions, with the performance benefits achieved being more evident in the second half of the time trial. However, in contrast to our third hypothesis, precooling failed to provide a clear performance benefit in temperate environmental conditions and instead was likely to impair performance, particularly on the first (flat) section of the course. These findings are of importance for athletes and coaches considering the use of a precooling strategy to prepare for competition in varying environmental conditions. The results of our study lead to three different themes of discussion, which include: i) the potential application of precooling on exercise performance in difference environmental conditions and over different types of courses, ii) insight into the complex mechanisms underpinning the relationship between thermoregulation and performance, and iii) the use of magnitude-based inferences to provide greater insight into the real-life significance of the outcomes.

In the current study, a practical precooling strategy involving slushie ingestion and iced-towel application achieved a noticeable (*large* and *moderate*) cooling effect on subjects who had been exposed to temperate and hot environmental conditions, respectively, for 30 min. Due to differences in the thermal gradients, greater heat loss and thus, more efficient heat exchange was observed following the standardized precooling strategy in temperate, compared with hot conditions. The greater absorption of heat from the environment in the warmer conditions attenuated the effectiveness of the strategy, such that a smaller reduction in rectal, mean skin and mean body temperature were observed. Indeed, Siegel et al. (52) proposed this idea, to explain the differences in rectal temperature observed (i.e., -0.66˚C v -0.43˚C) when their standardised precooling strategy of 7.5 $g \cdot kg^{-1}$ BM ice slurry ingestion was performed in temperate (24.5°C) and hot (34.0°C) environmental conditions. However, their observations were made over two investigations (47, 52) and included different subject pools. Therefore, our data supports, with greater confidence, their suggestion that the effectiveness of precooling likely depends on the environmental conditions where the protocol is performed. These results have implications for athletes, coaches and sport scientists utilizing precooling prior to competition.

Overall, the results of the present study support the findings of other studies in which endurance performance is impaired in the heat (2, 3) and precooling enhanced performance (20, 24, 54, 59, 65, 69, 71, 72). Our results add to this body of literature with the novelty that our study simulated real event performance using highly trained cyclists and a practical precooling strategy. It is also in line with the results of contemporary studies undertaken in temperate conditions (22, 80, 84, 96, 97, 103, 115), where precooling failed to improve exercise performance. A common theme throughout these previous studies was the lack of evidence showing a lowering of body temperature with the precooling treatments administered; either temperature was not assessed (103) or measurements showed no reduction in rectal (27, 58, 84, 115), gastrointestinal (80, 84), mean skin (78, 115) and/or mean body (27, 115) temperatures. Our findings that the precooling intervention lowered rectal, skin and mean body temperatures when administered in temperate conditions, but failed to alter subsequent self-paced exercise performance, supports only one of these studies (22).

There are two explanations for the lack of a performance improvement observed with precooling in temperate conditions. That is, the magnitude of cooling in temperate conditions was too great and this compromised performance, or the temperate conditions altered the efficacy of the precooling manoeuvre. Studies where precooling strategies (i.e., prolonged intermittent exposure to air at 0 - 5˚C) achieved performance improvements in temperate conditions (18, 23, 68), observed maximum temperature reductions of 0.37˚C for rectal, 3.4 to 4.5˚C for mean skin and 0.3 to 1.0˚C for mean body temperatures. In contrast, our precooling strategy achieved much larger reductions in deep body temperature (i.e., 0.7˚C at the end of application of the precooling and a maximum drop of 0.8˚C occurring during the warm-up), but lower reductions in mean skin temperature, such that the reduction in mean body temperature was similar. As such, these findings refute the general consensus that larger reductions in rectal temperature prior to an exercise task will achieve greater performance effects (15, 24). Instead, these data indicate the potential for thresholds, over which changes in rectal temperature may impair performance, or thresholds over which skin and body temperatures need to change before performance improvement is witnessed. Due to the differences in cooling achieved in the varying environmental conditions in the current study, it is uncertain whether this phenomenon is exclusive to temperate conditions. Further studies are warranted to systematically investigate the concept of such a threshold, and should include standardisation of both the magnitude and the timing of reductions in temperatures in relation to exercise commencement, since the current literature fails to address this (145). The separate and interactive effects of the environment also need systematic investigation.

Although the focus of the precooling strategy used in this study was to assisit in limiting hyperthermia-induced fatigue, we acknowledge that the consumption of the slushie in the current strategy provided additional fluid and carbohydrate; nutritional components that may also enhance performance. However, as we have previously discussed (65), it is unlikely that performance of our cycling protocol would be influenced by the small graduations in fluid levels or carbohydrate availability associated with this strategy, at least within the limits of detection of our protocol and under the control conditions of nutritional preparation (i.e., carbohydrate-rich meal and well hydrated). Furthermore, this study design was representative of real-life circumstances, whereby cyclists simply add the precooling strategy to their normal preparation.

As with our previous study (65), ratings of perceived exertion, heart rate, temperature, thermal sensation and stomach fullness recorded during the self-paced time trial were similar between trials that were matched for environmental temperature. This supports previous findings showing athletes will self-pace to similar subjective and objective levels of body perturbation (24, 64, 69, 71). The higher mean power outputs achieved with precooling in the heat elicited similar levels of body disturbances between conditions, but higher power outputs were not seen in the temperate condition. It is likely that this is because other factors in addition to thermoregulation, not measured in this study will also contribute to pacing or to muscular work output, such as metabolic (90) and force generating (91) capacity.

In sport, as with many other areas of practical decision-making, data are used to calculate the value of a statistic, which summarises the outcome of an experimental study. The appropriateness of different statistics for making meaningful inferences about the utility of an outcome has been discussed (126, 128). The traditional approach is the null-hypothesis test, in which an outcome statistic of probability (*P* value) is assigned to predict or infer statistical significance, based on the unlikely event of chance alone. This approach is used almost universally, but has been heavily criticised on a practical level, for failing to address the real-world importance of an outcome (126, 127). The analytical approach used in the present study centered on the practical significance of precooling on cycling performance. We made qualitative inferences about the true effect of the intervention under varying conditions based on the uncertainty of its effect compared to the smallest worthwhile change in performance time. We found strong support that performance is impaired in hot conditions and that cyclists will benefit from undertaking precooling techniques in this situation. The qualitative inference of almost certain impairment with heat and likely benefits with precooling are in line with the interpretations made from a statistical significance viewpoint. However, in the case of implementing precooling in temperate conditions, the qualitative inference of no likely benefit and possible harm is more illuminating than the “not statistically significant” or “no effect” outcome associated with a P value > 0.05. The results of our study provided a practical interpretation that would assist coaches and athletes to make critical decisions about implementing precooling strategies in competition situations under different environmental conditions.

An additional novelty of the current study is that we used an inferential approach to make separate analyses of performance over different portions of the time trial and sections of the course. These show both the influence of heat and our precooling strategy on pacing activities, and the contribution of different aspects of performance to the overall outcome of an event. The effect of heat caused an almost certain impairment to performance and was distributed uniformly across the different portions of the time trial (i.e., on lap 1 and 2), as well as across the different types of terrain (i.e., flat, uphill and downhill sections). Precooling in the heat was most influential on the second half of the time trial and on the uphill sections of the course. The effects of precooling on downhill- and flat-terrain cycling performance was less pronounced, moving from benefits that were *likely*, to benefits that were *possible*. Precooling in temperate conditions was most likely to be trivial across both halves of the time trial and on sections grouped by terrain type. However, on further inspection of the data, the effects of precooling on the first flat section of the course was *likely* to be harmful to cycling performance. These assessments are not only interesting for the current performances on this specific time trial course, but offer insights into conditions under which precooling might be useful in temperate conditions, such as a course in which a greater metabolic heat production or lower heat dissipation might be expected (e.g., predominantly uphill course or riding with the wind). Alternatively, different outcomes might be seen if subjects performed a longer or more intense warm-up that allowed a greater rise in body temperature prior to the start of the time trial. Moreover, we are currently unaware of the effect that a smaller magnitude of temperature reduction would have on cycling time trial performance under these conditions. Although speculative, it offers possibilities for future research on precooling strategies when environmental conditions are temperate.

In summary, we have confirmed that our practical precooling strategy combining internal- and external-cooling techniques is effective at reducing body temperatures prior to exercise, which translates into a performance enhancement in hot, but not temperate conditions. Athletes and coaches can use this information to guide decisions about the use of precooling strategies and to fine-tune warm-up and pacing strategies when exercising in various environmental conditions. Further studies are needed to examine precooling for exercise in temperature conditions both to understand the complex mechanisms that underpin self-paced athletic performance, as well as provide practical information on how athletes should prepare for competition in various environments.

CHAPTER 7 GENERAL DISCUSSION

The use of various precooling strategies to improve health and safety, increase thermal comfort and enhance exercise performance has dramatically increased over the past thirty years. An underlying premise of precooling is that its application and associated benefits depend on the degree to which precooling can be performed under real-life circumstances. However, some techniques are logistically more challenging than others, such that they can often be unfeasible to use in competition or field settings. Furthermore, the practicality of achieving effective cooling with individual strategies may be related to the context in which they are administered. Therefore, it was important to evaluate the limitations associated with established precooling methodologies, such that the development and further refinement of precooling protocols to implement within the rules, logistics and environmental conditions, could be made. Moreover, research addressing the application of cooling strategies relevant to improving field-based sports performance is of great interest and importance to athletes and coaches. Thus, the main purpose of this thesis was to examine the physiological responses of various precooling methods in order to develop a practical precooling strategy that would enable improvements in cycling time trial performance in a variety of environmental conditions. Improving our understanding in this area may allow further refinement of precooling methods that might enhance cycling performance and provide more practical options that are effective and simple to implement in the field setting.

The major findings from this thesis were that: i) the ingestion of a large slushie and the simultaneous application of iced towels represents a novel, practical and effective approach to precooling, ii) the new precooling strategy enhanced the performance of a laboratory cycling protocol simulating the Beijing Olympic Games time trial in hot and humid conditions, iii) when the new precooling strategy was performed after the consumption of a hyperhydrating solution without, but not with glycerol, there were further small reductions in deep body temperature, reductions in perceived exertion and improvements in time trial performance, iv) peak gastrointestinal temperatures consistent with hyperthermia-induced fatigue (>39°C) were observed during stages of two field-based road cycling events despite these races being performed in only temperate environmental conditions with mild (1.3%) fluid losses, and v) the effectiveness of the new precooling strategy was enhanced in temperate environmental conditions, but this failed to translate to clear performance benefits during a cycling time trial protocol. Instead, this strategy, when applied in temperate conditions, was likely to impair performance, particularly on the first section of an ergometer protocol simulating a flat portion of the Melbourne World Championship cycling time trial course.

This thesis includes a comprehensive review of the established precooling strategies available in the literature involving the application and ingestion of cold air, water and ice. While externally applied methods have been most commonly used (e.g., the use of tepid water immersion protocols and the application of ice via a range of garments), the benefits associated with internal precooling methods have gained more recent popularity. In Study One (Chapter 3), a selection of popular and novel strategies showing promise for their practical application were evaluated on the basis of their effectiveness for reducing deep body temperature and the resulting increase in heat storage capacity. In doing so, we categorised changes in rectal temperature that were <0.3˚C as small, 0.3 to 0.6˚C as moderate, 0.6 to 0.8˚C as large and >0.8˚C as very large. This system was established on the basis of magnitudes of cooling that have been achieved in the current literature, in order to differentiate between strategies that otherwise cannot be compared. As we have discussed previously (147), there are differences in the characteristics of these various cooling methods and this can explain why the effectiveness of each strategy is independent, and relies on many factors. However, we acknowledge through our findings in Studies 3 and 5 (Chapters 4 and 6, respectively) that a greater reduction in rectal temperature does not necessarily translate to greater performance effects. For the first time, these studies (148, 180) provide data to refute the existence of a direct relationship between the magnitude of cooling and functional outcome, which others have proposed (15, 24).

The results of extensive pilot work in Chapter 3, presented here as Study 1, demonstrated that the most successful cooling strategies were: i) plunge – whole-body immersion in 10°C water to the level of the mesosternale in a purpose -built inflatable pool for 10 min followed by 20-min seated rest, ii) ingestion of a large volume (1 L) of a sports drink slushie that was ingested with the aid of a straw and spoon to maximise the ingestion of ice in two boluses, served 15 min apart, and iii) large slushie and iced towels – the simultaneous application, over 30 min, of a large slushie ingestion (as previously described) while three pre-soaked bathroom towels (ice water) were constantly rotated to cover the skin of the torso and legs. The plunge and large slushie strategies achieved moderate cooling effects, whereas the large slushie and iced towels achieved a large cooling effect (Table 3.1). Furthermore, the latter strategy was subjectively rated higher as a more practical strategy with less logistical constraints than other less effective precooling techniques. Therefore, the precooling strategy used in subsequent studies of this thesis, was the concurrently applied combination strategy involving the ingestion of a 14 $g \cdot kg^{-1}$ BM (~1 L for a 70 kg cyclist) slushie made from sports drink while ice towels were externally applied to the skin of the torso and the legs.

A subsequent aim, and major focus of this thesis, was to test the effectiveness of this practical strategy against standard precooling practices in enhancing performance of a cycling protocol simulating the course profile characteristics of the 2008 Beijing Olympic Games individual time trial event. There was an observable effect on body temperature as a result of precooling with both the newly developed strategy as well as a comparison model involving the established technique of cold water immersion and an ice jacket. However, the important finding was that overall, the practical precooling strategy was associated with 3.0% increase in mean power output (8 W) and a 1.3% improvement in performance time (1:06 min), compared to the control condition (i.e., no cooling), with true likely effects ranging from trivial to large benefits. Furthermore, we determined that the benefits achieved by this strategy were most evident in the second half of the time trial on both the climb and descent portions. As such, this novel precooling technique represents a practical and effective strategy athletes could benefit from, by using in preparation for events when thermoregulatory challenges are presented.

An increase in the number of studies involving internal cooling methodologies has emerged in the recent literature (63, 74, 75, 119). While we are confident that the improvements in cycling performance, identified in Study 2, were due to the powerful cooling effect of the new practical strategy, we must also acknowledge the proposed benefits of internal strategies, including the addition of nutrients (i.e., carbohydrate, electrolytes and fluid) and sensory effects (i.e., activation of temperature sensitive regions of the brain and increased central drive) that could also explain changes in performance. In Study 3, we examined the effectiveness of the addition of a hyperhydration agent, glycerol, in an attempt to further refine our practical precooling strategy. The proposed mechanisms appear to offer performance benefits through complex and interrelated effects on hyperhydration (34) and improved thermoregulation (152, 157, 158) as others have seen. Therefore, in this study, we combined practical precooling and a hyperhydration strategy, with and without glycerol ingestion, to determine their combined effects on cycling time trial performance in the heat. We selected a large bolus of chilled sports drink as the control condition in this study to mask the flavour characteristics of the glycerol, and standardised fluid volume to simulate the real-life practices of athletes preparing for competition. The results of this study indicated that we partially achieved our aims, in that i) hyperhydration enhanced fluid retention when glycerol was co-ingested with the large bolus of fluid, and ii) the practical precooling technique caused further reductions in deep body temperature. However, when glycerol was added to the hyperhydration solution, this did not lead to clear improvements in overall performance. Rather, we detected a possible (i.e., 2% or 30 s) performance benefit on the second climb following practical precooling and hyperhydration without glycerol.

With the benefits of precooling in hot and/or humid environmental conditions well documented, we are confident athletes and coaches can use this information to be well informed as to how best to prepare for competition in such conditions. However, in the case of cycling competition during the 2012 London Olympic Games, it is possible, but unlikely that athletes will be presented with hot environmental conditions. Although there are anecdotal reports and laboratory-based evidence of increases in thermoregulatory strain despite temperate environmental conditions (2, 3), it was unclear whether practical precooling could also benefit performance in relatively cooler conditions. Preliminary laboratory-based research showed positive effects on endurance capacity (23, 69) and performance (18) when body temperatures were lowered via a prolonged and intermittent cold air exposure protocol. However, the question remained whether a practical precooling strategy, such as our own, would benefit athletes if it were to be used in preparation for competition performed in temperate conditions. As such, the rationale for Study 4 was to determine whether the body temperature of cyclists during racing in temperate conditions would be high enough to benefit from the thermoregulatory advantages gained from using a practical precooling manoeuvre.

Study 4 enabled the validation of these field observations, whereby high body temperatures, of magnitudes generally associated with hyperthermia-induced fatigue, were recorded during racing despite temperate (13 - 16˚C, 54 – 80% r.h.) environmental conditions. Indeed, a major finding of this study was that body temperatures >39°C were observed on 67% and 73% of the occasions measured during two multiday stage races, respectively. It is also noted that all cyclists recorded peak gastrointestinal temperatures >39°C but it is unclear whether these high body temperatures had any effect on cycling performance. It is likely that the high incidence of hyperthermia during cycling is related to overall exercise intensity and associated high metabolic rates. During mass start road race stages, thermoregulatory challenges are likely to be influenced by race tactics, which dictate which riders need to achieve sustained or repeated high-intensity efforts during a race; the team leader’s objective is to do as little work as possible until a tactically decisive manoeuvre is required, compared with a domestique who has spent 60% of the race on the front of the peloton. However, time trial cycling involves a different format; the winner is the rider who, riding alone (i.e., drafting is not permitted), achieves the fastest time over a set course. Therefore, to achieve success in a cycling time trial requires a maximal effort over a typical distance of 40-50 km (for men) in an Olympic, or World Championship event. Our study confirmed that the high metabolic heat loads associated with sustained and maximal efforts occur, despite a higher gradient for heat exchange in temperate versus hot conditions, and warrants further investigation.

Study 5 therefore investigated the influence of manipulating ambient temperature on the thermoregulatory responses during our practical precooling manoeuvre, as well as the subsequent effect on time trial performance in different ambient conditions. The main finding of this study was that our practical precooling strategy, when performed in temperate conditions, failed to provide a clear performance benefit. Instead we showed that precooling was likely to impair performance, particularly on the first (flat) section of the course. An important implication of these findings for athletes and coaches is that the effectiveness of precooling will be influenced by the environmental conditions under which they are conducted, whereby cooler environmental conditions facilitate a greater cooling effect. However, it was important for us to compare the complete strategy across the different ambient conditions, although, we acknowledge there may also have been merit in comparing magnitudes of cooling that were similar. These data, along with data from Study 3, provide evidence to refute the general consensus whereby a greater reduction in rectal temperature before an exercise task translates directly into better performances. In fact, our data suggest that there may be a threshold of body cooling beyond which reductions in body temperature may impair performance. Our data do not allow us to conclude, however, that precooling is detrimental, or even inappropriate for all cycling events undertaken in temperate conditions. Different precooling strategies or cycling events resulting in higher metabolic heat demands may produce different outcomes. Indeed, the low body temperatures seen at the end of our simulated time trial course suggest that performance was not compromised by hyperthermia. As such, it is possible that under circumstances of greater metabolic heat production (i.e., protocols involving longer warm-ups, courses involving a greater proportion of hill climbing, or tail-wind conditions where heat dissipation is reduced) we might see both a greater thermoregulatory strain and some beneficial effects on cycling performance associated with precooling in temperate conditions. Further work is therefore needed in this area. Despite the lack of a performance enhancement, this study provides information to guide the decisions of athletes and coaches regarding the appropriateness of a precooling strategy under varying environmental conditions.

This thesis used a simple practical problem-solving approach to systematically address a real-life scenario that was presented to Australian cyclists. The need for a practical solution to address the thermoregulatory challenges that were expected to impact Australian cyclists at major international cycling competitions was identified. Although there was clear evidence of performance benefits associated with established laboratory-based precooling strategies, the lack of event-specific research and the problems of transferring the application of these practices in the field, necessitated a fresh approach. Therefore, a strong emphasis in each of the studies was on the application of the various precooling techniques using high levels of ecological validity.

The research design and methods used in this thesis were based on real-life competition circumstances. We simulated race-day schedules involving high environmental heat loads and performance trials based on actual events (i.e., Beijing Olympic Games and the Melbourne World Championship road cycling individual time trial courses) with hills and appropriate levels of convective cooling. Furthermore, we implemented the various precooling strategies under ‘field conditions’, (i.e., the use of a portable plunge-bath and battery-operated commercial slushie machine), which enabled a comprehensive evaluation of the logistical and practical characteristics that were associated with each technique. Understandably, we could not apply this level of ecological validity across the entire protocol, but wherever possible, we selected equipment suitable for use in the field setting (i.e., iButtons for the determination of mean skin temperature, *LactatePro* to measure blood lactate concentration) to enable us to evaluate physiological responses and compare our findings to present or future data collected in actual competition. Our statistical analyses involving magnitude-based interpretations enabled us to quantify the likelihood of a performance outcome that would be meaningful to sporting events (i.e., the chance that an effect is beneficial, trivial or harmful). All these attributes were intended to provide better guidance for athletes and coaches in making practical decisions about the appropriateness of using a precooling strategy.

7.1 Reflection

A final comment on this body of work involves recognition of its unique model in working with elite coaches and athletes. This thesis has greater significance than simply presenting the findings from a series of interrelated projects on precooling. Collectively, this work represents a protocol in which scientists, coaches and athletes can work together to develop a practical but evidence-based approach to the enhancement of sports performance at the highest levels. The specific line of enquiry was to develop strategies to allow cyclists to perform optimally in road cycling events in which thermoregulatory challenges might limit performance. The goal was to produce precooling tactics that could be implemented in some specific events (i.e., Beijing Olympic Games, Delhi Commonwealth Games, Melbourne World Road Cycling Championships) and be further adapted to the challenges and logistical constraints of other competitive situations. Some of the elements that underpinned the success of this project could be incorporated into future work in applied research settings. These are briefly summarised:

1. Early and significant engagement with elite athletes and coaches for whom the outcomes of the research are directly focused. This activity is important in gaining insights into the problems that need to be addressed as well as creating interest within the targeted population to make use of the outcomes of the projects.

2. Identification of an immediate and significant real-world challenge, including understanding of the logistical difficulties in applying traditional or proven strategies to address it. This focus is important in overcoming practical limitations such that an effective and robust preparation strategy could be devised.
3. Systematic progression of the research theme in small increments to provide a thorough and in depth assessment of the problem. Building on the knowledge and practical outcomes of previous research allows subsequent work to be refined to further enhance the practical application of this strategy.
4. Our approach involved working in parallel with Australian cyclists, to streamline the best preparation strategies that allowed these athletes to prepare independently to the research being conducted. While there are certain benefits and limitations associated with this design, this model enabled us to remove ourselves from the coalface of athlete support in order to conduct rigorous and robust applied research.
5. Evaluation of the key research questions under high ecological validity. Previous research had failed to address practical precooling to the degree that was required to address the specific needs of a real-life event. Therefore, we examined our objectives using high levels of ecological validity, by simulating as many real-life contraints as possible, in order to enhance the transferability of the findings from our work.
6. Opportunity to implement the research findings in a real-world scenario. The unique part of this model was our ability to offer guidance and support to cyclists competing on the Australian National team. This was achieved by prescribing specific practical precooling protocols, providing education to

athletes and support staff, and guiding coaches' decisions with evidence-based advice.

7. The relationship between the coach and the scientist may be difficult to create and can take time to develop. A strong bond develops when they trust eachother's professional judgement and use their combined knowledge to make decisions. Often, the successful integration of a sports science program is levered off how well they know and like each other, share similar beliefs and philosophies toward a common goal. We were fortunate to work along side elite coaches who appreciated the benefits of scientific enquiry and learning from the outcomes of our research.
8. Transferability of the strategy beyond its original and intended purpose. This model was focused specifically for time trial cyclists to implement before competition, but the flow-on effect enabled cyclists of other disciplines, such as road cycling, track cycling, cross country (XC) and bicycle motocross (BMX), and athletes of other sports (e.g., rowing, triathlon, race walking and hockey) to benefit from this work.

7.2 Directions for Future Research

While the novel findings from these studies make a significant contribution to the current body of literature, they also highlight possible directions for future research. Suggestions for future research, are discussed under the following themes: i) individualising precooling, ii) internal precooling, iii) precooling in temperate environmental conditions, and iv) transferring precooling from the laboratory to the field setting.

The first study in this thesis identified a practical precooling strategy that was applied as a standard model across Studies 2, 3 and 5. As such, a ‘blanket-approach’ was employed to induce cooling across individual subjects who were of a range of physical shapes and sizes, with varying levels of body fat content. Although we included subjects with a relatively high-degree of homogeneity with regard to aerobic fitness level, there were differences in the characteristics of their physique that may have altered the efficacy of this precooling strategy. We proposed, from the findings of Studies 3 and 5, that if magnitudes of cooling were too great, a potential performance impairment could result. As such, future studies should investigate the concept of such a threshold, whereby standardisation of cooling magnitudes and the timing of temperature reductions in relation to different cooling methods can be established. Moreover, improving our understanding of the relationship that exists between the characteristics of physique (anthropometry) and the magnitude of cooling that is most beneficial is warranted. Further research into individualised precooling practices will assist practitioners on how best to prepare athletes in a range of sports for future events preformed in hot conditions.

We were interested in the practical benefits of ingesting a large slushie, which had implications for combining thermoregulatory, nutritional and sensory effects. Although we were not focused on the mechanisms underpinning the performance improvements that were found, future research in this area is warranted. For example, establishing the cooling benefits of individual body regions on performance, such as the mouth, brain or gastrointestinal tract, would be of interest. Indeed, the use of ice has been successful in safeguarding athlete health during exercise performed in high ambient temperatures; however, caution may be needed if temperature detection between the body and the brain is uncoupled. Although the studies in this thesis did not see any evidence to support such a phenomenon, others have reported higher rectal (48, 53) and gastrointestinal (180) temperatures at the end point of exercise following the ingestion of ice. These findings suggest that it is the brain temperature that is more closely regulated than core temperature per se (46). Thus, studies varying beverage temperature and volume are needed to provide a comprehensive understanding of the thermoregulatory advantages that are brought about by cold beverage or ice ingestion.

The existence of high body temperatures and the lack of a beneficial effect of precooling on cycling performance in temperate conditions are areas of research that also warrant further investigation. The relevance of precooling for athletes performing in temperate conditions is questionable based on the findings of this thesis. However, the findings of Study 5 reaffirmed that cycling performance is impaired in hot conditions, compared with a temperate environment. This suggests there is a point, somewhere along the continuums of body or environmental conditions, at which high internal temperatures begin to impair performance. Indeed, the individual differences between cyclists and the extent to which high temperatures may be detrimental is of importance. Alternatively, the results of Study 5 could suggest that the precooling strategy failed to work under the circumstances in which it was used, whereby the ambient temperature was too cool, the effectiveness of precooling too great, or the cycling protocol included too little climbing to challenge thermoregulation. As such, future studies examining body temperature and performance in temperate environmental conditions are warranted. Future research may include smaller graduations in ambient temperature or magnitudes of cooling to determine the level at which high body temperatures start to become relevant and impair cycling performance. A practical implication is that athletes may need more practice to be familiar with the sensations of cooling, or better educated as how to maximise the potential benefits (i.e., modifying the length or intensity of a warm-up, and altering pacing strategies) such that improvements in performance can be achieved. Better understanding of these factors will allow us to determine whether practical precooling in temperate conditions could be worthwhile.

The practical ease of precooling before competing in hot conditions can have implications for improved safety, comfort and endurance performance. As such, interest in this area of research is mounting. Although precooling in the field is fast becoming popular among professionals, there is a distinct lack of research that has been conducted under the constraints of actual competition. Based on established laboratory techniques, Study 1 of this thesis identified a practical strategy, which was evaluated in Studies 2, 3 and 5 under controlled laboratory conditions. Therefore, future research is needed to determine the transferability of performance improvements associated with this strategy from the laboratory environment to the field. Elite level athletes are often required to compete in hot and humid environments with competition and travel schedules that limit time (in location) for sufficient heat adaptation. Therefore, the acute benefits that can be achieved by employing a practical precooling manoeuvre will allow these athletes to remain competitive despite the environmental conditions and their status of heat acclimatisation. Future research should focus on elucidating the mechanisms associated with the performance benefits that are achieved as a result of a precooling manoeuvre.

7.3 Conclusion

The studies contained within this thesis have addressed the application of precooling strategies relevant to improving cycling time trial performance. The general purpose of this thesis was to examine the physiological responses to a variety of precooling methods in order to formulate a practical precooling strategy that cyclists could use before competition that is effective and logistically simple to implement in the field. The main findings from the studies of this thesis were that: i) a novel strategy involving the combined ingestion of a slushie and application of iced towels represents a practical and effective approach to precooling, ii) the practical precooling strategy lowered body temperature and enhanced performance of a cycling protocol simulating the Beijing Olympic Games time trial in hot and humid environmental conditions, iii) when practical precooling was performed after hyperhydration without, but not with, the co-ingestion of glycerol, there were further small reductions in deep body temperature, improvements in perceived exertion and enhancement of cycling performance that were evident in the second half (climb 2) of the time trial, iv) peak gastrointestinal temperatures, that are consistent with hyperthermia-induced fatigue (>39°C), were observed during stages of two field-based road cycling events despite only mild (1.3%) fluid losses and temperate environmental conditions, and v) the effectiveness of the new precooling strategy was enhanced in temperate conditions, but this failed to translate to *clear* performance benefits. Instead, this strategy was likely to impair performance, particularly on the first (flat) section of the course.

The studies in this thesis have shown that that a novel strategy involving the combined application of iced towels and the ingestion of a large slushie made from sports drink was effective at lowering body temperature and thus, enhancing heat storage capacity prior to a cycling time trial. However, this effect translated into a performance enhancement in hot, but not temperate environmental conditions. Further, the benefits to cycling time trial performance achieved by the practical precooling strategy were most evident in the second half of the time trial, long after the cooling effect had disappeared. Despite evidence to indicate that cyclists could benefit from a precooling manoeuvre in temperate conditions, the manoeuvre was more likely show impairment in performance. Together, these findings indicate that cyclists could benefit from applying this strategy before competition that is performed in hot and humid conditions. However, an implication of these findings is that efficacy of precooling may depend on the environmental conditions in which it is administered. Such findings are of practical significance for athletes, coaches and sport scientists, in understanding the factors that can influence the effectiveness of a precooling manoeuvre. This thesis represents a practical model for future precooling research to continue to emerge from the laboratory, into the field environment. Future research is warranted to further investigate the effectiveness of practical precooling strategies in competition or field-settings.

CHAPTER 8 REFERENCES

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CHAPTER 9 APPENDICES

Table 2.1 Cold air studies (external)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Lee & Haymes, 1995 (68)	"Physically fit runners" (n = 14 M) 56.5 ml.kg^{-1}.min^{-1}	~33 min of 5˚C, 68% r.h. exposure	Running Precooling; time trial to exhaustion @ 82% VO$_{2max}$ (~13.3 km.h^{-1} or ~46.4 ml.kg^{-1}.min^{-1})	24˚C 53% r.h. (or cold air)	24˚C 51-52% r.h.	↓ Rectal temperature (0.37°C; persisted for 25 min) ↓ Mean skin temperature (3.39°C; persisted for 25 min) ↓ Mean body temperature (0.75°C; persisted for 25 min) ↑ Heat storage (25 W.m^2; 21%) ↓ Heart rate (9 bpm; persisted for 15 min) ↓ Oxygen consumption (persisted for 10 min) ↓ Sweat rate (315 g.hr^{-1}.m^2) ↔ Final rectal temperature, blood lactate concentration, rate of perceived exertion @ exhaustion	Improvement ↑ Time to exhaustion (3.8 min; ~17%; P<0.01)	The transient warming period allowed subjects to recover from extreme vasoconstriction and Authors presume an increase preliminary perfusion of leg muscles during the rewarming recovery period
Olschewski & Bruck, 1988 (23)	"Healthy, young" (n = 7 M) 60.0 ml.kg^{-1}.min^{-1}	5-10˚C double exposure with re-warming (total ~100 min)	Cycling Precooling; time trial to exhaustion @ 80% VO$_{2peak}$	26-28.5˚C (or cold air)	18˚C 50% r.h.	↓ Skin temperature (4°C; persisted throughout) ↓ Oesophageal temperature (0.2°C at 0 min; max = 0.8°C at 20 min; persisted throughout) ↓ Mean body temperature (0.34°C; persisted throughout) ↑ Heat storage (116 kJ.m^2; 44%) ↓ Sub-maximal heart rate (12.5 bpm) Delayed onset of sweating (4.5 min) ↓ Threshold of sweat onset (0.34°C) ↓ Sweat rate (37%) ↓ Skin blood flow (39%) ↓ Pedal rate (9%) ↔ Heart rate, sweat rate, pedal rate @ exhaustion	Improvement ↑ Time to exhaustion (2.3 min; 12%; P<0.05)	Authors term the sustained lowing of body temperature "central short-term adaptation"

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Hessemer et al., 1984 (18)	"Well-trained, young, rowers" (n = 8 M) 65.7 ml.kg^{-1}.min^{-1}	5-10˚C double exposure with re-warming (total ~100 min)	Cycling precooling; 60 min maximal time trial	28˚C 50% r.h. (or cold air)	18˚C 50% r.h.	↓ Skin temperature (4.5°C; diminished gradually) ↓ Mean body temperature (1.0°C) ↓ Tympanic temperature (0.8°C) ↓ Oesophageal temperature (0.4°C) ↑ Oxygen consumption (0.25 ml.min^{-1}.kg^{-1}; 9.6%) ↑ Oxygen pulse (1 ml; 5.6%) ↓ Sweat rate (0.27 mg.cm^{2}.min^{-1}; 20.3%) ↔ Heart rate, efficiency, plasma lactic acid, blood acid-base @ time trial end	Improvement ↑ Power output (at all times) (11 W; 6.8%, P = 0.024)	Author criticism - danger of the distortion of muscles and tendons due to low temperatures; not recommended for athletes performing short-lasting exercise that either requires maximal force and aerobic power from the beginning or that is performed largely anaerobically such as short distance running
Schmidt & Bruck, 1981 (22)	"Well-trained rowers; some German national competition winners" (n = 9 M, 3 F) 61.5 ml.kg^{-1}.min^{-1} Maximal work rate = 287 W	5-10˚C double exposure with re-warming (total ~100 min)	Cycling precooling; progressive maximal test (Individual workloads set)	28˚C (or cold air)	18˚C	↓ Skin, tympanic and oesophageal temperatures (values not reported; persisted throughout) ↓ Mean body temperature (~1°C; persisted throughout) ↓ Heart rate (mean value not reported; 5 bpm @ exhaustion) ↓ Sweat accumulation Dealyed onset of sweating ↔ Peak oxygen uptake	No substantial difference? ↑ Time to exhaustion (~30 s; ~2.8%; P>0.05) ↔ Total work, maximum work rate (P>0.05)	Authors state no substantial change in performance but data show possible differences related to calibre and/or sex: Of 3 female subjects (= three lowest VO$_{2peak}$); 2/3 increase maximal workload, all 3 increased total work and time to exhaustion, and 1/3 increased VO$_{2peak}$ Shivering threshold was found to decrease after precooling

F = females, M = males, P = probability, W = watts

Table 2.2 Cold water studies (external)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Siegel et al., 2012 (52)^	"Healthy, non-heat acclimatised" (n = 8 M) 54.2 ml.kg^{-1}.min^{-1}	30 min of 24.8 - 23.4˚C water immersion to the level of the mid-sternum (iCoolPortacovery, iCool, Queensland Australia)	Running 30 min seated rest; 30 min precooling; time trial to exhaustion @ ventilatory threshold$_1$ speed on treadmill	34˚C 52% r.h.	34˚C 52% r.h.	↓ Rectal temperature (0.44˚C; @ 15-40 min exercise) ↓ Rise in rectal temperature (0.05˚C.5 min^{-1}; during exercise) ↓ Mean skin temperature (2.02˚C; @ 0 min precooling - 40 min exercise) ↓ Mean body temperature (0.54˚C; @ 0 min precooling - 40 min exercise) ↑ Heat loss (-80.66 W.$^{m-2}$; during precooling) ↑ Heat storage (30.19 W.$^{m-2}$; during exercise) ↓ Heart rate (8 bpm; @ 0-35 min exercise) ↓ Sweat rate (0.44 L.h^{-1}; during exercise) ↓ Thermal sensation (1.4 units; during precooling / 0.7 units; @ 0-40 min exercise) ↓ Rate of perceived exertion (0.6 units; @ 0-40 min exercise) ↔ Pre-exercise rectal temperature, rate of heat storage ↔ Rectal temperature, mean skin temperature, mean body temperature, heart rate, thermal sensation, rate of perceived exertion @ exhaustion	Improvement ↑ Time to exhaustion (10.1 min; 21.6%; d = 1.53, 90% CI = 0.69-2.36, "moderate to very large benefit"; P=0.008)	Study included two experimental treatment interventions, including 1) water immersion; and, 2) ice slurry ingestion (see table 5 and 7 for individual and comparative results) Note that control and water immersion treatments included intake of 7.5 g.kg^{-1} of 37˚C 5% CHO drink to control for fluid intake associated with ice slurry

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Vaile et al., 2011 (48)	"Endurance trained cyclists" (n = 10 M) 66.7 ml.kg^{-1}.min^{-1}	15 min of 15˚C water immersion to the level of the neck in inflatable bath with refrigeration unit (iCool Portacovery, Queensland Australia); performed at 5-20 min recovery	Cycling 10 min lying supine; 5 min standardised warm-up; 15 min @ 75% peak power output; 15 min maximal time trial; 60 min recovery including 5 min standardised cool-down and 15 min recovery intervention and 40 min passive rest; 5 min standardised warm-up; 15 min @ 75% peak power output; 15 min maximal time trial	33°C 44% r.h.	33°C 44% r.h.	↓ Rectal temperature (0.5-3.5°C; @ 10 min recovery cooling until end of exercise) ↓ Arm blood flow (13.21 ml.100 ml^{-1}.min^{-1}; @ end of recovery cooling - end of exercise) ↓ Leg blood flow (~3-5 ml.100 ml-1.min-1; @ end of recovery cooling - end of passive recovery) ↑ Arm:leg blood flow ratio (~100-200%; @ end of recovery cooling - end of passive recovery) Correlation between Δ arm;Leg blood flow rate and Δ rectal temperature (r=0.58) Correlation between gain in performance from control to recovery cooling and ↓ in rectal temperature (r=-0.70) Correlation between gain in performance from control to recovery cooling and arm:leg blood flow ratio (r=-0.73) ↓ Heart Rate (~12 bpm; during recovery cooling - 5 min of second exercise bout) ↑ Blood lactate concentration (2.2 mM; @ end of recovery cooling) ↔ Arm:leg blood flow ratio @ end of second exercise bout	Improvement Control: ↓ Total work in time trial 2 (Δ total work TT2 - TT1 = -1.8%; P<0.05) Treatment: ↔ Total work in time trial 2 (Δ total work TT2 - TT1 = 0.1%; P>0.05)	Unexpected finding of negative correlation between the change in rectal temperature and change in performance between trials, raises the possibility of an optimal cooling threshold below which there is no further performance benefit, or even a performance decrement Authors propose individualised cooling strategies with the view to account for athlete's mass, body composition and body surface area

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Racinais et al., 2009 (96)	"Physical education students" (n = 7 M) No subject characteristics provided to indicate performance capability	30 min of 16˚C water immersion to the level of the pelvis	Cycling Precooling; Best of three ~7 s maximal sprint trials	22˚C 60% r.h.	22˚C 60% r.h.	↓ Skin temperature (5.6˚C; following cooling)	Impairment ↓ Maximal power (14%; P<0.05) ↓ Maximal force (8%; P<0.05) ↓ Maximal velocity (11%; P<0.05)	Separate intervention investigating diurnal variation showed no substantial differences in impairment of performance leading authors to advise athletes to "strictly avoid any cooling before a sprint exercise irrespective of time-of-day" Results reported in text are brief
Goosey-Tolfrey et al., 2008 (70)†	"Able-bodied, sport science students, physically trained, exercised 4-5 d.wk^{-1}" (n = 7 M) 49.3 ml.kg^{-1}.min^{-1}	10 min of 10˚C water immersion of both hands to the level of the wrist	Cycling 5 x (10 min @ 50% VO_{2max} + 2 min passive rest); precooling; 3 km time trial	31˚C 61% r.h. No fan used	31˚C 61% r.h. No fan used	↓ Auditory canal temperature (1.2˚C; 4-10 min precooling, no data during or post 3 km time trial) ↓ Mean skin temperature (1.33˚C; @ end precooling) ↓ Heart Rate (4 bpm; @ end of precooling) Correlation of Δ auditory canal temperature & final auditory canal temperature @ end of exercise (r=-0.86)	Improvement ↓ Time to complete 3 km time trial (14 s; 5.2%; P<0.05)	Separate subject population investigating wheelchair athletes not included
Peiffer et al., 2008 (51)	"Australian national A/B grade-level, competitive cyclists, >1 y training history, >200 km.wk^{-1} training volume" (n = 10 M) 56.5 ml.kg^{-1}.min^{-1}	5 min of 14˚C water immersion to the level of the mid-sternum in inflatable bath with refrigeration unit (iCool Portacovery, Queensland Australia)	Cycling Repeat maximal 1 km time trial separated by 20 min seated rest including recovery cooling manoeuvre at 12.5 - 17.5 min	35˚C* 40% r.h.*	35˚C 40% r.h.	↓ Muscle temperature (1.3˚C; @ end of second time trial) ↔ Rectal temperature	No substantial difference ↔ Δ Isokinetic concentric torque production from pre time trial 1 - post time trial 2 (data pooled; P=0.32) ↔ Δ Average peak power from time trial 1 - time trial 2 (data pooled; P=0.42) ↔ Δ Peak power, time trial 1 - time trial 2 (data poled; P=0.48) ↔ Δ time to complete 1 km time trial; time trial 1 - time trial 2 (data pooled; P=0.5)	*Recovery cooling manoeuver (cooling prior to second 1 km time trial) Mean time trial 1 and 2 data for water immersion and control groups is presented graphically but data are pooled in text.

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Peiffer et al., 2008 (50)	"Well-trained cyclists, >3 y training history, >250 km.wk^{-1} training volume" (n = 10 M) 60.5 ml.kg^{-1}.min^{-1}	5 min of 14°C water immersion to the level of the mid-sternum in inflatable bath with refrigeration unit (iCool Portacovery, Queensland Australia)	Cycling Repeat bout of 25 min @ 255 W (65% VO$_{2\,max}$) + 4 km maximal time trial, separated by 15 min including recovery cooling manoeuvre at 5-10 min	35°C* 40% r.h.*	35°C 40% r.h.	↓ Rectal temperature (0.4°C; @ 0 min of second steady state exercise until end of second 4 km time trial) ↑ Cadence (3%; @ second steady state exercise) ↓ Rating of perceived exertion (2.5 units; @ end of second steady state exercise) ↔ Rise in rectal temperature (throughout exercise following recovery cooling), VO$_{2\,max}$	Improvement ↓ Time to complete second 4 km time (18 s; P<0.05) ↓ Δ Average power output; time trial 1 - time trial 2 (Δ 17%; P<0.05)	Authors comment that results indicate that immersing hyperthermic (>38.5°C) athletes in 14°C water for 5 min can significantly decrease rectal temperature. *Recovery cooling manoeuvre (cooling prior to repeat exercise performance)
Vaile et al., 2008 (49)	"Well-trained, non-heat acclimatized, cyclists" (n = 10 M) 70.7 ml.kg^{-1}.min^{-1}	15 min involving 1 min of 10°C water immersion to the level of the neck in inflatable bath with refrigeration unit (iCool Portacovery, Queensland Australia) followed by 2 min out of the bath; protocol repeated 5 times	Cycling 5 min standardised warm-up; 15 min @ 75% peak power output; 15 min maximal time trial; 5 min standardised cool-down; 15 min recovery cooling; 40 min passive rest; 5 min standardised warm-up; 15 min @ 75% peak power output; 15 min maximal time trial	29.2°C* 58% r.h.*	34°C 39% r.h.	↓ Mean body temperature (3.6°C; @ end of recovery cooling - end of second exercise task) ↑ Blood lactate concentration (~2 mM; @ end of recovery cooling) ↓ Rating of perceived exertion[#] (2.4-5.7 units; @ midpoint of second bout of sub-maximal and maximal exercise) ↓ Thermal sensation (~0.6-3.8 units; @ end of recovery cooling - end of exercise) ↓ Heart rate (42 bpm; @ end of recovery cooling until 40 min passive recovery) ↔ Rating of perceived exertion @ end of exercise	Improvement Control: ↓ Total work in time trial 2 (Δ total work TT2 - TT1 = -22 kJ; -4.1%; P=0.00) Treatment: ↔ Total work in time trial 2 (Δ total work TT2 - TT1 = -3 kJ; -0.6%; P>0.05)	Study included four experimental treatment interventions, including 1) 10°C intermittent; 2) 15°C intermittent; 3) 20°C intermittent; and, 4) 20°C constant (see table 7 for comparative results) Control was 15 min active recovery (cycling) performed at 40% VO$_{2peak}$ *Recovery cooling manoeuvre (cooling prior to repeat exercise performance) [#] 95% confidence interval reported Authors comment that water immersion treatments were intended as a post-exercise recovery strategy as opposed to targeted precooling strategy. Although together, the two strategies may be important for understanding possible mechanisms, they cannot be directly compared.

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Vaile et al., 2008 (49) Cont.	As above	As above; with 15˚C water immersion	As above	29.2˚C* 58% r.h.*	34˚C 39% r.h.	↓ Mean body temperature (2.9˚C; @ end of recovery cooling - end of second exercise task) ↑ Blood lactate concentration (~1.5 mM; @ end of recovery cooling) ↓ Rating of perceived exertion# (0.3-1.4 units; @ midpoint of second bout of sub-maximal and maximal exercise) ↓ Thermal sensation (~0.6-2.8 units; @ end of recovery cooling - end of exercise) ↓ Heart rate (48 bpm; @ end of recovery cooling until 40 min passive recovery) ↔ Rating of perceived exertion @ end of exercise	Improvement Control: ↓ Total work in time trial 2 (Δ total work TT2 - TT1 = -22 kJ; -4.1%; P=0.00) Treatment: ↔ Total work in time trial 2 (Δ total work TT2 - TT1 = 2 kJ; 0.4%; P>0.05)	As above
		As above; with 20˚C water immersion	As above	29.2˚C* 58% r.h.*	34˚C 39% r.h.	↓ Mean body temperature (1.7˚C; @ end of recovery cooling - end of submaximal component of second exercise task) ↑ Blood lactate concentration (~1 mM; @ end of recovery cooling) ↓ Thermal sensation (~0.6-2.0 units; @ end of recovery cooling - end of exercise) ↓ Heart rate (47 bpm; @ end of recovery cooling) ↔ Rating of perceived exertion	Improvement Control: ↓ Total work in time trial 2 (Δ total work TT2 - TT1 = -22 kJ; -4.1%; P=0.00) Treatment: ↔ Total work in time trial 2 (Δ total work TT2 - TT1 = -5 kJ; -0.1%; P>0.05)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Vaile et al., 2008 (49) Cont.	As above	15 minute of 20˚C water immersion to the level of the neck in inflatable bath with refrigeration unit (iCool Portacovery, Queensland Australia)	As above	29.2˚C* 58% r.h.*	34˚C 39% r.h.	↓ Mean body temperature (2.1˚C; @ end of recovery cooling - end of second exercise task) ↑ Blood lactate concentration (~1.5 mM; @ end of recovery cooling) ↓ Rating of perceived exertion[#] (0.6-2.2 units; @ midpoint of second bout of sub-maximal and maximal exercise) ↓ Thermal sensation (~0.6-3.6 units; @ end of recovery cooling - end of exercise) ↓ Heart rate (47 bpm; @ end of recovery cooling until 40 min passive recovery) ↔ Rating of perceived exertion @ end of exercise	Improvement Control: ↓ Total work in time trial 2 (Δ total work TT2 - TT1 = -22 kJ; -4.1%; P=0.00) Treatment: ↔ Total work in time trial 2 (Δ total work TT2 - TT1 = -3 kJ; -0.6%; P>0.05)	As above

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Castle et al., 2006 (59)^	"English county standard, trained and/or competitive, soccer or rugby players, experienced (>3 d.wk^{-1}) in team game activities, non heat acclimatised " (n = 12 M) 82.5 kg 3.9 L.min^{-1}	20 min of 17.8°C water immersion to the level of the shoulders	Cycling intermittent sprint protocol 20 min precooling; 6 min warm up; intermittent sprint exercise (involving 20 x (10 s passive rest; 5 s sprint @ 7.5% BM; 105 s active rest))	Not stated, but assumed under typical laboratory conditions	34°C 52% r.h.	↑ Rate of rectal temperature cooling (0.009°C.min^{-1}; precooling) ↓ Rectal temperature (0.3°C; @ 0 min exercise) ↑ Rate of muscle temperature cooling (0.06°C.min^{-1}; precooling) ↓ Skin temperature (~2.5-11.5°C; throughout trial) ↑ Heart rate (~10-20 bpm; precooling) ↓ Heart rate (~12-18 bpm; 0-16 min exercise) ↓ Thermal sensation (magnitude not reported; precooling - end of warm up) ↓ Rate of increase in physiological strain index (0.08 units.min^{-1}) ↓ Peak physiological strain index (1.6 units) ↓ Peak thermal sensation (0.8 units) ↓ Muscle temperature (0.8°C; throughout exercise) ↔ Δ body mass ↔ Rating of perceived exertion, mean blood lactate concentration, oxygen uptake, respiratory exchange ratio @ end of exercise	No substantial improvement ↓ Peak power output (6 W; 0.5%; P>0.05) ↑ Work done each sprint (1.8 J; 0.5%; P>0.05) ↑ Total work done (0.1 kJ; 1.5%; P>0.05) ↓ Peak power output in Sprint #1 and #2 (~80-85 W; P<0.01) ↑ Peak power output in final sprint (Δ power output sprint # 20 - sprint #19 = 25 W, where control Δ↑ = 21 W; P>0.05)	Study included three experimental treatment interventions, including 1) cooling vest; 2) silicate gel pack application; and, 3) water immersion (see table 3 and 7 for independent and comparative results) Muscle temperature data presented for n=7 subjects

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Yeargin et al., 2006 (77)	"Highly trained, heat acclimatized, local and college team members, actively competitive in > 5 km races, extensive race history, training volume = 87 km.wk^{-1}, distance runners" (n = 12 M, 3 F) No subject characteristics provided to indicate performance capability	12 min of 5°C water immersion of the torso and upper legs	Running ~90 min pre-load at "challenging, yet comfortable" pace matched for distance; 12 min recovery cooling, 2 mile race	Performed "under open-air shaded pavilion" WBGT = 26.6 - 27.2 (All trials, P>0.05)	Performed "outdoors over hilly terrain on asphalt surface" WBGT = 26.6 - 27.2 (All trials, P>0.05)	↓ Thermal sensation (1.4 units; @ post-immersion) ↑ Blood lactate concentration (0.6 mmol/L; @post immersion) ↓ Heart rate (7 bpm; @ 1 mile) ↓ Rectal temperature (0.68°C; @ post-immersion - post race) ↔ Sweat rate, percentage dehydration, urine specific gravity, environmental symptoms, rate of perceived exertion	No substantial difference ↓ Time to complete 2 mile race (20 s; 2.6%; d = 0.22, "Small"; P>0.05)	Study included two experimental treatment interventions, including 1) 5°C; and, 2) 14°C (see table 7 for comparative results) Anecdotal reports of feeling "stiff and cold" following 5°C water immersion Field study limitations listed include small differences in testing temperature and relative humidity, different exercise intensities during pre-load and race, failed to mimic specific sporting activity but resembled the confines of many sporting activities Authors supported practical application of water immersion strategies evidenced by ease of set-up, low expense, physiological and some psychological benefits, and performance benefits Authors speculate that performance may be enhanced further if subjects used body cooling in conjunction with proper hydration
		12 min of 14°C water immersion of the torso and upper legs	As above	As above	As above	↓ Thermal sensation (1 unit; @ post-immersion) ↓ Heart rate (5 bpm; @ 1 mile) ↓ Rectal temperature (0.43°C; @ post-immersion - post race) ↔ Sweat rate, percentage dehydration, urine specific gravity, environmental symptoms, rate of perceived exertion	Improvement ↓ Time to complete 2 mile race (44 s; 5.7%; d = 0.41, "Medium"; P<0.05)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Cheung & Robinson, 2004 (97)	"Trained, competitive, local club cyclists and triathletes" (n = 7 M, 3 F) 59.0 $ml.kg^{-1}.min^{-1}$	5˚C water perfused jacket with hood and long sleeves (Med-Eng Inc., Pembroke, Canada) to lower T_{rec} 0.5˚C or for maximum of 75 min	Cycling precooling; 30 min @ 50% $VO_{2\ peak}$ with 10 s maximal sprint every 5 min (total of 7 sprints)	22˚C 40% r.h.	22˚C 40% r.h.	↓ Rectal temperature (0.5˚C; @ 0 min exercise) ↓ Mean skin temperature (1.4˚C; @ 0-30 min exercise) ↓ Mean body temperature (0.8˚C; @ 0-30 min exercise) ↓ Heart rate (4 bpm; @ 0-30 min exercise) ↓ Thermal comfort (@ pre- to 10 min exercise) Delayed visible sweating (10 min) ↔ Rating of perceived exertion, oxygen uptake, blood lactate	No substantial difference ↓ Peak or mean power output (11 W, 1.3; 9 W, 1.1%, respectively, P=0.325)	Authors propose that precooling targeting the upper body may have precluded any ergogenic effect through thermal manipulation of the active leg musculature before the initial sprint. Authors propose the ideal precooling protocol for repeated sprint performance might consist of upper body cooling combined with passive or exercise-induced active warming of active musculature
Mitchell et al., 2003 (92)	"Endurance trained, competitive history" (n = 11 M) 54.8 $ml.kg^{-1}.min^{-1}$	20 min standing in front of a large industrial fan rotating 180˚ every 2 min while water was sprayed in a fine mist (50 $ml.min^{-1}$) over the exposed surface area of the body (neck to feet)	Running Precooling; 2 min warm up @ 60% $VO_{2\ max}$; time trial to exhaustion @ 100% $VO_{2\ max}$	22˚C 4 $m.s^{-1}$	38˚C 40% r.h.	↓ Oesophageal temperature (0.5˚C; @ post warm up - end of performance trial) ↓ Rate of oesophageal temperature rise (0.08˚$C.min^{-1}$) ↓ Skin temperature (6˚C; end of precooling - end of performance trial) ↑ Heat content (<256 kJ; warm up and performance trial) ↓ Heat storage (Δ <-257 kJ; warm up and performance trial) ↑ Thermal comfort (1.6 units; before warm up) ↑ Thermal sensation (0.9 - 2.9 units; before warm up - 3 min performance trial) ↓ Heart rate (>10 bpm; post warm up - end of performance trial) ↔ Blood lactate concentration	Impairment ↓ Time to exhaustion (30 s; 8.1%; P<0.05)	Authors report very high rate of oesophageal temperature rise (0.31˚$C.min^{-1}$) and attribute this rise to exercise intensity 9 out of 11 subjects performed equal or reduced time to exhaustion following precooling Subjects consistently reported sensations of "heaviness" and "lack of spring" in their legs during the performance trial following precooling Authors discusses the possibility of a critical level of exercise intensity above which pre-exercise cooling impairs performance, as at or near maximal levels and including supra-maximal intensities

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Palmer et al., 2001 (98)	"Distance runners" (n = 14 M) 62.0 ml.kg^{-1}.min^{-1}	60 min seated rest while wearing a 1˚C water perfused hood (1.1 L.min^{-1}; 6.3 m PVC tubing)	Running Precooling; 30 min @ 60% VO$_{2\ max}$; 15 min maximal run time trial	33˚C 55% r.h.	33˚C 55% r.h.	↓ Core temperature (0.15-0.2˚C; @ 0 min exercise) ↓ Heart rate (5-8 bpm; @ 0 min exercise) ↓ Sweat rate (0.06 L.h^{-1}; @ rest) ↔ Heart rate and rate of perceived exertion @ end of exercise	Unclear Data suggest non-significant (~ 0.8%) improvement in distance covered in 15 min	Study included two experimental treatment interventions, including 1) both prior to and during exercise, and; 2) during exercise only. Results show improvement in performance only when cooling administered before and during exercise. Data pertaining to these treatments is not included due to their limited practical application
Drust et al., 2000 (83)	"University soccer players" (n = 6 M) 58.9 ml.kg^{-1}.min^{-1}	60 min standing under a 28-24˚C shower	Soccer specific Intermittent protocol Precooling; 15 min transition; 2 x 45 min intermittent activity involving standardised cycle of standing, walking (4 km.h$^{-1)}$, jogging (8 km.h^{-1}), cruising (10 km.h^{-1}), sprinting (maximal) separated by 15 min recovery	20.5˚C 68.3% r.h.	20.5˚C 68.3% r.h.	↓ Rectal temperature (0.6˚C; pre-exercise) ↑ Rectal temperature rise (data not reported; @ 45-90 min exercise) ↓ Plasma glucose concentration (data not reported; @ 45-90 min exercise) ↔ Oxygen consumption, heart rate, plasma lactate concentration, free fatty acid concentration, rate of perceived exertion, sweat production, minute ventilation	No substantial difference ↓ Total distance covered (100m; 1%; statistic not reported)	Study included additional experimental treatment intervention whereby the soccer specific intermittent protocol was performed in increased ambient conditions (26C / 62% r.h.). No precooling was performed during this treatment and is therefore not included

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Gonzalez-Alonso et al., 1999 (5)	"Healthy endurance - trained" (n = 7 M) 65.9 ml.kg^{-1}.min^{-1}	30 min of 17˚C water, whole-body immersion	Cycling Precooling; time trial to exhaustion @ 60% VO$_{2\ max}$ (228 W, 88 rpm)	Not stated, but assumed under typical laboratory conditions	40˚C 19% r.h.	↓ Esophageal temperature (1.5˚C; @ 0 min exercise) ↓ Muscle temperature (3˚C; @ 0 min exercise) ↓ Mean skin temperature (4.7˚C; @ 0 min exercise) ↓ Forearm blood flow (6.6 ml.100ml^{-1}.min^{-1}; 3-8 min exercise) ↑ Cardiac output (0.7 L.min^{-1}; @10 min exercise) ↓ HR (26 bpm; @ 10 min exercise) Correlation of increases in heart rates from 130 bpm to almost maximal levels(196-198 bpm) and increases in oesophageal temperature (r^2=0.98) ↔ Oxygen consumption (@ 10 min) ↔ Esophageal temperature, muscle temperature, mean skin temperature, cardiac output, stroke volume, heart rate, arterial mixed-venous O$_2$ difference, blood lactate, blood glucose, rate of perceived exertion @ exhaustion ↔ Rate of heat storage, body weight loss	Improvement ↑ Time to exhaustion (17 min, 37%, P<0.05)	This study also investigated the influence of rate of heat storage (0.10 versus 0.05˚C.min^{-1}) controlled by wearing a water perfused suit during a time trial @ 60% VO$_{2\ max}$ to exhaustion. Due to the lack of practical application of this cooling method to sport, these data have not been included Authors conclude that time to exhaustion in hot environments in trained subjects is inversely related to the initial level of body temperature (and directly related to the rate of heat storage)
Marsh & Sleivert, 1999 (72)	"New Zealand national and international level representative cyclists" (n = 13 M) 66.1 ml.kg^{-1}.min^{-1}	30 min of 18-12°C torso-only water immersion (or maximal rectal temperature reduction of 0.3°C)	Cycling precooling; 10 min warm up @ 60% VO$_{2\ peak}$ + stretches; 70 s maximal power test	Not stated, but assumed under typical laboratory conditions	29°C 80% r.h.	↓ Rectal temperature (0.3˚C; @ throughout) ↓ Mean body temperature (@ throughout) ↓ Mean upper body skin temperature (@ throughout) ↓ Mean lower body skin temperature (throughout 10 min warm-up) ↓ Heart rate (@ 5 -10 min of warm up) ↑ Rate of perceived exertion (0.8 units; @ 0 min of warm-up) ↓ Rating of perceived exertion (0.7 units; @ 10 min of warm up) ↔ Blood lactate concentration	Improvement ↑ Power output (22 W; 3.3%, P<0.005)	Authors propose that performance improvements may be related to cold induced vasoconstriction of the upper body skin resulting in an increased central blood volume and blood availability to the working muscles

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Kay et al., 1999 (71)	"Moderate- to well-trained, healthy, competitive cyclists" (n = 7 M) 64.5 ml.kg^{-1}.min^{-1}	58.6 min of 29.7-25.8°C water immersion to the level of the neck (shell cooling; without a concomitant reduction in core temperature)	Cycling precooling; 30 min maximal time trial	31°C 60% r.h.	31°C 60% r.h.	↓ Skin temperature (4.9°C; throughout exercise) ↓ Mean body temperature (~0.2-1.8°C; throughout exercise) ↓ Rectal temperature (~0.4-0.5°C; @ 15-25 min exercise) ↑ Heat storage (69 W.m^{-2}) ↓ Total body sweat (0.6 L) ↔ Fluid volume ingested, blood lactate concentration, oxygen consumption, heart rate, rate of perceived exertion	Improvement ↑ Maximal distance cycled (0.9 km; 6%; P<0.05)	Study reports no difference in blood lactate concentration between precooling and control groups at any time. However, following control treatment there was a substantial increase above pre-exercise values @ 10 min exercise and remained relatively unchanged throughout. Following precooling, there was an increase above pre-exercise values @ 20 min and further again at 30 min. Authors suggest that pre-cooled cyclists may have increased exercise intensity within the final 10 min of exercise, where as the controls remained unchanged throughout.
Booth et al., 1997 (69)	"Healthy, local club, competitive runners" (n = 5 M, 3 F) 63.1 ml.kg^{-1}.min^{-1}	60 min of 29-22°C water immersion to the level of the neck (or until onset of continuous cold shivering)	Running precooling; 30 min maximal time trial	Not stated, but assumed under typical laboratory conditions	32°C 60% r.h.	↓ Mean skin temperature (5.9˚C; @ 15 min precooling to 25 min exercise) ↓ Mean body temperature (2.7˚C; @ 30 min precooling throughout 30 min exercise) ↓ Rectal temperature (0.7˚C; @ 0-20 min exercise) ↑ Heat storage (136 W.m^{-2}) ↓ Heart rate (13% at t=0; 9% at t=5; 10% at t=10) ↑ Blood lactate concentraion (2.5 mmol.L^{-1}; @ end of time trial) ↓ Thermal comfort during exercise (0-15 min) ↔ Total body sweat, oxygen uptake	Improvement ↑ Maximal running distance (304 m, 4.2%, P<0.05)	Authors suggest water immersion may offer greater practical application to athletic performance over cold air exposure Thermal comfort reported as "comfortably cool" in first 30 min immersion, and "too cool" in second 30 min immersion n = 1 subject removed from immersion at t=45 min due to the onset of a continuous cold shivering response Following water immersion subjects self-selected high running speeds at all times throughout the test

BM = body mass, CHO = carbohydrate, CI = confidence interval, d = effect size, F = females, M = males, P = probability, PVC = polyvinyl chloride, rpm = revolutions per minute, t = time, TT = time trial, r = correlation coefficient, r^2 = coefficient of determination, T_{rec} = rectal temperature, W = watts, WBGT = wet bulb globe temperature, ^ indicates study is reported multiple times, † indicates that data is reported on able-bodied subjects only.

Table 2.3 Ice studies (external)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Clarke et al., 2011 (67)^	"University soccer players" (n = 12 M) 61.3 ml.kg^{-1}.min^{-1}	60 min seated rest while wearing a cooling vest (Cool Vest, Jackson Technical Solutions Ltd., Kent, UK) before the commencement of exercise and during 15 min mid-exercise recovery	Soccer specific Intermittent running protocol Precooling; 45 min standardised intermittent sprint activity (1st half); 15 min recovery; 1st half repeated (2nd half); Performance tests*	30.5°C 42.2% r.h.	30.5°C 42.2% r.h.	↓ Gastrointestinal temperature (0.6˚C; @ 60 min precooling - 30 min exercise) ↓ Muscle temperature (0.9˚C; @ 60 min precooling) ↓ Thermal sensation (2 units, @ 60 min precooling; and, 1 unit, @ end of mid-exercise recovery cooling) ↔ Plasma glucose concentration, plasma non-esterified fatty acid concentration	No substantial improvement ↑ Self-selected running speed (0.3 km.h-1; 2.7%; P>0.05) ↑ Time to exhaustion @ 12.9 km.h^{-1} with 20% incline (Cunningham Faulkner test) (12.9 s; 22.6%; P=0.072)	Study involved a 2x2 Latin square design (precooling and carbohydrate ingestion; see table 6 for combined results and table 7 for comparative results). Intervention involving carbohydrate only has been excluded due to lack of relevance. * Performance tests include a mental concentration test (performed 4 min after every 15 min block of exercise, concurrent with exercise; involved simple arithmetic), self-chosen work rate test (a 3 min test at self selected 30 min running pace) and Cunningham Faulkner Test (running time to exhaustion at 12.9 km.h^{-1} with treadmill at 20% incline)
Minett et al., 2011 (53)^	"Well trained, regional level, cricket and rugby union athletes, training (≥3 d.wk^{-1}) involved skill-based, strength and conditioning sessions " (n = 10 M); 77.8 kg No subject characteristics provided to indicate performance capability	20 min pre-exercise and 5 min mid-exercise application of towels soaked in 5°C water and placed over the head & neck (Head)	Intermittent-sprint running protocol precooling; 5 min warm up; 35 min intermittent-sprint protocol (Spell 1); 15 min recovery; Spell 1 repeated (Spell 2)	33˚C 33% r.h.	33˚C 33% r.h.	↓ Skin temperature (during precooling) ↓ Rating of perceived exertion (0.3 units; during exercise) ↓ Mean thermal sensation (0.5 units; throughout trial) ↔ Gastrointestinal temperature, heart rate, sweat loss, mean voluntary contraction, time to peak torque, blood biochemical measures	Improvement ↓ Spell 1 decline in sprint time (1.38%; d = 0.92) ↑ Total running distance (231 m; d = 0.62; P=0.02) ↑ Total Spell 2 hard running distance (92.3 m; P=0.04)	Study included three experimental treatment interventions, including 1) head; 2) head and hands; and, 3) whole body, to investigate precooling in dose response manner (see table 6 for combined results and table 7 for comparative results)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Stannard et al., 2011 (80)	"Experienced (12 y), trained (~54 $km.wk^{-1}$), local, competitive (5 km - marathon distance), endurance runners" (N = 7 M) 61.5 $ml.kg^{-1}.min^{-1}$	30 min wearing a airprene breathable material cooling vest (StaCool^{TM} Under Vest, StaCool Industries Inc, Brooksville, USA) with 4 pockets packed with 'thermopacks' during the warm up	Running 30 min standardised warm up; 10 km time trial	24-26°C 29-33% r.h.	24-26°C 29-33% r.h.	↔ Gastrointestinal temperature, heart rate, rating of perceived exertion, thermal sensation, Δ body mass, pre-time trial urine specific gravity	No substantial difference ↑ Time to complete 10 km (10 s; 0.4%; d = 0.07; P=0.746) ↔ 2 km split times (P=0.761)	4/7 subjects ran faster 10 km times following cooling vest exposure Thermopacks contain a non-toxic polymer material which remain flexible when frozen
Tyler & Sunderland, 2011 (54)	"Healthy, trained, non-acclimated" (n = 7 M) 55.3 $ml.kg^{-1}.min^{-1}$	90 min wearing modified neck-cooling collar (Black Ice, LLC, Lakeland USA) during 75 min pre-load exercise and 15 min performance trial	Running 75 min pre-load at 60% VO2 max (9.0 km.hr-1); 15 min maximal time trial	Treatment undertaken during exercise rather than pre-cooling	30.4°C 53% r.h.	↓ Mean neck skin temperature (P<0.05; @ 0-55 min) ↓ Thermal sensation of the neck (trial effect, P=0.006) ↔ Heart rate, rectal temperature, Rating of perceived exertion, feeling scale, thermal sensation of the whole body, water consumed, sweat volume, blood concentrations of lactate, glucose, cortisol, serotonin and dopamine	Improvement ↑ Distance covered in 15 min (182 m; 7.3%; d=0.67; P=0.007)	Study included two experimental treatment interventions, including 1) collar; and, 2) collar replaced (see table 7 for comparative results) Modified version of commercial product
		As above, with collar replaced @ 30- and 60 min	As above	Treatment undertaken during exercise rather than pre-cooling	As above	↓ Mean neck skin temperature (P<0.001; throughout) ↓ Thermal sensation of the neck (trial effect, P=0.003) ↔ Heart rate, rectal temperature, Rating of perceived exertion, feeling scale, thermal sensation of the whole body, water consumed, sweat volume, blood concentrations of lactate, glucose, cortisol, serotonin and dopamine	Improvement ↑ Distance covered in 15 min (179 m; 6.9%; d=0.62; P=0.008)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Tyler & Sunderland, 2011 (55)	"Endurance trained, non-acclimated, regional running and triathlon club members" (n = 8 M) 56.2 ml.kg^{-1}.min^{-1}	Wearing modified cooling collar (Black Ice, LLC, Lakeland, USA) during time trial to exhaustion test	Running 8 min standardised warm up; time trial to exhaustion at 70% VO$_{2max}$	Treatment undertaken during exercise rather than pre-cooling	32˚C 53% r.h.	↓ Mean neck skin temperature* (-17.91°C; throughout trial) ↑ Rectal temperature (0.43°C; @ exhaustion) ↑ Heart rate (3bpm; @ exhaustion) ↓ Thermal sensation of the neck (throughout trial) ↔ Rating of perceived exertion, thermal sensation, perceived feeling, *ad libitum* water consumption, sweat loss	Improvement ↑ Time to exhaustion (4.95 min; 13.0%; d=0.44; P<0.001)	All subjects improved time to exhaustion following cooling collar exposure (range = 11.1-24.4% improvement) * Assumptions of sphericity violated and Greenhouse-Geisser correction factor used for mean skin temperature, heart rate, rectal temperature Subjects commenced exercise and reached fatigue at higher rectal temperatures (0.2°C and 0.43°C, respectively)
Bogerd et al., 2010 (56)	"Healthy" (n = 8 M) 57.1 ml.kg^{-1}.min^{-1}	45 min wearing cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia), against bare torso skin	Cycling precooling; 5 min standardised warm up at 50% VO$_{2\ peak}$; time trial to exhaustion at 65% VO$_{2\ peak}$ (or stopped at 60 min)	24.6°C 24% r.h.	29.3°C 80% r.h.	↓ Skin blood flow of back, chest, finger and shoulder regions (by ~1/2 - 2/3; @ end of precooling) ↓ Mean skin temperature (2.7°C; @ 25 min precooling - end of exercise) ↓ Mean body temperature (0.8°C; @ end of precooling) ↓ Body heat content (31.8 W.m^{-2}) ↓ Thermal sensation (3 units; @ end of precooling) ↔ Rectal temperature, oxygen consumption, carbon dioxide production and metabolic heat production @ end of precooling, whereas control was reduced by 0.2°C, 22 ml.min^{-1} and 27 ml.min^{-1} and 4.3 W.m^{-2}, respectively. ↔ Respiratory exchange ratio, heart rate, rating of perceived exertion, sweat rate, volume of fluid ingested	Improvement ↑ Time to exhaustion for n=4 (5:02 min, 1.2%, P=0.03) ↑ Time cycled for n=2 (these subjects completed 60 min following treatment and became exhausted at 46:46 min following control treatment; statistic not provided)	Study included two experimental treatment interventions, including 1) Mild; and, 2) Strong cooling (see table 7 for comparative results) The weight of the activated cooling vest was ~ 1650 g The weight of the activated cooling shirt was ~ 310 g n=2 subjects cycled for 60 min in all trials Authors provide mean performance improvement, which included trials that were stopped at 60 min. Therefore magnitude of improvement reported in paper somewhat underestimated.

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Bogerd et al., 2010 (56) Cont.	As above	45 min wearing tailored evaporative cooling shirt (Unico, Alpnachstad, Switzerland)	As above	As above	As above	↓ Skin blood flow of back, chest and finger regions (by ~1/2 at each site; @ end of precooling) ↓ Mean skin temperature (1.5°C; @ 25 min precooling - end of exercise) ↓ Mean body temperature (0.5°C; @ end of precooling) ↓ Body heat content (13.5 W.m^{-2}) ↔ Rectal temperature, oxygen consumption, carbon dioxide production and metabolic heat production @ end of precooling, whereas control was reduced by 0.2°C, 22 ml.min^{-1} and 27 ml.min^{-1} and 4.3 W.m^{-2}, respectively. ↔ Respiratory exchange ratio, heart rate, thermal sensation, rating of perceived exertion, sweat rate, volume of fluid ingested	Improvement ↑ Time to exhaustion for n=6 (5:09 min, 1.3%, P=0.05)	As above
Mujika et al., 2010 (103)	"Highly trained fixed-seat traditional rowers" (n=18 M) Peak aerobic power (PAP) = 322.1 W	Wearing sweatbands soaked in alcohol- and menthol-based evaporative cooling solution (Energicer, Liquid Ice CosMedicals AG, Unterägeri, Switzerland) on both forearms continuously for the duration of the trial (~42 min)	Rowing 10 min warm-up at 55% PAP; 5 min rest; 10 min at 70% PAP; 10 min rest; 2000 m maximal time trial	25˚C 65% r.h.	25˚C 65% r.h.	↔ Heart rate, blood lactate, rating of perceived exertion, stroke rate, sweat loss	No substantial difference ↓ Time to complete set distance (3 s; 0.7%; d = 0.3; P=0.09)	Control condition involved wearing the same sweatbands soaked in cool water

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Tyler et al., 2010 (57)	"Healthy, recreational, unacclimatised, runners" (n = 9 M) 54.2 ml.kg^{-1}.min^{-1}	75 min wearing modified neck-cooling collar (Black Ice, LLC, Lakeland, USA) during pre-load exercise (Study A)	Running 75 min pre-load at 60% VO$_{2\ max}$ (9.0 km.hr^{-1}); 15 min maximal time trial	Treatment undertaken during exercise rather than pre-cooling	30.4°C 53% r.h.	↓ Skin temperature of the neck (d = 1.42; during pre-load) ↓ Thermal sensation (d = 0.46; during pre-load) ↔ Rectal temperature, heart rate, sweat rate, blood concentration of various stress hormones and neurotransmitters	Improvement ↑ Distance covered in 15 min (146 m; 5.9%; d = 0.28; 95% CI -15.6 - 301.6 m; P = 0.041)	Study included two experimental treatment interventions, including 1) Collar during pre-load; and, 2) collar during exercise (see table 7 for comparative results) Modified version of commercial product
	(n = 8 M) 54.9 ml.kg^{-1}.min^{-1}	Wearing modified neck cooling collar during performance trial (Study B)	Running 5 min warm-up; 15 min maximal time trial	Treatment undertaken during exercise rather than pre-cooling	30.4°C 53% r.h.	↓ Skin temperature of the neck (d = 5.01; throughout time trial) ↓ Thermal sensation (d = 0.57; throughout time trial) ↓ Voluntary water consumption (0.03 L) ↔ Self-selected running speed, heart rate, rectal temperature, rating of perceived exertion, sweat loss	No substantial difference ↑ Distance covered in 15 min (59 m; 1.8%; d = 0.04; P = 0.351)	
Johnson et al., 2008 (58)	"Trained cyclists" (n = 6 M; 1 F) 69.3 ml.kg^{-1}.min^{-1}	65 min wearing ice vest (Thermo Blazer, Whites Diving, Victoria BC, Canada) during 45 min seated rest and a warm up	Cycling Precooling; 20 min warm up; 20 km maximal time trial	25˚C	25˚C	↔ Core temperature	No substantial difference ↓ Mean power output (3 W; 1.1%; P>0.05)	Study involved a 2x2 Latin square design (precooling and ambient temperature; see table 7 for comparative results). Treatments are compared to relative ambient temperature control conditions. Due to elevated core temperatures >39.5˚C, the data for n=4 is presented in the 30˚C control condition
		As above	As above	30˚C	30˚C	↓ Core temperature (0.6˚C; @ 0 min exercise)	Improvement ↑ Mean power output (14 W; 5.2%, P<0.05)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Quod et al., 2008 (24)^	"Well-trained cyclists, members of local cycling community, 6 y cycling experience" (n = 6 M) 71.4 ml.kg^{-1}.min^{-1} Maximal aerobic power = 384 W	40 min wearing a phase change material waist-length jacket with long arms & hood (RMIT University, Melbourne, Australia)	Cycling 30 min seated rest; 40 min precooling; 20 min standardized warm up; ~40 min performance trial (consisting of 20 min @ 75% of maximal aerobic power; ~ 20 min self paced maximal effort matched for total work (kJ))	34˚C 41% r.h. Free of direct air flow and radient heat source	34˚C 41% r.h. 18-20 km.h^{-1} RHL = 6 x 500 W lights @ 2 m	↓ Skin temperature (2°C; throughout precooling) ↑ Negative heat storage (-14.7 W.m^{-2}; precooling) ↓ Thermal sensation (~2.5-3.5 units; during precooling) ↓ Heart rate (@ 20-25, 35 min precooling and @ 0 min exercise) ↑ Blood lactate concentration (4.0 mmol.L^{-1}; @ exhaustion) ↔ Rectal temperature, mean body temperature, rating of perceived exertion, Δ body mass, bladder void mass, estimated sweat loss, urine specific gravity, blood bicarbonate, blood pH, blood glucose	No substantial difference ↓ Time to complete performance task (16 s; 5 W; 1.5%; P=0.35)	Study included two experimental treatment interventions, including 1) Jacket; and; 2) Plunge + Jacket (see table 6 and 7 for combined and comparative results) Jacket not commercially available Authors comment that use of cooling jacket may only be appropriate for use as an external heat sink to attenuate the rise in core body temperature during a warm up as opposed to an active precooling technique *per se*
Duffield & Marino, 2007 (102)^	"Moderate- to well-trained, club-level rugby players" (n = 9 M) 85.2 kg No subject characteristics provided to indicate performance capability	Repeated exposure of wearing cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia). Worn 15 min pre-exercise, 9 min warm up and 10 min recovery	Intermittent-sprint running protocol 15 min precooling; 9 min standardized warm up; 30 min intermittent-sprint protocol (first half); 10 min recovery cooling; 30 min intermittent-sprint protocol repeated (second half)	32˚C 30% r.h. subjects seated within 5 m of radiant heat source	32˚C 30% r.h.	↓ Chest skin temperature (~4-9.5°C; @ 0 min warm up - 10 min exercise, 40 min exercise) ↑ Negative heat storage (-4.5 - -9.5J.g^{-1}; @ 0 min warm up - 0 min exercise) ↓ Thermal comfort (0.9 units; @ 0 min warm up, 40 min exercise) ↔ Gastrointestinal temperature, mean skin temperature, heart rate, sweat loss, blood lactate concentration, blood pH, blood sodium, blood potassium, hematocrit, rating of perceived exertion	No substantial difference ↔15 m sprint time ↔ Total sprint time for all sprints ↔ Percentage decline in sprint time ↔ Mean and total hard running distance ↔ Mean and total jogging distance ↔ Mean and total walking distance (All P>0.05)	Study included two experimental treatment interventions, including 1) Cooling vest repeated exposure; and, 2) water immersion + cooling vest repeated exposure (see table 6 and 7 for combined and comparative results)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Uckert & Joch, 2007 (21)	"Physical education students, endurance and strength trained, participated in athletics and soccer" (n = 20 M) No subject characteristics provided to indicate performance capability	20 min wearing 0-5°C cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia), against bare torso skin	Running Precooling; 5 min rest; Incremental test to exhaustion (9 km.h^{-1}, increasing 1 km.h^{-1} every 5 min)	30-32°C 50% r.h.	30-32°C 50% r.h.	↓ Skin temperature (0.8°C; 0 min exercise) ↑ Tympanic temperature (0.38°C; @ 0-5 min exercise) ↓ Heart rate (7 bpm; 0 min exercise) ↓ Rise in tympanic temperature (1.76°C.h^{-1}) ↔ Maximal heart rate, blood lactate concentration, skin temperature @ exhaustion	Improvement ↑ Time to exhaustion (2.2 min; 7.2%, P<0.001)	Study included two experimental treatment interventions, including: 1) precooling; and, 2) warm up prior to the incremental test to exhaustion. Due to the lack of relevance, data relating to the warm up trial is not included The weight of the activated vest was reported to be ~1000g
Castle et al., 2006 (59)^	"English county standard, trained and/or competitive, soccer or rugby players, experienced (>3 d.wk^{-1}) in team game activities, non heat acclimatized " (n = 12 M) 82.5 kg 3.9 L.min^{-1}	20 min wearing cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia)	Cycling intermittent sprint protocol 20 min precooling; 6 min warm up; intermittent sprint exercise (consisted of 20 x (10 s passive rest; 5 s sprint @ 7.5% BM; 105 s active rest))	Not stated, but assumed under typical laboratory condtions	34°C 52% r.h.	↑ Rate of rectal temperature cooling (0.006°C.min^{-1}; precooling) ↓ Rectal temperature (0.3°C; @ 0 min exercise) ↓ Skin temperature (~1-1.5°C ; @ 2-8 min exercise) ↓ Thermal sensation (magnitude not reported; throughout precooling) Weaker correlation between muscle temperature and work done (r = -0.50 v -0.90 for cooling vest and control, respectively) ↔ Muscle temperature, rate or peak physiological strain index, heart rate, Δ body mass ↔Thermal sensation, rating of perceived exertion, mean blood lactate concentration, oxygen uptake, respiratory exchange ratio @ end of exercise	No substantial difference ↑ Total work done (0.3 kJ; 4.5%; P<0.01) ↑ Power output (17 W; 1.5%; P>0.05) ↑ Peak power output in final sprint (Δ power output sprint # 20 - sprint #19 = 93 W, where control Δ↑ = 21 W; P<0.01) ↑ Work done each sprint (7.3 J; 2.1%; P>0.05)	Study included three experimental treatment interventions, including 1) cooling vest; 2) silicate gel pack application; and, 3) water immersion (see table 2 and 7 for independent and comparative results) Cooling vest surface temperature = 10.7°C and mass = 1.4 kg Cold pack surface temperature = -16.0°C Muscle temperature data presented for n=7 subjects

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Castle et al., 2006 (59)^ Cont.	As above	20 min of -16°C silicate gel pack (3M, Birkshire, United Kingdom), covered with thin cotton cloth and secured to the anterior, lateral and posterior aspects of the thighs	As above	As above	As above	↑ Rate of rectal temperature cooling (0.012°C.min^{-1}; precooling) ↓ Rectal temperature (0.2°C; @ 0 min exercise) ↑ Rate of muscle temperature cooling (0.1°C.min^{-1}; precooling) ↓ Muscle temperature (1.0°C; @ 0 -16 min exercise) ↓ Skin temperature (~1-1.5°C; @ 0 min precooling - 2 min warm up, 2-8 min exercise) ↓ Thermal sensation (magnitude not reported; throughout precooling) ↓ Rate of increase in physiological strain index (0.08 units.min^{-1}) ↓ Peak physiological strain index (1.6 units) Weaker correlation between peak power output and physiological strain index (r = -0.75 v -0.95 for packs and control, respectively) Weaker correlation between peak power output and muscle temperature (r = -0.65 v -0.92 for packs and control, respectively) Weaker correlation between muscle temperature and work done (r = -0.70 v -0.92 for packs and control) ↔ Heart rate, Δ body mass ↔Thermal sensation, rating of perceived exertion, mean blood lactate concentration, oxygen uptake, respiratory exchange ratio @ end of exercise	Improvement ↑ Peak power output (49 W; 4.3%, $P<0.05$) ↑ Work done each sprint (17.7 J; 19.7%; $P<0.05$) ↑ Total work done (0.3 kJ; 4.5%; $P<0.01$) ↑ Peak power output in final sprint (Δ power output sprint # 20 - sprint #19 = 64 W, where control Δ↑ = 21 W; $P>0.05$)	As above

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Hornery et al., 2005 (78)	"Competitive, experienced (>5 y), trained (>150 km.wk^{-1}), local club, road and mountain bike cyclists" (n = 10 M; 4 F) ~57.1 ml.kg^{-1}.min^{-1}	10 min wearing cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia)	Cycling 30 min @ 75% $VO_{2\,max}$; 10 min recovery cooling; 20 min @ 75 min $VO_{2\,max}$; 10 min maximal performance trial	21˚C 33% r.h.	21˚C 33% r.h.	↑ Pre exercise psychological rating ("inspiration", 0.6 units) ↓ Oxygen consumption (0.04 L.min^{-1}; sub-maximal exercise) ↑ Heart rate (3 bpm; @ 5 min performance trial) ↑ Rating of perceived exertion (1 unit; @ final minute of sub-maximal exercise) ↑ post exercise psychological rating ("proudness", 0.5 units; "alertness", 0.6 units) ↑ Blood lactate concentration (1.4 mmol.L^{-1}; 6 min post exercise) ↔ Rectal temperature$^{\#,}$ mean skin temperature, total fluid loss$^{\$,}$ rating of perceived exertion (maximal exercise), thermal sensation, mid-exercise psychological rating	No substantial difference ↑ Total work done* (6.1 kJ; 3.7%; d=0.21 "small"; P=0.09) ↑ Minute by minute power output for 8th minute of performance trial (1.3 kJ; 8.3%; P=0.006)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Webster et al., 2005 (60)	"Competitive team sport athletes, active" (n = 8 M; 8 F) No subject characteristics provided to indicate performance capability	35 min wearing 359 g cooling vest filed with 2450 g coolant (total mass = 2810 g) with adjustable straps to provide a close fit; rate of melting = 1.44˚C(100g)$^{-1}$; heat capacity = 134.3 cal.g^{-1} (Vest A) during seated rest, stretching and warm up	Running 20 min seated rest; 5 min stretching; 10 min warm up @ 50% VO$_{2max}$; 30 min @ 70% VO$_{2max}$; Time trial to exhaustion @ 95% VO$_{2max}$	37˚C 50% r.h.	37˚C 50% r.h.	↓ Skin temperature (~3-7°C (abdominals), ~1-2°C (biceps); from start of preccoling - 10 min sub-maximal run) ↓ Rectal temperature (~0.3-0.5°C; throughout exercise) ↓ Sweat rate (~0.127 L.h^{-1}) ↓ Thermal sensation (~0.3-1 units; @ start of precooling - 10 min sub-maximal run) ↔ Heart rate	No substantial difference ↔ Time to exhaustion (raw data not reported)	
		35 min wearing 4444 g cooling vest filled with 2556 g coolant (total mass = 3000 g) with adjustable straps to provide a close fit; rate of melting = 1.5 ˚C(100g)$^{-1}$; heat capacity = 142.6 cal.g^{-1} (Vest B) during seated rest, stretching and warm up	As above	As above	As above	↓ Skin temperature (~3-9.5°C (abdominals), ~1-2°C (biceps); from start of preccoling - 10 min sub-maximal run) ↓ Sweat rate (~0.175 L.h^{-1}) ↓ Thermal sensation (~1-3 units; @ start of precooling - 10 min sub-maximal run) ↔ Hear rate, rectal temperature	Improvement ↑ Time to exhaustion (49.3 s; 30%, P≤0.01)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Arngrimsson et al., 2004 (20)	"Healthy, competitive collegiate and club, middle- and long-distance runners, accustomed to exercising in a hot environment" (n = 9 M, 8 F) M = 66.7 ml.kg^{-1}.min^{-1} F = 58.0 ml.kg^{-1}.min^{-1}	Neoprene vest with 8 pockets packed with ice (Neptune Wetsuits Australia, Smithfield West, Australia) worn during 38 min standardized sport-specific warm up	Running precooling; 5 km running TT (first 1.6 km externally paced)	32°C 60% r.h.	32°C 60% r.h.	↓ Rectal temperature* (0.21°C; 20 min warm-up - 3.2 km) ↓ Esophageal temperature* (0.28°C; 30 min warm-up - 1.6 km) ↓ Mean body temperature* (0.42°C; 10 min warm-up - 1.6 km) ↓ Mean skin temperature* (1.79°C; 10 min warm-up - 0 km) ↓ Heart rate* (11 bpm; 10 min warm-up - 1.6 km) ↓ Thermal comfort* (0.6 units, "felt cooler"; 30 min warm-up - 0 km) ↓ Rating of perceived exertion (@ 30 min warm-up) ↑ Heat storage (41 kJ; 29%) ↓ Δ Body mass (0.2 kg) ↔ Oxygen uptake, rise in rectal temperature ↔ Heart rate, rating of perceived exertion, blood lactate concentration, rectal temperature, skin temperature, esophageal temperature mean body temperature @ exhaustion	Improvement ↓ Time to complete 5 km (13 s; 1.1%; P<0.05)	

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Duffield et al., 2003 (79)	"1st grade field hockey players" (n = 7 M) No subject characteristics provided to indicate performance capability	Neoprene vest with pockets packed with cube ice (*Neptune Wetsuits Australia, Smithfield West, Australia) worn during recovery phases (5 min pre exercise and between each sprint protocol (2 x 5 min and 1 x 10 min); vest worn over exercise attire	Cycling intermittent sprint protocol 15 min seated rest; 5 min standardized warm up; 5 min recovery; 4 x 15 min intermittent sprint protocol (consisting of 5 s sprint; 55 s recovery @ varying intensities + extra sprints at 2.5, 7.5 and 12.5 min) separated by 5, 10 and 5 min rest periods	30˚C 60% r.h.	30˚C 60% r.h.	↓ Chest (skin) temperature (4.4-9.9˚C; start of each 15 min intermittent sprint protocol) ↓ Thermal comfort (1.6-2.3 units; @ 0, 20, 45 and 60 min intermittent sprint protocol) ↓ Mean rating of perceived thirst (0.2 units; throughout trial) ↔ Core temperature, skin temperature, heart rate, blood lactate concentration, Δ body mass, rating of perceived exertion, perceived ratings of "fatigue" or "vigour"	No substantial improvement? ↑ Total work done$^{\#}$ (9.6 kJ; 4.1%; d<0.3, "small"; P>0.05) ↑ Mean work done each sprint in sprint protocol 2 and 4 (0.1 kJ; 2.7%; d<0.3, "small"; P>0.05) ↑ Mean power output$^{\#}$ (22 W; 2.4%; d<0.3, "small"; P>0.05)	
Smith et al., 1997 (6)	"Triathletes" (n = 9 M)	Neoprene ice-vest (Neptune Wetsuits Australia, Smithfield West, Australia) worn during 15 min warm-up (75 - 175 W increasing 25 W every 3 min)	Cycling Standardised warm up; progressive maximal test to exhaustion (200 W increasing 25 W every 3 min)	32°C 60% r.h.	32°C 60% r.h.	↓ Skin temperature (10°C; local and transient) ↑ Thermal comfort ↔ Core temperature, rate of perceived exertion, blood lactate concentration	Improvement ↑ Time to exhaustion ↑ Peak power output (54 s; 3.2%; 9 W; P<0.05)	

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Yates et al., 1996 (61)	"Well trained, competitive rowers" (n = 7 M, 4 F) 57.0 ml.kg^{-1}.min^{-1}	Neoprene ice-vest (Neptune Wetsuits Australia, Smithfield West, Australia) worn during 30 min warm-up	Rowing Standardised warm up; 10 min seated rest; 2000 m rowing time trial (externally paced for 1000 m; self-paced for 1000 m)	32°C 60% r.h.	32°C 60% r.h.	↓ Rectal temperature (0.34˚C; persisted through warm up) ↓ Δ Body mass (0.17 kg; @ end of warm-up) ↑ Thermal comfort (persisted throughout) ↓ Rate of perceived exertion (0.6 units) ↓ pH (0.061) ↔ Mean skin temperature, oxygen consumption, blood lactate concentration, heart rate	Improvement ↓ Time to complete 1000 m (3 s; 1.3%; P=0.03)	
Myler et al., 1989 (19)	"Range of Australian national team to second grade club rowers" (n = 5 M, 7 F) No subject characteristics provided to indicate performance capability	5 min intermittent application of ice packed in damp towels applied to the head, face, arms and thighs; after warm-up	Rowing 8 min seated rest; 10 min standardised warm-up; 5 min precooling; 6 min maximal rowing time trial	30˚C 30% r.h.	30˚C 30% r.h.	↓ Mean skin temperature (4.3°C; persisted throughout exercise) ↓ pH (0.05) ↓ Tympanic temperature (0.7˚C; persisted throughout exercise) ↓ Heart rate (3 bpm; persisted throughout exercise) ↔ Oxygen consumption, ventilation, carbon dioxide output, respiratory exchange ratio, blood lactate concentration)	Improvement ↑ Distance covered (17 m; ~1%; equivalent to 4-5 s over 2000 m; P=0.02)	

BM = body mass, CI = confidence interval, d = effect size, F = females, M = males, P = probability, r = correlation coefficient, RHL = radiant heat load, W = watts, ^ indicates study is reported multiple times.

Table 2.4 Cold water / fluid studies (internal)

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Burdon et al., 2010 (73)^	"Healthy, non-acclimatized cyclists, regionally competitive" (n = 7 M) 59.4 ml.kg^{-1}.min^{-1}	4˚C, 7.4% CHO beverage @ 10 min intervals (2.3 ml.kg^{-1} BM) during 90 min sub-maximal component of the test	Cycling 90 min @ 63% VO_{2peak}; 5 min rest; 15 min maximal time trial	Treatment undertaken during exercise rather than pre-cooling	28˚C 70% r.h. 3.6 km.h^{-1}	*Steady state:* ↓ Δ Skin temperature (0.9˚C) ↓ Δ Mean body temperature (Δ 0.4˚C) ↓ Heat storage (15 J.˚C^{-1}.min^{-1}) ↓ Convective heat flow (7.1 W.m^{-2}) *Performance trial:* ↓ Skin temperature (0.7˚C @ 0 min) ↓ Mean body temperature (0.5˚C @ 0 min) ↔ Rectal temperature at time trial end	Improvement ↑ Total work / power output (11 kJ / 12 W; 4.9%; P=0.004)	Study included two experimental treatment interventions, including 1) ice puree ingestion; and, 2) 4˚C beverage ingestion (see table 5 and 7 for individual and comparative results) Control was a 37 deg C beverage matched for volume
Mundel & Jones, 2010 (74)	"Healthy, non-heat-acclimated" (n = 9 M) 54.0 ml.kg^{-1}.min^{-1} MAP = 320 W	25 ml swill held in the mouth for 10 s; 19˚C L(-)-menthol (0.01%) solution every 10 min duing exercise	Cycling time trial to exhaustion @ 65% W_{max} (222 ± 23 W)	Treatment undertaken during exercise rather than pre-cooling	34˚C 27% r.h. 0.5 m.sec^{-1}	↑ Ventilation (8 L.min^{-1}; persisted throughout) ↓ Cardiopulmonary rate of perceived exertion (15%) ↔ Rectal temperature, mean skin temperature, sweat rate, heart rate, oxygen consumption, carbon dioxide production, blood lactate	Improvement ↑ Time to exhaustion (5 min; ~9%; P<0.043)	Orange flavored placebo solution provided as control and drinking water was available *ad libitum* Authors propose that performance improvements were brought about by stimulating the oropharyngeal cold receptors by menthol as evidenced by a reduced effort of breathing

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Lee et al., 2008 (75)	"Moderately active, recreational, non-heat acclimatized" (n = 8 M) 57.8 $ml.kg^{-1}.min^{-1}$	3 x 300 ml 4˚C flavored water ingestion 30, 20 & 10 min before exercise + 100 ml of same beverage every 10 min during exercise	Cycling 45 min seated rest; time trial to exhaustion @ 66% $VO_{2\ peak}$	27˚C 20% r.h.	35˚C 60% r.h.	↓ Rectal temperature (0.5˚C @ start of time trial) ↓ Mean rectal temperature (0.3˚C; during time trial) ↓ Skin temperature (0.3-0.7°C; @ 20-45 min exercise) ↓ Mean body temperature (from -15 to 45 min exercise) ↓ Body heat content (from -10 to 45 min exercise) ↓ Heart rate (5-8 bpm; @ -5-35 min exercise) ↓ Sweat rate (0.26 $L.h^{-1}$) Correlation of skin temperature & sweat rate @ 0-45 min (r=0.65, P<0.01) ↓ Thermal sensation (3 units; @ 40 min seated rest throughout exercise) ↓ Rate of perceived exertion (1 unit; throughout exercise) ↔ Rectal temperature, rate of rise in rectal temperature, skin temperature, mean body temperature, body heat content, heart rate, thermal sensation, rate of perceived exertion @ exhaustion	Improvement ↑ Time to exhaustion (11.9 min; 23%; P<0.001)	Control was same beverage @ 37 deg C, matched for volume
Lee et al., 2008 (115)	"Moderately active, recreational, non-heat acclimatized" (n = 8 M) 53.8 $ml.kg^{-1}.min^{-1}$	4 x 400 ml 10˚C flavored water ingestion 30, 45, 60 and 75 min of 90 min submaximal exercise bout	Cycling 90 min @ 50% $VO_{2\ peak}$, 60 $rev.min^{-1}$; time trial to exhaustion @ 95% $VO_{2\ peak}$, 57-63 rpm	25˚C 60% r.h. Wet bulb globe temperature = 21˚C Thermal stress = "moderate"	25˚C 60% r.h. Wet bulb globe temperature = 21˚C Thermal stress = "moderate"	↓ Heart rate (2 bpm; @ 30 -90 min sub-maximal exercise) ↔ Rectal temperature, mean skin temperature, mean body temperature, total body heat content; volume of urine production; mean sweat losses; rating of perceived exertion; rating of thermal sensation; rating of stomach fullness	No substantial difference ↓ Time to exhaustion (8 s; 3.8%; P>0.05)	Study included two experimental treatment interventions, including 1) 10˚C; and, 2) 50˚C compared to a control (37˚C) and therefore only the 10˚C beverage ingestion is reported

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Lee & Sherriffs, 2007 (27)	"Moderately active, recreational, non-heat acclimatized" (n = 9 M) 50.0 ml.kg^{-1}.min^{-1}	1 L of 10˚C flavored water ingestion @ 30-40 min sub-maximal cycling, given as 4 x 250 ml every 2.5 min	Cycling 90 min @ 53% VO$_{2\ peak}$, 60-80 rev.min^{-1}; time trial to exhaustion @ 95% VO$_{2\ peak}$, >60 rpm	25˚C 60% r.h. Wet bulb globe temperature = 21˚C Thermal stress = "moderate"	25˚C 60% r.h. Wet bulb globe temperature = 21˚C Thermal stress = "moderate"	↓ Mean skin temperature (0.2˚C; @ 35 min - 90 min sub-maximal exercise) ↓ Thermal sensation (~1.8 units; @ 40-45 min sub-maximal exercise) Correlation between average mean skin temperature @ 30-90 min sub-maximal exercise and total sweat loss (r=0.72; P<0.01) ↔ Rectal temperature, mean body temperature, Δ total body heat content, heart rate, sweat loss, percentage change in plasma volume, mean serum osmolality, serum sodium, chlorine or potassium, blood glucose concentration, rating of perceived exertion	No substantial difference ↑ Time to exhaustion* (20 s; 9.3%; P>0.05)	Study included two experimental treatment interventions, including 1) 10˚C; and, 2) 50˚C compared to a control (37˚C) and therefore only the 10˚C beverage ingestion is reported *Time trial to exhaustion component of the test was performed by only 7 out of 9 subjects who reported feeling unwell but had already completed the 90 min sub-maximal component The 1 L volume flavored water was tolerated well by all subjects
Mundel et al., 2006 (82)	"Healthy, non-heat acclimatized" (n = 8 M) 54.0 ml.kg^{-1}.min^{-1} W_{max} = 306 W	*Ad libitum* 4˚C flavored water ingestion (0.2% carbohydrate) during exercise with a minimum of 300 ml every 15 min to maintain euhydration	Cycling time trial to exhaustion @ ~68.5% VO$_{2\ max}$	34˚C 28% r.h. 0.5 m.s^{-1}	34˚C 28% r.h. 0.5 m.s^{-1}	↑ Volume of beverage consumed (0.3 L.h^{-1}; throughout trial) Attenuated rise in rectal temperature (0.4°C.h^{-1}) Attenuated rise in heart rate (6 bpm.h^{-1}) ↔ Mean skin temperature, heart rate, ventilation, oxygen uptake, respiratory exchange ratio, sweat rate, heat storage, blood lactate concentration, blood glucose concentration, blood prolactin concentration and release, Δ plasma volume, rating of perceived exertion	Improvement ↑ Time to exhaustion* (7 min; 12.7%; P=0.04)	Control was same beverage served at 19˚C *6 out of 8 subjects cycled longer following ingestion of 4˚C beverage Authors suggest that the 4˚C beverage was more palatable than the 19˚C as demonstrated by a significantly greater intake, and that it significantly improves endurance, probably as a result of reducing the exercise-induced rise in core temperature

CHO = carbohydrate, M = males, MAP = maximal aerobic power, P = probability, r = correlation coefficient, rpm = revolutions per minute, W = watts, ^ indicates study is reported multiple times.

Table 2.5 Ice / slurry studies (internal)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Siegel et al., 2012 (52)^	"Healthy, non-heat acclimatised" (n = 8 M) 54.2 ml.kg^{-1}.min^{-1}	7.5 g.kg^{-1} BM of a -1˚C, 5% CHO ice slurry (given as 1.25 g.kg^{-1} BM every 5 min)	Running 30 min seated rest; 30 min precooling; time trial to exhaustion @ ventilatory threshold$_1$ speed on treadmill	34˚C 52% r.h.	34˚C 52% r.h.	↓ Rectal temperature (0.34˚C; @ 25 min precooling - 5 min exercise) ↑ Rise in rectal temperature (0.06˚C.5 min^{-1}; during exercise) ↑ Rectal temperature (0.28˚C; @ exhaustion) ↑ Heat loss (-12.08 W.m^{-2}; during precooling) ↑ Heat storage (26.42 W.m^{-2}; during exercise) ↓ Thermal sensation (0.6; during precooling / 0.7;@ 0-35 min exercise) ↓ Rate of perceived exertion (1 unit; @ 0-40 min exercise) ↔ Mean skin temperature, mean body temperature ↔ Heart rate, thermal sensation and rate of perceived exertion @ exhaustion	Improvement ↑ Time to exhaustion (6.0 min, 12.8%; d = 0.77, 90% CI = -0.07-1.6, "trivial to large benefit"; P=0.005)	Study included two experimental treatment interventions, including 1) water immersion; and, 2) ice slurry ingestion (see table 2 and 7 for individual and comparative results) Note that control and water immersion treatments included intake of 7.5 g.kg^{-1} of 37˚C 5% CHO drink to control for fluid intake associated with ice slurry 6 out of 8 subjects experienced sphenopalatineganglioneuralgia ("brain freeze") with ice slurry ingestion

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Siegel et al., 2010 (47)	"Healthy" (n = 10 M) 56.4 ml.kg^{-1}.min^{-1}	7.5 g.kg^{-1} BM of a -1˚C, 5% CHO ice slurry (given as 1.25 g.kg^{-1} BM every 5 min) during seated rest	Running 30 min precooling; time trial to exhaustion @ ventilatory threshold$_1$ speed on treadmill	25˚C	34˚C 54-56% r.h.	↓ Rectal temperature (0.41˚C; @ 20 min ice ingestion - 30 min exercise) ↓ Skin temperature (0.22 - 0.36˚C; @ 20 min ice ingestion - 0 min exercise) ↓ Mean body temperature (0.38˚C; @ 0 - 30 min exercise) ↑ Negative heat storage (-10.44 W.m^{-2}; precooling) ↓ Forced vital capacity (0.14 L; precooling) ↑ Heat storage (21.17 W.m^{-2}; during exercise) ↓ thermal sensation ($\leq$1.6 units; following during ingestion - 30 min exercise) ↓ Rating of perceived exertion (~1 unit; @ 10, 20, 25 and 30 min exercise) ↑ Rectal temperature (0.31˚C; @ exhaustion) ↑ Mean body temperature (0.32; @ exhaustion) ↔ Thermal sensation and rating of perceived exertion @ exhaustion ↔ Mean rate of heat storage, heart rate, sweat rate, hydration status	Improvement ↑ Time to exhaustion* (9.5 min, 23.3%; P=0.001)	Control treatment was 7.5 g.kg^{-1} BM of a 4˚C, 5% CHO beverage matched for timing of ingestion 3 out of 10 subjects experienced sphenopalatineganglioneuralgia ("brain freeze") with ice slurry ingestion All 10 subjects recorded longer run time to exhaustion following ice slurry ingestion Authors advocate the use of ice slurry ingestion as a practical precooling strategy for improving endurance performance
Burdon et al., 2010 (73)^	"Healthy, non-acclimatized cyclists, regionally competitive" (n = 7 M) 59.4 ml.kg^{-1}.min^{-1}	37˚C, 7.4% CHO beverage @ 10 min intervals + 30 ml of 7.4% CHO ice puree @ 5 min intervals and held in the mouth for 30 s before swallowing (2.3 ml.kg^{-1} BM)	Cycling 90 min @ 63% VO_{2peak}; 5 min rest; 15 min maximal TT	Treatment undertaken during exercise rather than pre-cooling	28˚C 70% r.h. 3.6 km.h^{-1}	↓ Mean body temperature (0.4˚C @ 0 min) ↑ Δ Mean body temperature (Δ 0.6˚C) ↔ Rectal temperature	No substantial difference ↑ Total work performed (4 kJ; 1.6%; P=0.62) ↑ Power output (2 W; 0.7%; P=0.31)	Study included two experimental treatment interventions, including 1) ice puree ingestion; and, 2) 4˚C beverage ingestion (see table 4 and 7 for individual and comparative results) Control was a 37 deg C beverage matched for volume

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Ihsan et al., 2010 (62)	"Endurance trained, regularly competitive, cycled > 4 sessions.wk^{-1}; cycled > 150 km.wk^{-1}; cyclists and triathletes" (n = 7 M) No subject characteristics provided to indicate performance capability	6.8 g.kg-1 BM of 1.5˚C ice slurry ingestion, given in serial aliquots of 150-200 g @ 8-10 min intervals	Cycling 30 min precooling; 10 min standardised warm up; 1200 kJ time trial	Not reported but assumed under typical laboratory conditions	30˚C 74% r.h.	↓ Gastrointestinal temperature (~0.4-0.9°C; @ 20 min precooling - 100 kJ cycling) ↓ Thermal sensation (≤1.5 units; @ end of precooling; 200 kJ cycling) ↔ Mean skin temperature, heart rate, rating of perceived exertion, blood lactate	Improvement ↓ Time to complete 1200 kJ work (348 s; 6.5%; P=0.49) ↓ Time to complete 100 kJ intervals (35-42 s; @ 900 - 1100 kJ; P<0.03) ↑ Mean power output (16 W; 6.9%; P=0.06)	Control treatment was 6.8 g.kg-1 BM of 27˚C tap water matched for timing of ingestion Authors acknowledge the practicality of ice ingestion as a precooling strategy; and the combined benefits of ice ingestion in allowing the athlete to cool and hydrate simultaneously
Stanley et al., 2010 (63)	"Trained (≥ 10 h.wk^{-1}), non-heat acclimatised cyclists and triathletes" (n = 10 M) 60.0 ml.kg^{-1}.min^{-1}	-0.8˚C, 5.7% CHO ice slurry ingested intermittently 45 min (400 ml), 35-, 25- and 15-min (each 200 ml) as recovery cooling strategy	Cycling 75 min @ 58% peak power output; 50 min recovery cooling; performance trial based on a individualized set amount of work (calculated as 75% peak power output x 30 min)	34˚C 60% r.h. 18 km.h^{-1}	34˚C 60% r.h. 18 km.h^{-1}	↓ Rectal temperature (0.4˚C; @ 20 min recovery cooling - 10 min exercise) ↑ Rise in rectal temperature (0.05˚C.min^{-1}; @ 5-10 min exercise) ↓ Physiological strain index (0.9; @ end of exercise) ↓ Mean thermal sensation (throughout trial) ↓ Sweat loss (41%; during exercise) ↔ Heart rate; Δ plasma volume, blood variables ↔ Rectal temperature @ exhaustion	No substantial difference ↓ Time to complete matched volume of work (33 s; 1.9%; 5 W; d = 0.22; P=0.263)	Control was 18.5˚C beverage of similar volume. Magnitude of performance benefit from ice slurry may have been underestimated since it was compared to cooling via cold beverage ingestion

BM = body mass, CHO = carbohydrate, CI = confidence interval, d = effect size, M = males, P = probability, W = watts, ^ indicates study is reported multiple times.

Table 2.6 Combination studies: a) external and external, b) external and internal

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
a. External and External								
Skein et al., 2011 (119)	"Healthy, physically active, regular sub-elite team sport exercise (> 3 training sessions.wk^{-1}, 1-2 competition games.wk^{-1}) (n = 10 M) No subject characteristics provided to indicate performance capability	*Water immersion and ice towels* 15 min @ 10˚C water immersion to the level of the suprasternal notch in a custom design bath (CSU, Australia) followed by 5˚C iced towels placed over the shoulders and torso during post-precooling isometric contraction testing	Intermittent-sprint running protocol 15 maximal isometric contractions; 15 min precooling; 15 isometric contractions repeated; 3 min warm up; 50 min self-paced intermittent sprint protocol (consisting of a 15 m maximal sprint every minute separated by rotation of hard running, jogging, walking or deep-squat double-leg bounds)	19˚C 24% r.h.	31˚C 33% r.h.	↓ Gastrointestinal temperature (0.57˚C; @ 0 - 20 min exercise) ↓ Skin temperature (>12˚C; @ 3 - 15 min precooling) ↓ Heart rate (~10 bpm; @ 10 min precoling - 0 min exercise) ↓ Physiological strain index (1.6-2 units; @ 10 - 30 min exercise) ↓ Rating of perceived exertion (0.4 units; @15 min exercise) ↓ Sweat rate (0.4 kg; exercise) ↔ Blood pH, blood lactate concentration, blood glucose concentration, thermal stress ↓ Δ Percentage maximal voluntary contraction post-pre exercise (Δ 12%; d = 1.2 "large"; P>0.05) ↔ Maximal voluntary torque and voluntary activation, twitch contractile properties (peak potential twitch torque, rate of torque development, time to peak torque, rate of relaxation, half relaxation time (although d=0.9 "large"), contraction duration); all P>0.05	No substantial difference ↔ Total and mean sprint time, hard running distance; jogging distance, walking distance, bounding distance (all P>0.05) ↑ Distance covered (~50 m; @ 41 - 50 min exercise; d=0.8, "large"; P>0.05)	Study included two experimental treatment interventions 1) precooling; and, 2) preheating. Only precooling data are detailed here Authors propose that the reduced sprint times following precooling may be due to the minimal (3 min) warm up provided and acknowledged that the practice was not a likely scenario in a competition environment

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Minett et al., 2011 (53)^	"Well trained, regional level, cricket and rugby union athletes, training (≥3 d.wk^{-1}) involved skill-based, strength and conditioning sessions " (n = 10 M) No subject characteristics provided to indicate performance capability	Head and hands cooling 20 min pre-exercise and 5 min mid-exercise application of towel soaked in 5°C water placed over the head and neck (Head) while each hand was immersed in 9°C water to the level of the wrist (Hands)	Intermittent-sprint running protocol precooling; 5 min warm up; 35 min intermittent-sprint protocol (Spell 1); 15 min recovery; Spell 1 repeated (Spell 2)	33°C 33% r.h.	33°C 33% r.h.	↓ Gastrointestinal temperature (throughout trial) ↓ Skin temperature (during precooling) ↓ Heart rate (during exercise) Maintained MVC (↔ Δ MVC pre-post exercise) ↓ Rating of perceived exertion (0.3 units; during exercise) ↓ Mean thermal sensation (0.6 units; throughout trial) ↔ Blood biochemical measured, time to peak torque, sweat loss	Improvement ↓ Mean Spell 2 sprint time (0.08 s; d = 1.07) ↓ Spell 1 decline in sprint time (1.85%; d = 1.26) ↑ Total running distance (231 m; d = 0.81; P=0.001) ↑ Total Spell 1 hard running distance (64.4 m; P=0.01) ↑ Total Spell 2 hard running distance (96.4 m; d = 0.87; P=0.000) ↑ Total Spell 1 jogging distance (20.8 m; P=0.01) ↑ Mean and total Spell 2 jogging distance (43.1 m; P=0.01)	Study included two experimental treatment interventions, including 1) head; 2) head and hands; and, 3) whole body, to investigate precooling in dose response manner (see table 3 for individual results and table 7 for comparative results)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Minett et al., 2011 (53)^ Cont.	As above	Head and hand cooling plus cooling vest and thigh cooling pack As above with the addition of a cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Berleigh Heads, Australia) covering the torso and frozen ice packs containing a refrigerant polymer applied to the quadriceps (Techni Ice , Frankston, Australia)	As above	33˚C 33% r.h.	33˚C 33% r.h.	↓ Gastrointestinal temperature (throughout trial) ↓ Skin temperature (throughout trial) ↓ Heart rate (during exercise) ↓ Sweat loss (0.4 L; @ end of exercise) Maintained MVC (↔ Δ MVC pre-post exercise) ↓ Blood lactate concentration (mid-exercise) ↓ Rating of perceived exertion (0.7 units; during exercise) ↓ Mean thermal sensation (1.1 units; throughout trial) ↔ Blood biochemical measures, time to peak torque	Improvement ↓ Mean Spell 2 sprint time (0.07 s; d = 0.94) ↓ Spell 1 decline in sprint time (1.29%; d = 0.87) ↓ Spell 2 decline in sprint time (1.05%; P=0.004) ↑ Total running distance (420 m; d = 1.26; P=0.001) ↑ Total hard running distance (309.5 m; d = 1.49; P=0.001) ↑ Total Spell 1 jogging distance (44.4 m; P=0.03) ↑ Total Spell 2 jogging distance (52.6 m; P=0.02)	As above

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Duffield et al., 2010 (64)	"Moderate- to well-trained cyclists" (n = 8 M) Lactate threshold = 221 W	Water immersion and thigh cooling pack 20 min lower-body (to level of greater trochanter) 14˚C water immersion followed by application of gel-based cold packs (3M, Boots, Nottingham, UK) to thigh during warm up	Cycling Water immersion; 5 min warm up unloaded cycling @ 60 rpm; 40 min cycling time trial	22˚C	33˚C 50% r.h. No convective airflow (fan)	↓ Skin and mean body temperature (1-3°C; during precooling until 20 min time trial) ↓ Muscle temperature (10°C; @ end of immersion, start of time trial) ↓ Rectal temperature (0.2°C; @ 5 - 15 min of time trial) ↑ Thermal stress (@ end precooling - 15 min of time trial) ↓ Blood lactate concentration (@ end of immersion, start of time trial) ↓ sweat loss (300 ml; @ completion of time trial) ↔ Heart rate, rate of perceived exertion, blood glucose ↔ Blood lactate @ exhaustion	Improvement ↑ Mean power / estimated distance covered (20 W, 11% / ~1.3 km, ~7%; P = 0.05) ↑ % of lactate threshold maintained (10%)	Differences in minute power output between conditions were present during the last 10 min time trial (29-33 min & 37-40 min) when a significantly increased power output was produced in the cooling condition (P<0.02), despite the measured cooling-induced physiological benefits had dissipated Authors propose that the performance advantages of precooling result from the prevention of the down-regulation of exercise intensity present in the heat

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Quod et al., 2008 (24)^	"Well-trained cyclists, members of local cycling community, 6 y cycling experience" (n = 6 M) 71.4 ml.kg^{-1}.min^{-1} Maximal aerobic power = 384 W	*Water immersion and cooling jacket* 30 min of 28.8 - 24°C water immersion to the level of the neck in inflatable bath (Portacovery, Canberra, Australia) with ice progressively added, followed by 40 min wearing a phase change material waist-length jacket with long arms & hood (RMIT University, Melbourne, Australia)	Cycling 70 min precooling (consisting of 30 min plunge + 40 min jacket); 20 min standardized warm up; ~40 min performance trial (consisting of 20 min @ 75% of maximal aerobic power; ~ 20 min self paced maximal effort matched for total work (kJ))	*Plunge* 24°C 42% r.h. *Jacket* 34°C 41% r.h. Free of direct air flow and radiant heat source	34˚C 41% r.h. 18-20 km.h^{-1} RHL = 6 x 500 W lights @ 2 m	↓ Rectal temperature (0.7°C; @ 20 min jacket - 25 min exercise) ↓ Skin temperature (8.1°C; @ start of plunge - 15 min warm up) ↓ Mean body temperature (0.4°C; throughout trial) ↑ Δ Mean body temperature (0.7°C) ↑ Negative heat storage (-82.6 W.m^{-2}; precooling) ↓ Heart rate (14 bpm; @ 15 min jacket cooling - 5 min warm up) ↓ Thermal sensation (during precooling - 15 min warm up and @ 0, 10 and 20 min exercise) ↑ Bladder void mass (0.39 kg) ↑ Blood lactate (1.7 mmol.L^{-1}; @ exhaustion) ↔ Rating of perceived exertion, Δ body mass; estimated sweat loss, urine specific gravity, blood bicarbonate, blood pH, blood glucose	Improvement ↓ Time to complete performance task (42 s; ↑ 12 W; 3.8%; P=0.009)	Study included two experimental treatment interventions, including 1) Jacket; and; 2) Plunge + Jacket (see table 3 and 7 for individual and comparative results) Authors report 1.8% performance improvement which should read as 3.8%
Ross et al., 2011 (65)^	"Well trained, A-grade, local community, cyclists" (n = 11 M) 71.6 ml.kg^{-1}.min^{-1}	Water immersion and cooling jacket 10 min 10˚C water immersion to the level of the mesosternale followed by ~ 20 min wearing a phase change material waist-length jacket with long arms & hood (RMIT University, Melbourne, Australia)	Cycling 60 min heat stabilisation; 30 min precooling; 20 min standardised warm up; 10 min final preparation; 46.4 km maximal time trial	34˚C 54% r.h.	34˚C 54% r.h. variable fan speed	↓ Rectal temperature (~1.2˚C; @ 25 min precooling - 0 min exercise) ↓ Percentage of maximal heart rate (6-11%; @ 5 -10, and 20 - 25 min warm up) ↓ Thermal comfort (~4.6 units; @ 5 min precooling - 3 min warm up) ↔ Body mass; stomach fullness ↔ Rectal temperature, heart rate, blood lactate concentration; subjective ratings (effort given, sensation, motivation, comfort) during exercise	No substantial improvement ↑ Mean climb 1 power output (6 W; 1.8%; "trivial to large benefit"; P=0.1) ↑ Time to complete descent 1 (10.7 km) (22.5 s; 2.8%; "trivial to extremely large harm"; P=0.07) ↔ Mean power output (3 W; 1.1%; "unclear"; P=0.43)	Study included two experimental treatment interventions, including 1) water immersion + cooling jacket; and, 2) ice-slushie ingestion + iced towels (see table 6b and 7 for combined and comparative results)

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Duffield & Marino, 2007 (102)^	"Moderate- to well-trained, club-level rugby players" (n = 9 M) No measure of performance characteristic provided	Water immersion plus cooling vest. Water immersion 15 min @ 14˚C water immersion to the level of the suprasternal notch in a custom design bath (CSU, Australia) plus the repeated exposure of wearing cooling vest with 7 integrated crystal-filled cooling panels (Arctic Heat, Burleigh Heads, Australia), worn during 9 min warm up and 10 min recovery	Intermittent-sprint running protocol 15 min water immersion; 9 min standardized warm up; 30 min intermittent-sprint protocol (first half); 10 min recovery cooling; 30 min intermittent-sprint protocol repeated (second half)	32˚C 30% r.h. subjects seated within 5 m of radiant heat source	32˚C 30% r.h.	↓ Gastrointestinal temperature (~0.3 - 0.9; @ 0 min warm up - 40 min exercise) ↓ Mean skin temperature (~2-14°C; @ 0 min warm up - 10 min exercise) ↓ Chest temperature (~3.5-14°C; @ 0 min warm up - 10 min exercise, 40 min exercise) ↑ Negative heat storage (~0.5-1 $J.g^{-1}$; @ 0 min warm up - 0 min exercise) ↓ Heart rate (~10-24 bpm; @ 0 min warm up - 5 min exercise) ↓ Sweat loss (0.4 kg) ↓ Thermal comfort (3.4 units; @ 0 min warm up - 0 min exercise, 40 min exercise) ↔ Blood lactate concentration, blood pH, blood sodium, blood potassium, hematocrit, rating of perceived exertion	No significant difference? ↑ Mean first half hard run distance covered (14.1 m; 11.5%; d = >0.8, "Large") ↑ Mean second half hard run distance covered (15.1 m; 13.3%; d = >0.8, "Large") ↑ Total first half hard run distance covered (127.9 m; 11.6%; d = >0.8, "Large") ↑ Total second half hard run distance covered (136.1 m; 13.3%; d = >0.8, "Large") ↔ Mean and total jogging distance ↔ Mean and total walking distance ↔15 m sprint time ↔ Total sprint time for all sprints ↔ Percentage decline in sprint time (All P>0.05)	Study included two experimental treatment interventions, including 1) cooling vest repeated exposure; and, 2) water immersion + cooling vest repeated exposure (see table 3 and 7 for independent and comparative results) Authors raise the possibility that the effects of precooling on intermittent-sprint performance are minor and only manifest when the thermal and exercise stress is sufficient to induce heat strain Despite non-significant sub-maximal distances covered, authors pool data and report a 372.5 m increase in total sub-maximal running distance (8.3%) but do not indicate the statistical significance of this improvement. The concluding statement featured in this study suggests that the ergogenic benefits of combined cooling via water immersion and cooling vest may be evident during sub-maximal bouts of exercise.

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Hornery et al., 2007 (84)	"Highly-trained (15-20 $h.wk^{-1}$), >5 y competitive tournament experience, tennis players" (n = 12 M) No measure of performance characteristic provided	*Water immersion plus cooling jacket* 30 min 29-24°C water immersion to the level of the sternum in inflatable bath (Portacovery, Canberra, Australia) with ice progressively added plus waist length, sleeveless cooling jacket and hood (RMIT University, Melbourne, Australia) worn during breaks in play	Simulated tennis match play 30 min precooling; prolonged simulated match play (4 sets; 2 h 40 min) against a ball machine on indoor court	21°C 48-51% r.h.	21°C 48-51% r.h.	↑ Gastrointestinal temperature (@ end of precooling) ↓ Thermal strain (@ end of precooling) ↔ Heart rate, rating of perceived exertion, body mass, total fluid loss, urine specific gravity, blood glucose concentration, blood lactate concentration, creatine kinase, prolactin	No performance benefit ↔ Serve and ground stroke velocity and accuracy ↔ Serve kinematics ↔ Perceptual skill (All $P>0.05$)	Study included two other potential ergogenic treatment interventions during prolonged simulated tennis match conditions, including the ingestion of: 1) caffeine; and, 2) carbohydrate and hence these data are not included Performance findings might be explained by insufficient warm-up prior to assessment and the temperate environmental conditions which failed to induce sufficient thermoregulatory strain on subjects

Reference	**Subjects**	**Precooling Protocol**	**Exercise Protocol**	**Environment (Precooling)**	**Environment (Exercise)**	**Physiological outcomes (compared to control)**	**Performance (compared to control)**	**Comment**
Cotter et al., 2001 (66)	"Habitually active" (n = 9 M) 51.0 ml.kg^{-1}.min^{-1}	*Cold air exposure and cooling vest plus thigh cooling cuffs* Repeated 45 min 3˚C air exposure while wearing a cooling vest containing ~1.2 L of a water-gel mix (Cool.1.nz, Dunedin, New Zealand) on the torso and ~4˚C water-perfused cryogenic cuffs (Aircast Autochill System, Aircast, NJ, USA) on the anterior and lateral thigh surfaces	Cycling (see companion paper for preliminary methodology); ~15 min recovery; 45 min precooling; 35 min cycling (including 20 min @ 65% VO2 peak + 15 min self-paced maximal performance trial)	31˚C (or cold air)	35˚C 60% r.h. 0.5 m.s^{-1}	↓ Body heat content (~401 kJ) ↓ Mean core temperature (2.8˚C; throughout exercise) ↓ Skin temperature (~13˚C; throughout exercise) ↓ Muscle temperature (1.5˚C; @ 0 min exercise) ↓ Heart rate (~14 bpm; @ 0 - 20 min exercise) ↓ Oxygen pulse (2.5 ml.beat-1; @ 5 min exercise) ↓ Forearm blood flow (7-12 ml.100 ml tissue^{-1}.min^{-1}; @ 0 - 5 and 35 min exercise) ↓ Thermal sensation (~ 2 units; @ 0 -20 min exercise) ↑ thermal discomfort (~0.8 units; @ 0 - 5 min exercise) ↓ Rating of perceived exertion (~1 unit; @ 0 - 20 min exercise) ↓ Rating of leg exertion (~0.5 unit; @ 20 min) ↔ Oxygen consumption, sweat rate, urine production	Improvement ↑ Power output (0.39 W.kg^{-1}; 15.5%; P=0.00)	Only physiological outcomes and performance data reported for 35 min performance trial following repeated cooling exposure (see companion paper - Sleivert et al., 2001) Study involved two experimental treatment interventions including, 1) cold air exposure, cooling vest + thigh cooling; and, 2) cold air exposure, cooling vest + thigh warming and therefore only treatment intervention with thigh cooling is reported Authors suggest that cooling garments should not be used on the local musculature involved in exercise if there is a requirement for significant anaerobic work to be performed. Alternatively, authors suggest that it may be unimportant during sustained heavy work where local muscle heat production and temperature of arterial blood perfusion of the muscle is high

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Sleivert et al., 2001 (81)	"Habitually active" (n = 9 M) 51.0 ml.kg^{-1}.min^{-1}	*Cold air exposure and cooling vest plus thigh cooling cuffs* 45 min 3˚C air exposure while wearing a cooling vest containing ~1.2 L of a water-gel mix (Cool.1.nz, Dunedin, New Zealand) on the torso and ~4˚C water-perfused cryogenic cuffs (Aircast Autochill System, Aircast, NJ, USA) on the anterior and lateral thigh surfaces	Cycling 45 min precooling; 6 min active warm up; 6-7 min rest; 45 s maximal sprint	31˚C (or cold air)	33˚C 60% r.h.	↓ Core temperature (~0.6˚C; @ end of precooling) ↓ Skin temperature (~7.5˚C; @ end of precooling) ↓ Muscle temperature (~3˚C; without warm up) ↓ Heart rate (~15 bpm; before and during power test) ↓ Forearm blood flow (~5 ml.100 ml tissue^{-1}.min^{-1}; pre-exercise) ↔ Muscle temperature after warm up	Impairment ↓ Peak power output with and without warm up, respectively (-3.5%; -7.5%; P<0.05) ↓ Mean power output with and without warm up, respectively (-4%; -7.5%; P<0.05)	Study included two experimental treatment interventions, including 1) cold air exposure, cooling vest + thigh cooling; and, 2) cold air exposure, cooling vest + thigh warming and therefore only treatment intervention with thigh cooling is reported

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
b. External and Internal								
Clarke et al., 2011 (67)^	"University soccer players" (n = 12 M) 61.3 ml.kg^{-1}.min^{-1}	*Ice vest application and carbohydrate beverage ingestion* 60 min wearing cooling vest (Cool Vest, Jackson Technology Solutions Ltd., Kent, UK) pre-exercise plus 15 min mid-exercise recovery plus 18 g.kg^{-1} BM (1,338 ml) of a 6.6% CHO beverage (given as 6 x 223 ml @ 15 min intervals during exercise)	"Soccer specific Intermittent running protocol Precooling; 45 min standardised intermittent sprint activity (1st half); 15 min recovery; 1st half repeated (2nd half); Performance tests*"	30.5°C 42.2% r.h.	30.5°C 42.2% r.h.	↓ Gastrointestinal temperature (0.6˚C, @ 60 precooling - 30 min exercise; and, 0.3-0.4˚C, @ 60-90 min exercise) ↓ Muscle temperature (0.9˚C; @ 60 min precooling) ↓ Thermal sensation (2 units, @ 60 min precooling; and, 1 unit, @ end of mid-exercise recovery cooling) ↑ Plasma glucose concentration (1 mmol.L^{-1}; @ 45-90 min exercise) ↓ Plasma non-esterified fatty acid concentration (0.15-0.4 mmol.L^{-1}; @ 45-90 min exercise) ↓ Rise in plasma non-esterified fatty acid concentration (0.27 mmol.L^{-1}; @ 45-90 min exercise) ↓ Plasma glycerol concentration (175-250 µmol.L^{-1}; @45-90 min exercise) ↓ Rise in plasma glycerol concentration (113 µmol.L-1; @ 45-90 min exercise)	Improvement ↑ Self-selected running speed (self-chosen work rate test) (1.2 km.h-1; 10.6%; P=0.006) ↑ Time to exhaustion @ 12.9 km.h^{-1} with 20% incline (Cunningham Faulkner test) (22.7 s; 39.8%; P=0.000) ↑ Mental concentration test (4-6%; @ 4,34 and 49 min exercise; trial effect where P=0.025)	Study involved a 2x2 Latin square design (precooling and carbohydrate ingestion; see table 3 for individual results and table 7 for comparative results). Intervention involving carbohydrate only has been excluded due to lack of relevance. * Performance tests include a mental concentration test (performed 4 min after every 15 min block of exercise, concurrent with exercise; involved simple arithmetic), self-chosen work rate test (a 3 min test at self selected 30 min running pace) and Cunningham Faulkner Test (running time to exhaustion at 12.9 km.h^{-1} with treadmill at 20% incline) Beverage ingestion temperature not reported; control treatment matched for fluid volume with placebo beverage Authors suggest that part-success of temperature reduction achieved in the current strategy involved the seated-rest while wearing the cooling vest, which may be compromised if worn during a warm up

Reference	Subjects	Precooling Protocol	Exercise Protocol	Environment (Precooling)	Environment (Exercise)	Physiological outcomes (compared to control)	Performance (compared to control)	Comment
Ross et al., 2011 (65)^	"Well trained, A-grade, local community, cyclists" (n = 11 M) 71.6 ml.kg^{-1}.min^{-1}	*Ice slurry ingestion and cold towel application* 14 g.kg^{-1} BM of a 6% CHO ice slurry (given as 7 g.kg^{-1} BM 15 min apart) while wearing iced-towels draped over the torso and legs	Cycling 60 min heat stabilisation; 30 min precooling; 20 min standardised warm up; 10 min final preparation; 46.4 km maximal time trial	34˚C 54% r.h.	34˚C 54% r.h. variable fan speed	↓ Rectal temperature (~0.7˚C; @ 5 min warm up - 0 min exercise) ↓ Percentage of maximal heart rate (4-8%; @ 5 -10, and 20 - 25 min warm up) ↓ Δ Body mass (-0.76 kg; -3.1%) ↓ Thermal comfort (~4.6 units; @ 0 -30 min precooling) ↔ Stomach fullness ↔ Rectal temperature, heart rate, blood lactate concentration; subjective ratings (effort given, sensation, motivation, comfort) during exercise	Improvement* ↑ Mean power output (8 W; 3%; "trivial to large benefit"; P=0.04) ↑ Mean Lap 1 power output (5 W; 1.7%; "trivial to moderate benefit"; P=0.19) ↑ Mean lap 2 power output (10 W; 3.6%; "trivial to large benefit"; P=0.06) ↑ Mean climb 1 power output (5 W; 1.6%; "trivial to large benefit"; P=0.15) ↑ Mean climb 2 power output (9 W; 3.2%; "small to extremely large benefit"; P=0.09) ↑ Mean descent 2 power output (9 W; 4.4%; "small to moderate benefit"; P=0.05) ↔ Mean descent 1 power output (6 W; 2.1%; "small to moderate benefit"; P=0.34)	Study included two experimental treatment interventions, including 1) water immersion + cooling jacket; and, 2) ice-slushie ingestion + iced towels (see table 6a for combined and table 7 for comparative results) *Changes in power output data reported were matched with respective changes in time to complete respective sections of the course but not detailed here Authors acknowledge precooling strategy provided additional amounts of fluid and carbohydrate over control but believe performance improvements were achieved by its cooling effect rather than improved carbohydrate or hydration status Authors discus the practical implications of using this precooling strategy in the event location

CHO = carbohydrate, CSU = Charles Sturt University, d = effect size, M = males, MVC = maximal voluntary contraction, P = probability, W = watts, ^ indicates study is reported multiple times.

Appendix G

Table 2.7 Comparative precooling interventions

Reference	Precooling Interventions for Comparison	Physiological outcomes (comparative results)	Performance (comparative results)	Comment
Clarke et al., 2011 (67)	Cooling vest (V) compared to cooling vest and 18 ml.kg^{-1} BM (1,338 ml) of 6.6% CHO beverage ingestion (V+CHO)	*Gastrointestinal temperature* V > V+CHO (0.35°C; @ 60-90 min exercise) *Plasma Glucose concentration* V < V+CHO (0.7-0.8 mmol.L^{-1}; @ 45-90 min exercise) *Plasma non-esterified fatty acid concentration and rate of increase* V > V+CHO (0.25-0.35 mmol.L^{-1}, 0.21 mmol.h^{-1}, respectively; @ 45-90 min exercise) *Plasma glycerol concentration and rate of increase* V > V+CHO (130-195 µmol.L^{-1}; 213 µmol.h^{-1}, respectively; @ 90 min exercise) V ↔ V+CHO (Muscle temperature, thermal sensation)	Improvement ↓ Self-selected running speed (self-chosen work rate test) with V (0.9 km.h-1; 7.8%; P=0.006) ↓ Time to exhaustion @ 12.9 km.h^{-1} with 20% incline (Cunningham Faulkner test) with V (9.8 s; 14%; P>0.05) ↔ Mental concentration test	

Reference	Precooling Interventions for Comparison	Physiological outcomes (comparative results)	Performance (comparative results)	Comment
Siegel et al., 2011 (52)	7.5 $g.kg^{-1}$ BM ice slurry (ICE) compared to 30 min whole-body water immersion (CWI)	*Rectal temperature* ICE < CWI (0.47˚C; @ 15-30 min precooling) ICE > CWI (0.43˚C; @ 20-40 min exercise) *Skin temperature* ICE > CWI (6.03˚C: @ 0-40 min exercise) *Mean body temperature* ICE > CWI (0.50-1.52˚C; @0-40 min exercise) *Heat storage / rate of heat storage* ICE < CWI (-68.58 $W.m^{-2}$; during precooling) ICE > CWI (0.84 $W.m^{-2}.5\ min^{-1}$; 0-20 min exercise) *Heart Rate* ICE > CWI (7 bpm; @ 0-35 min exercise) *Sweat Rate* ICE > CWI (0.22 $L.h^{-1}$; during exercise) *Thermal Sensation* ICE > CWI (0.8 units; during precooling) ICE ↔ CWI (Heat storage & rate of perceived exertion; during exercise)	No substantial difference ↑ Time to exhaustion with CWI (4.1 min; 7.8%; d = 0.60, 90% CI=-0.24-1.44, "unclear"; P=0.355)	2 out of 8 subjects ran for longer following ICE compared with CWI Authors suggest ICE may be a more preferred strategy due to logistical demands, comfort and potential muscle impairment caused by peripheral vasoconstriction associated with CWI Authors attribute greater rate of rectal temperature rise during early phase of exercise following ICE to the lower core-to-skin temperature gradient, reducing the ability to reduce heat transfer to the environment Authors speculate about mechanisms responsible for efficacy of ICE
Tyler et al., 2011 (54)	Cooling collar (CC) compared to cooling collar replaced (CC_R) @ 30 and 60 min pre-load exercise	*Neck skin temperature* CC > CC_R (3.5-11˚C; @ second collar application - throughout trial) *Thermal sensation of neck region* CC > CC_R (0.5-2.5 units; during pre-load - start of performance trial) *Whole body thermal sensation* CC > CC_R (magnitude not reported; @ start of performance trial) CC ↔ CC_R (rectal temperature, heart rate, rating of perceived exertion, FS, fluid intake, sweat loss, change in plasma volume, blood lactate, glucose cortisol, serotonin and dopamine concentration)	No substantial difference ↑ Distance covered in 15 min with CC (3 m; 0.1%; P=0.998)	Authors state that no cumulative or additional benefit is gained by continually replacing the warmed cooling collar with a colder "refreshed" one Although there was a lower perception of thermal sensation reported with the CC_R, authors suggest that there is a limit to the extent of deception and the beneficial effect of altered perception Authors propose that cooling the neck enhances performance by masking the extent of thermal strain

Reference	Precooling Interventions for Comparison	Physiological outcomes (comparative results)	Performance (comparative results)	Comment
Minett et al., 2011 (53)	Head cooling using iced towels (Head; H), head cooling plus both hands immersed in water (Head and Hands; HH); whole body cooling using head cooling, hand cooling plus cooling vest and gel packs applied to the thighs (Whole Body; WB); comparison of all treatment interventions	*Gastrointestinal temperature* WB & HH < H (0.1-0.3°C; @ end of precooling) *Skin temperature* WB < HH & H (magnitude not reported; throughout trial) *Heart rate* WB & HH < H (magnitude not reported; @ end of precooling) *Blood lactate concentration* WB < H (~1.2 mM; mid-exercise) *Thermal sensation*WB < HH & H (0.5-0.6 units; precooling) ↔ All treatments (mean voluntary or evoked force, time to peak torque, blood measures of glucose, pH, bicarbonate;creatine kinase, C-reactive protein, testosterone & cortisol, rating of percieved exertion)	Substantial differences reported ↑ Total distance accumulated with WB & HH (WB & HH > H; where WB = 4833 m; HH = 4644 m; H = 4602 m; d = 0.7-1.26; P=0.001-0.04) ↑ Mean spell 1 hard running distance with WB (WB > H; 10.2 m; 6.4%; d >0.08; P<0.05) ↑ Mean spell 2 hard running distance with WB (WB > H & HH; 11.4 m, 7.4%; 10.9 m, 7.1% respectively; d >0.08; P<0.05) ↑ Total spell 1 hard running distance with WB (WB > H; 81.6 m; 6.4%; d >0.08; P<0.05) ↑ Total spell 2 hard running distance with WB (WB > H & HH; 91.6 m, 7.5%; 87.5 m, 7.1% respectively; d >0.08; P<0.05) ↑ Mean spell 1 jogging distance with WB (WB > H; 4.3 m; 4.1%; d >0.08; P=0.02) ↑ Total spell 1 jogging distance with WB (WB > H; 34.6 m; 4.1%; d >0.08; P=0.02) ↔ Mean sprint times, peak sprint speeds	Authors suggest that a relationship between precooling volume and exercise performance seems apparent, in that a larger surface area coverage resulted in increased work capacity with greater suppression of physiological loadAuthors advise field-based practitioners to select interventions that allow for sufficient volume of cooling within the logistical constraints of individual team contexts

Reference	Precooling Interventions for Comparison	Physiological outcomes (comparative results)	Performance (comparative results)	Comment
Ross et al., 2011 (65)	10 min water immersion + 20 min wearing cooling jacket (Immersion + Jacket; I+J) compared to ingesting a 14 g.kg^{-1} BM ice-slurry + wearing iced towels ("Slushie" + towels; S+T)	*Δ Body mass* I+J > S+T (0.63 kg; 0.8%) *Δ Rectal temperature* I+J < S+T (0.3-0.5˚C; @ 30 min precooling - 0 min performance trial) *Percentage of maximal heart rate* I+J > S+T (4%; @ -5 min from start of performance trial) I+J ↔ S+T (blood lactate concentration, thermal comfort, stomach fullness, ratings of effort given, sensation, motivation, comfort)	Substantial difference ↑ Power output during descent 2 with S+T (~ 14 W; 4.9%; "small to very large benefit"; P=0.03) ↓ Time to complete descent 2 with S+T (12.2 s; 1.6%; "small to large benefit"; P=0.009) ↑ Mean power output with S+T (5 W; 1.8%; P>0.05) ↓ Time to complete performance trial (36 s; 0.8%; P>0.05)	There was no individual response detected when subjects were exposed to the S+T treatment intervention Authors recommend S+T treatment as a practical and effective precooling strategy *per se*, as well as over the I+J strategy Authors comment that comparisons of heart rate, rectal temperature and rating of perceived exertion for each treatment intervention can not be made during self-paced performance trials Authors acknowledge treatment interventions offer different benefits including fluid, carbohydrate and electrolytes ingested with the S+T strategy but suggest performance improvements were a result of cooling effects
Burdon et al., 2010 (73)	4˚C beverage @ 10 min intervals (COLD) exercise compared to 37˚C beverage @ 10 min intervals + 30 ml of ice puree @ 5 min intervals (ICE), during 90 min pre-load exercise	COLD ↔ ICE (rectal temperature, skin temperature, convective heat flow, mean absolute temperature change, rate of heat storage, serum osmolality, Δ body mass, calculated sweat rate, mean heart rate, mean oxygen consumption, rating of perceived exertion, thermal comfort)	No substantial difference ↑ Mean power output with COLD (10 W; P=0.31)	Both treatment interventions were matched for fluid volume ingested The beverage was well tolerated by all participants with a mean visual analogue scale ratin gof 1.4-1.7/10, indicating only minor bloating Authors comment on the measurement of rectal temperature in this study may not give a true indication of "body core temperature" (or differences between treatment interventions) due to the proximity of the temperature sensor to the heat sink

Reference	**Precooling Interventions for Comparison**	**Physiological outcomes (comparative results)**	**Performance (comparative results)**	**Comment**
Bogerd et al., 2010 (56)	Wearing of evaporative cooling shirt (Mild; MC) compared to cooling vest (Strong; SC)	*Mean skin temperature* MC > SC (~1.5˚C; @ 25-45 min precooling) MC > SC (0.4˚C; @ end of exercise) *Mean body temperature* MC > SC (0.4˚C; @ end of precooling) *Reduction in body heat content* MC < SC (18.3 W.m^{-2}; precooling) MC ↔ SC (rectal temperature, skin blood flow, heart rate, thermal perception, respiratory exchange ratio, oxygen uptake, metabolic heat production, sweat rate, fluid intake, rating of perceived exertion)	Unclear Data suggest non-significant improvement in time to exhaustion with SC when compared to MC. ↑ Time cycled with SC* (6:50 min; n=2) ↑ Time to exhaustion with SC (30 s; n=4)	n=2 subjects cycled for 60 min in both trials *n=2 subjects were stopped at 60 min following SC, but exhausted earlier during MC Authors provide mean performance improvement, which included trials that were stopped at 60 min. Therefore magnitude of improvement reported in paper somewhat underestimated. Authors attribute longer cycle time to a greater reduction in body heat content
Vaile et al., 2008 (49)	Intermittent 10˚C water immersion (10˚C), Intermittent 15˚C water immersion (15˚C), Intermittent 20˚C water immersion (20˚C), continuous 20˚C water immersion (20˚C+); Comparison of all treatment interventions	*Mean body temperature* 10˚C < 15˚C < 20˚C+ < 20˚C (10˚C = 34.6˚C; 15˚C = 35.3˚C; 20˚C+ = 36.1˚C; 20˚C = 36.5˚C; @ end of cooling - 15 min of TT2) *Thermal sensation* 10˚C < 15˚C, 10˚C < 20˚C, 20˚+C < 20˚C (1-, 1.8-, 1.5-units respectively; @ end of precooling) 10˚C < 15˚C, 10˚C <20˚C, 10˚C < 20˚+,15˚C < 20˚C (0.6-, 0.7-, 0.8-, 0.3-units, respectively; @ end of passive recovery) ↔ All treatments (blood lactate concentration, heart rate, ratings of perceived exertion)	No substantial difference ↔ Δ Total work in time trial 2-1(All treatments compared; P>0.05)	Authors comment that the use of cold water immersion of varying temperatures and exposures assisted in enhanced ability to maintain performance, although there were no differences between treatments

Reference	Precooling Interventions for Comparison	Physiological outcomes (comparative results)	Performance (comparative results)	Comment
Quod et al., 2008 (24)	30 min water immersion plus 40 min wearing a cooling jacket (Combined; C) compared to 40 min wearing cooling jacket only (Jacket; J)	*Rectal temperature* C < J (0.5˚C; @ end of precooling - end of performance trial) *Skin temperature* C < J (7.9˚C; @ end of water immersion - 5 min warm up) C < J (Δ 1.7˚C; throughout trial) *Mean Body temperature* C < J (0.3-1.0˚C; @ all times except 30-35 min performance trial) C < J (Δ 0.8˚C; throughout trial) *Negative heat storage* C > J (-67.9 $W.m^{-2}$; precooling) *Thermal sensation* C < J (1-4 units; @ 5-30 min plunge, start of warm up) *Heart rate* C < J (14 bpm; @ 5-10 min warm up) *Blood lactate concentration* C < J (2.3 $mmol.L^{-1}$; @ end of performance trial) C ↔ J (Δ rectal temperature, rating of perceived exertion, Δ body mass, bladder voided mass, estimated sweat loss, urine specific gravity, blood bicarbonate, pH and blood glucose)	No substantial difference ↓ Time to complete performance task with C (26 s; ↑ 7 W; 2.4%; P=0.06)	Results support greater rectal temperatures prior to an exercise task translating to greater performance effects Authors propose the appropriate use of cooling jackets may be to act as an external heat sink to attenuate the rise in core body temperature during a warm up in contrast to active cooling *per se*
Duffield & Marino, 2007 (78)	Repeated exposure of wearing a cooling vest (Vest; V) compared to water immersion followed by repeated exposure of wearing a cooling vest (Immersion + Vest; I+V)	*Gastrointestinal temperature* I+V < V (0.4-0.9˚C; @ 0 min warm up - 40 min exercise) *Mean skin temperature* I+V < V (2-13˚C; @0 min warm up - 10 min exercise) *Negative heat storage* I+V > V (3.6-8.5 $J.g^{-1}$; @ end of precooling - 0 min exercise) I+V ↔ V (heart rate, sweat loss, chest temperature, blood concentrations of lactate, pH, sodium, potassium, Δ hematocrit, rating of perceived exertion, thermal comfort)	No substantial differences ↔ Mean and total sprint time ↔ Decline in sprint time ↔ Mean or total distance covered in hard running, jogging or walking (All P>0.05)	

Reference	**Precooling Interventions for Comparison**	**Physiological outcomes (comparative results)**	**Performance (comparative results)**	**Comment**
Yeargin et al., 2006 (77)	5˚C water immersion of the torso and upper legs (IWI) compared to 14˚C water immersion of the torso and upper legs (CWI)	*Rectal temperature* IWI < CWI (0.39˚C; @ end of performance trial) IWI ↔ CWI (thermal sensation, rating of perceived exertion, blood lactate concentration, heart rate, percentage dehydration, sweat rate, urine specific gravity, environmental symptoms)	No substantial difference ↑ Time to complete 2 mile with IWI (54 s; 1.1%; P>0.05)	
Castle et al., 2006 (59)	Cooling vest (Vest; V), 17.8˚C whole body water immersion (Water; W); -16˚C silicate gel pack thigh application (Pack; P); Comparison of all treatment interventions	*Muscle temperature*V > W and P (V = 39.0˚C; W = 38.2˚C; P = 38.4˚C; main effect)↔ All treatments (rectal temperature, Δ body mass, thermal sensation, rating of perceived exertion, mean blood lactate concentration, oxygen uptake, respiratory exchange ratio)	No substantial difference? ↔ Peak power output (V = 1149 W; W = 1126 W; P = 1181 W; No comparison made) ↔ Work done each sprint (V = 356.4 J; W = 350.9 J; P = 366.8; No comparison made) ↔ Total work done (V = 7.1 kJ; W = 6.9 kJ; P = 7.1 kJ; No comparison made)	The aim of the investigation was to examine three treatment interventions compared to a control. Authors acknowledge that all treatments improved thermoregulation in a dose dependant response, but comparisons between treatments are not detailedAll subjects reported feeling a bearable, but painful buring sensation on the thighs from cold packsWith substantial differences reported between *Packs* and *Control* treatments, and similar performance data presented for *Water* and *Control* treatments there may be performance difference that exist between *Packs* and *Water* treatment interventions
Webster et al., 2005 (60)	Wearing a 2810 g fitted vest with rate of melting = 1.44˚C(100g)$^{-1}$; heat capacity = 134.3 cal.g^{-1} (Vest A; A) compared to a 3000 g fitted vest with rate of melting = 1.5˚C(100g)$^{-1}$; heat capacity = 142.6 cal.g^{-1} (Vest B; B) during seated rest, stretching and warm up	*Acceptability of vests* A > B (1 unit; @ 20 min rest) A ↔ B (sweat rate, heart rate, skin temperature, rectal temperature, perceptions of heat, perceptions of skin wetness)	No substantial difference Authors report a non significant increase in time to exhaustion with Vest B	Study also included a third vest (Vest C) which was developed for industrial use and hence comparison is not included Shivering was not evident in any participant wearing vest A

BM = body mass, CHO = carbohydrate, CI = confidence interval, d = effect size, P = probability, W = watts.

Table 2.8 Implementation of a) external and b) internal precooling methodologies: Practical benefits and limitations

Precooling Method or Device	Description of Implementation	Pros	Cons
a. External Methodologies			
Air exposure	Repeat exposure of 5-10˚C air in an environmental chamber with an intermittent re-warming period. Typical duration of exposure including the re-warming period is ~100 min, however more recent research has used a single exposure of ~33 min.	Provides whole-body cooling Transfer time from cooling to exercise is fast (i.e. subjects already dressed for exercise and clothing is dry)	Requires climate controlled environmental chamber or equivalent Can effectively only be used pre-exercise Protocol can be time consuming
Cooling collar	Wearing a modified version of a commercial cooling collar (Black Ice LLC, Lakeland USA) around the neck before and during exercise. The collar (375 mm x 60 mm x 15 mm; 155 g) made of a thin plastic casing consisting of five compartments is drained of the original cooling reagent and filled with ~120 g gel refrigerant (BDH Laboratory supplies, Poole, Dorset, England). The cooling collar is held in place by a 600 mm neoprene wrap secured with hook and loop fastenings at the anterior aspect of the neck. The modified collar is prepared by storing in an -80˚C freezer for 24-48 h and then left for ~10 min in ambient conditions and cleared of any surface frost prior to application. Typically worn for a prolonged single exposure (75-90 min).	Provides part-body cooling (neck region) Can be worn during sports competition Can be removed quickly before commencing exercise Does not hinder athlete's physical movement	Studied collar is a modification of commercially available option, which has not been evaluated Requires insulated storage for transfer to competition venue No further performance benefit gained by continually replacing collar with colder/refreshed one
Cooling jacket RMIT University Bundoora, Australia	Wearing a waist length jacket with hood constructed of a polyester blend outer shell with a phase change material sewn on the inside, designed to change phase at 20˚C. Jacket i s to be stored at <20˚C or to optimise use can be stored in a refrigerator or freezer prior to use to enhance heat storage capacity. Effective cooling is achieved by wearing the jacket for 40 min after 30 min 29-24˚C water immersion.	Provides cooling for large body surface area (torso, arms & head) Provides dry cooling Can be worn over athlete's clothing Can be used without prior storage in refrigerator or freezer Can be removed quickly before commencing exercise	Existed only for research purposes; No longer produced Heavy (~8 kg) and bulky making handling and portability difficult and hence is not advised for large groups requiring 1x jacket each Requires access to adequate refrigerator / freezer space Requires sufficient insulated storage for transfer to competition venue
Cooling vest Arctic Heat ™ Burleigh Heads, Queensland, Australia www.arcticheat.com.au	Wearing a cooling vest with 7 integrated crystal-filled cooling panels made from sportwool™ material for 20-45 min. Vest is prepared for use by submersion in water at the desired temperature of use for ~15 min to allow the crystals to hydrate. Vest weighs 0.8 - 1 kg when activated. Storage in a freezer will further prolong the cooling capacity of the vest. Effective cooling has been achieved by wearing the jacket with and without exposure to other forms of cooling. Commercially available (AUD$198).	Provides torso cooling Once activated the vest can be stored in refrigerator or freezer for future use Freezing vest prolongs cooling effectiveness Can be worn during warm up	Requires pre-hydrating, refrigeration/freezing and transfer in iceboxes if preparing vests prior to arrival at competition venue Requires availability of sufficient ice and water at competition venue if preparing vests at the competition location Provides wet cooling (e.g., athlete gets wet and may need to change of clothing prior to competition) Vest takes time to dry and return gel into crystal form (5 days) Can not be stored while crystals remain hydrated (=gel form)

Precooling Method or Device	**Description of Implementation**	**Pros**	**Cons**
Cooling vest cool.1.NZ™ University of Otago, Dunedin, New Zealand www.otago.ac.nz	Wearing a cooling vest with 1.2 L coolant (water-gel mix) packs. Vest is prepared for use by storage in a freezer. Commercially available (NZ$186).	Provides torso cooling Provides dry cooling Can be removed quickly before commencing exercise	Requires access to adequate refrigerator / freezer space for activation Requires insulated storage for transfer to competition venue Prolonged exposure (~100 min) required
Cooling vest Cool Vest Jackson Technical Solutions Ltd., Kent, UK www.jacksontechnical.co.uk	Wearing of a pullover vest with ventilation panels and scoop neck. Vest is prepared for use by submersion in cold water for 'a couple of minutes' and gently squeezed to remove excess water prior to application. Advertised to provide at least 5 h cooling per single preparation. Commercially available (GBP£55).	Provides torso cooling	Requires availability of sufficient ice and water at competition venue if preparing vests in the competition location Provides wet cooling (e.g., athlete gets wet and may need to change of clothing prior to competition) Drying time required prior to storage
Cooling vest Neptune Wetsuits Australia Smithfield West, Australia	Wearing of a neoprene vest with eight pockets packed with ice (450-500 ml each), including two on the chest, two on the stomach, two over the shoulder blades and two on the lower back. Weight of the vest reported as ~4.5 kg.	Provides torso cooling Can be worn during warm up Wearing vest does not interfere with physical movement Effective in humid heat Can be removed quickly before commencing exercise Ice packed into plastic bags and then placed in vest pockets provides dryer cooling than ice placed in pockets and melting accordingly	Not commercially available Requires sufficient ice to fill (and potentially refill) each vest Ice requires insulated storage for transfer to competition venue Complaints reported during warm up include the weight and skin irritation caused by rubbing of the vest Wearing the vest during active warm up was shown to increase the cost of running
Cooling vest StaCool^{TM} Undervest StaCool Industries Inc Brooksville, USA www.stacoolvest.com	Wearing of a lightweight airprene-material vest, with spandex sides for additional comfort and flexibility and front zip for easy dress and removal. Vest contains 4 pockets (positioned vertically on the front and back of the torso, on the left and right sides) that are used to place 'Thermopacks' in. 'Thermopacks' are reusable and made of individual cells that contain a non-toxic polymer material which remain flexible when frozen. The weight of the activated vest is ~2.3-2.5 kg. Vest is commercially available (USD$210).	Provides torso cooling Provides dry cooling Can be worn during warm up Can be removed quickly before commencing exercise	No evidence of lowering core temperature Requires storage of Thermopacks in freezer prior to use Thermopacks require insulated storage for transfer to competition venue

Precooling Method or Device	Description of Implementation	Pros	Cons
Cyrogenic cuffs AutoChil® system with Cryo/Cuf® cooler Aircast, DJO Global, Inc., Vista, CA, USA www.aircast.com	Wearing of portable water perfused cuff system, which combines benefits of cooling and pulsating compression. Cooling is achieved by circulating chilled water from a portable cooler to the cuff. Cuffs are anatomically designed to fit body parts including the ankle, knee, shoulder and back/hip/rib, and provides automatic 30 s on/off intermittent compression and cold therapy. Commercially available (AUD$92).	Contains sufficient water and ice for 6-8 h cooling Provides part body cooling Provides dry cooling	Designed specifically for therapeutic use and not as a precooling device *per se* Requires access to mains power Athlete is 'tethered' to the pump and therefore is not mobile during cooling / not practical for use during exercise
Evaporative cooling solution Energicer, Liquid Ice CosMedicals AG, Unterägeri, Switzerland www.energicer.com	~40 min wearing sweatbands soaked in alcohol- and menthol-based evaporative cooling solution on both forearms continuously during warm-up, rest and exercise, additional option of wearing second pair of sweatbands for additional cooling available. Commercially available; 1 set inclusive of solution and sweatbands (GBP£47)	Sweatbands are reusable Does not require refrigeration "Dip, squeeze, go" Can be worn during rest, warm up and competition	Effectiveness reduced in humid heat Sweat bands cover small total body surface area
Evaporative cooling shirt Personal Cooling System UNICO swiss tex GmbH Alpnachstad, Switzerland www.unico-swiss-tex.ch	45 min wearing garment made of textile-based 3-layer laminate of two waterproof, but water vapour-permeable polyester membranes, which coat a hydrophilic fabric acting as water reservoir. By addition of a small quantity of water, the hydrophilic fabric is moistened and the evaporation of water through the outer polyester membrane leads to a local lowering of the skin temperature (4-5˚C over ~40 min). Once the water evaporates, it can be re-filled as often as required. The weight of the activated cooling shirt weighs ~ 310 g. Garment advertised as a medical device class 1, for multiple sclerosis patients to improve their physical efficiency, but offers application for sporting and other uses. Other garments available. Commercially available (CHF260-280)	Garment can be worn under (evaporative) clothing and does not restrict movement Cooling pad is thin and flexible and can be refilled with water as required Follows basic washing instructions Available standard sizes or can be custom-fit	Provides 'mild' cooling of the torso

Precooling Method or Device	Description of Implementation	Pros	Cons
Fan with water spray	20 min standing in front of a large industrial fan rotating 180° every 2 min while water was sprayed in a fine mist (50 $ml.min^{-1}$) over the exposed surface area of the body (neck to feet).	Provides whole body cooling	Effectiveness reduced in humid heat Provides wet cooling (e.g., athlete gets wet and may need to change of clothing prior to competition) Fan requires access to mains power May require automated water dispenser or personnel to administer Limited evidence found performance inpairment Requires standing for prolonged periods prior to exercise
Iced towels	Bathroom towels are dunked in icy water and wrung to extract the liquid. For application, towels are draped over the skin (i.e. torso, head, legs) and "reactivated" towels are constantly rotated for 5-30 min. Shaved ice is preferable. Cooling associated with performance benefits achieved with 5-30 min application with and without additional cooling methods.	Ice and towels are readily available (low cost option) Long term storage of ice (hours) can be maximised by adding water minutes prior to commencing precooling Small volumes of water to add to ice required Provides wet cooling to the skin, but subjects clothing can remain dry if sufficient water is squeezed from the towel prior to application, if not placed directly over clothing Easy to increase (or decrease) intensity of cooling via greater (or less) skin surface area covered and length of each towel application Additional application may be achieved once athlete is dressed and awaiting competition start (i.e. placed around neck)	Requires assistance to continuously prepare and apply towels which makes this difficult for a large number of athletes requiring cooling concurrently Requires athlete to be seated during application May require athletes to dress for competition if large surface of skin is exposed during application Ice requires insulated storage for transfer to competition venue
Ice Pack Dry Ice Packs Techni-Ice Frankston, Australia www.techniice.com	20 min application of 'ice packs' to the skin of the thighs. Packs contain food grade product, which remains flexible when frozen. Outer shell consists of two heavy-duty, washable plastic surfaces on both sides, plus a two-layer textile sheath on the inside to contain the polymer and resist puncture. Commercially available (AUD$25; for x72 (3 sheets of 24 packs).	Localised cooling Reusable cooling packs Provides dry cooling Packs sold in sheets and can be cut to required size	Pack does not encounter phase change Preparation requires access to freezer prior to use Packs require insulated storage for transfer to competition venue Packs require strapping for securing to body part

Precooling Method or Device	Description of Implementation	Pros	Cons
Ice Pack 3M Birkshire, UK www.3Mselect.co.uk	20 min application of silicate gel pack covered in a thin cotton cloth, to the skin of the thigh. Commercially available (<AUD$20).	Provides local cooling Reusable cooling packs Provides dry cooling Wide commercial availability	Pack does not encounter phase change Preparation requires access to freezer prior to use Packs require insulated storage for transfer to competition venue Packs require strapping for securing to body part
Shower	60 min standing under a 28-24˚C shower of water.	Provides whole body cooling May be performed seated	Requires access to shower facilities Poor use of environmental resource Athletes need time to towel dry and dress for competition Does not allow athletes to perform other activities during cooling manoeuvre Prolonged standing prior to exercise task not recommended
Water immersion Part-body	10-12 min part-body immersion in 10-14˚C water, including hand, torso or leg cooling	Part-body immersion may allow athlete to cool certain body parts without having to change clothes / greater thermal comfort Immersing non-active body parts may increase blood flow to the exercising musculature Popular strategy for precooling mid- and post-exercise recovery	Athletes may need time to towel dry and dress for competition
Water immersion Whole-body	30-60 min whole body immersion in water with the temperature reduced over the duration form 29-22˚C, OR ≤30 min whole body immersion in ~17C water temperature, OR Recovery cooling for 5-15 min at 10-20˚C intermittent (1 min immersion; 2 min recovery; repeated 5 times) or constant exposure. Whole body immersion is typically to the level of the neck, shoulders or mid-sternum and is performed using a permanent and specialized facility, a custom designed bath (CSU, Australia) or portable inflatable bath (see water immersion - icoolsport)	Whole body water exposure associated with high heat transfer Popular strategy for precooling,mid- and post- exercise recovery	Athletes need time to towel dry and dress for competition Thermal comfort compromised with prolonged exposure Large groups may be time consuming, logistically challenging or too difficult to precool for prolonged water immersion

Precooling Method or Device	Description of Implementation	Pros	Cons
Water immersion iCoolsport www.icoolsport.com	Portable inflatable bath (~10.5 kg) is filled with water and cooled by adding sufficient ice to achieve desired temperature or by connecting a portable automatic cooling unit (~28-34 kg) used to circulate and cool the water to a set temperature. The bath (previously known as 'Portacovery') and cooling unit are commercially available (USD$1350 & USD$ 4990-5970, respectively). iCoolsport also offers a range of cooling baths and cooling units for a wide variety of uses within sport.	Whole body cooling Portable & automated system Suitable for large groups	Combined bath and cooling system plus hoses, power leads and robust travel case are heavy (~50-55 kg total) Requires access to sufficient water to fill bath at competition location Cooling unit requires mains power for use at competition venue, or sufficient ice is required to cool water temperature Requires adequate drainage for emptying of bath after use (i.e. not suitable for hotel rooms) System must be dried before long term storage to prevent build up of mildew
Water perfused garments	>60 min wearing 1-5˚C water perfused garments including a jacket and hood. Water is pumped from a cooling unit and circulated through the garment.	Provides dry cooling Provides part-body cooling	Athlete is 'tethered' to the pump and therefore is not mobile during cooling / not practical during exercise
b. Internal Methodologies			
Air inhalation	Cold air is breathed from the outflow of a heat exchanger through a two-way valve. Cool air is achieved by compressed atmospheric air, which flows down a pressure gradient through two homocentric tubes each encircled by a copper coil filled with liquid nitrogen.	Shows promise as an effective cooling strategy	Method is untested on performance of well-trained subjects Requires specific respiratory device and equipment Not commercially available
Beverage ingestion	Ingestion of large volumes (>1 L) of 4̊C fluid consisting of water or sports drink given as a single bolus or serial feeding.	Provides additional nutritional and hydration benefits Easy to administer / incorporate into athlete's routine Low cost cooling strategy Many sports support the consumption of fluids during competition Large volumes have typically been well tolerated	Considerations for gastrointestinal comfort and time course of large volumes of fluid consumption Requires control of fluid temperature (e.g., storage on ice or refrigeration)

Precooling Method or Device	**Description of Implementation**	**Pros**	**Cons**
Ice 'slushie' beverage	Ingestion of ice beverage (0.5-1.0 L) made from commercial sports drink by a 'slushie'-making machine (Essential Slush Co, Burleigh Heads, Queesnland Australia). Ingestion of the beverage is typically over a serial feeding regimen during seated rest, or during sub-maximal pre-load exercise.	Provides additional nutritional and hydration benefits Commercial portable machine powered by battery or mains power supply Commercial machine available in two sizes Beverage can alternatively be made by pre-freezing and part-thawing commercially available sports drink The beverage can be ingested with the aid of a straw and spoon to maximise the ingestion of solid ice Large volumes have typically been well tolerated Theoretically, similar cooling could be achieved from lower volume of slushie beverage ingested than a liquid beverage	Requires robust and portable 'slushie' machine for use in competition location Requires operation time to change liquid beverage into ice slurry prior to ingestion, which is dependant on ambient and beverage temperatures Athletes may not tolerate sensations of "brain freeze"
Intravenous saline	Chilled saline is intravenously injected		Method is untested on performance of well-trained subjects Against the rules of some sports / competitions Requires invasive techniques performed by accredited personnel (e.g., doctor to insert cannula)
Menthol mouth rinse	25 ml swill; 19°C L(-)-menthol (0.01%) solution every 10 min during exercise. Typically given orally, menthol exerts its sensation of cooling by making subsequent stimuli (air breathed, water consumed) feel cool. Oral administration of menthol causes a subjective sensation of improved airflow without actual changes in airway resistance, most likely as a result of the stimulation of the oropharangeal cold receptors.	Provides sensory cooling Cooling perceived as "refreshing" and "stimulating" Sensations of reduced effort of breathing reported	May be difficult to access during some sports competition May be limited by fluid carrying capacity; athletes may prefer to carry ingestible fluids during prolonged competition

AUD = Australian dollar, CHF = Swiss franc, CHO = carbohydrate, GBP = British pound, NZD = New Zealand dollar, USD = United States Dollar

Table 4.1 Summary of cycling time trial performance data (performance time and power output)

Course Profile		Treatment	Performance Time			Power Output			Qualitative Inference
Phase	**Distance** (km)	**Intervention**	**mean ± SD** (h:min:sec.0)	**Mean Δ; ±90% CL** (%)	**P**	**mean ± SD** (W)	**Mean Δ; ±90% CL** (%)	**P**	(% Chance of positive / trivial / negative outcome compared to CON)
Total	0 - 46.4	CON	1:18:47 ± 5:09	-	-	276 ± 37	-	-	-
		PC	1:18:28 ± 4:40	-0.4; ±0.9	0.49	277 ± 34	0.5; ±2.0	0.66	Unclear (4/96/0)
		PC+G	1:18:47 ± 5:10	0.0; ±1.5	0.99	278 ± 40	0.5; ±3.7	0.79	Unclear (7/87/6)
		(PC V PC+G)	-	-0.4; ±1.2	0.60	-	0; ±3.2	0.99	Unclear (8/91/1)
Lap 1	0 – 23.2	CON	38:55 ± 2:23	-	-	279 ± 36	-	-	-
		PC	39:06 ± 2:23	0.5; ±1.3	0.55	277 ± 36	-0.6; ±2.2	0.63	Unclear (21/84/14)
		PC+G	39:17 ± 2:34	0.9; ±1.5	0.31	276 ± 41	-1.3; ±3.3	0.51	Unclear (1/66/32)
		(PC V PC+G)	-	-0.4; ± 1.3	0.54	-	0.7; ±3.3	0.72	Unclear (13/86/2)
Lap 2	23.2 – 46.4	CON	39:52 ± 2:50	-	-	273 ± 39	-	-	-
		PC	39:22 ± 2:28	-1.2; ±1.1	0.07	276 ± 33	1.4; ±2.6	0.34	Possible improvement (31/69/0); OR>66
		PC+G	39:29 ± 2:45	-0.9; ±2.0	0.41	278 ± 43	2.4; ±5.2	0.41	Unclear (30/68/2); OR<66
		(PC V PC+G)	-	-0.3; ±1.7	0.78	-	-0.6; ±4.5	0.82	Unclear (11/85/4)
Climb 1	0 – 12.5	CON	25:46.6 ± 1:58.1	-	-	289 ± 31	-	-	-
		PC	25:55.6 ± 1:59.0	0.6; ±1.7	0.54	291 ± 37	0.4; ±2.5	0.77	Unclear (2/84/14)
		PC+G	26:03.8 ± 2:09.2	1.1; ±2.1	0.39	291 ± 42	0; ±3.8	0.99	Unclear (2/66/32)
		(PC V PC+G)	-	-0.5; ±1.6	0.61	-	0.4; ±3.1	0.81	Unclear (11/87/2)
Climb 2	23.2 – 35.7	CON	26:56.7 ± 2:22.0	-	-	274 ± 39	-	-	-
		PC	26:26.2 ± 2:05.5	-1.8; ±1.2	0.02	280 ± 33	2.4; ±2.1	0.07	Possible improvement (49/51/0); OR>66
		PC+G	26:36.9 ± 2:21.0	-1.2; ±2.4	0.37	280 ± 43	2.8; ±4.7	0.29	Unclear (33/65/2); OR<66
		(PC V PC+G)	-	-0.6; ±2.2	0.63	-	-0.1; ±4.6	0.97	Unclear (16/80/3)

Table 4.1 cont.

Course Profile		Treatment	Performance Time			Power Output			Qualitative Inference
Phase	**Distance** (km)	**Intervention**	**mean ± SD** (h:min:sec.0)	**Mean Δ; ±90% CL** (%)	**P**	**mean ± SD** (W)	**Mean Δ; ±90% CL** (%)	**P**	(% Chance of positive / trivial / negative outcome compared to CON)
Descent 1	12.5 – 23.2	CON	13:08.7 ± 35.2	-	-	254 ± 38	-	-	-
		PC	13:10.3 ± 32.3	0.2; ±0.8	0.65	251 ± 35	-1.0; ±3.1	0.56	Unclear (1/91/7)
		PC+G	13:13.3 ± 36.2	0.6; ±0.9	0.25	248 ± 41	-2.4; ±4.9	0.38	Likely trivial (0/77/23)
		(PC V PC+G)	-	-0.4; ±0.9	0.49	-	1.4; ±4.2	0.56	Unclear (14/85/1)
Descent 2	37.5 – 46.4	CON	12:54.9 ± 37.3	-	-	270 ± 42	-	-	-
		PC	12:55.7 ± 32.3	0.1; ±0.8	0.78	267 ± 35	-0.6; ±4.1	0.80	Unclear (1/95/4)
		PC+G	12:52.5 ± 35.3	-0.3; ±1.1	0.63	273 ± 44	1.8; ±6.4	0.61	Unclear (13/84/3)
		(PC V PC+G)	-	0.4; ±0.7	0.29	-	-1.7; ±4.8	0.53	Likely trivial (0/92/8)

Note: CL = confidence limits; OR = odds ratio; P = probability; Outcomes were assessed by using the following criteria: trivial <0.4%, small 0.4 – 1.1%, moderate 1.2-2.0%, large 2.1-3.2%, very large 3.3 – 5.1%, and extremely large >5.2% change in performance time.

Table 6.1 Summary of cycling time trial performance data (performance time and power output)

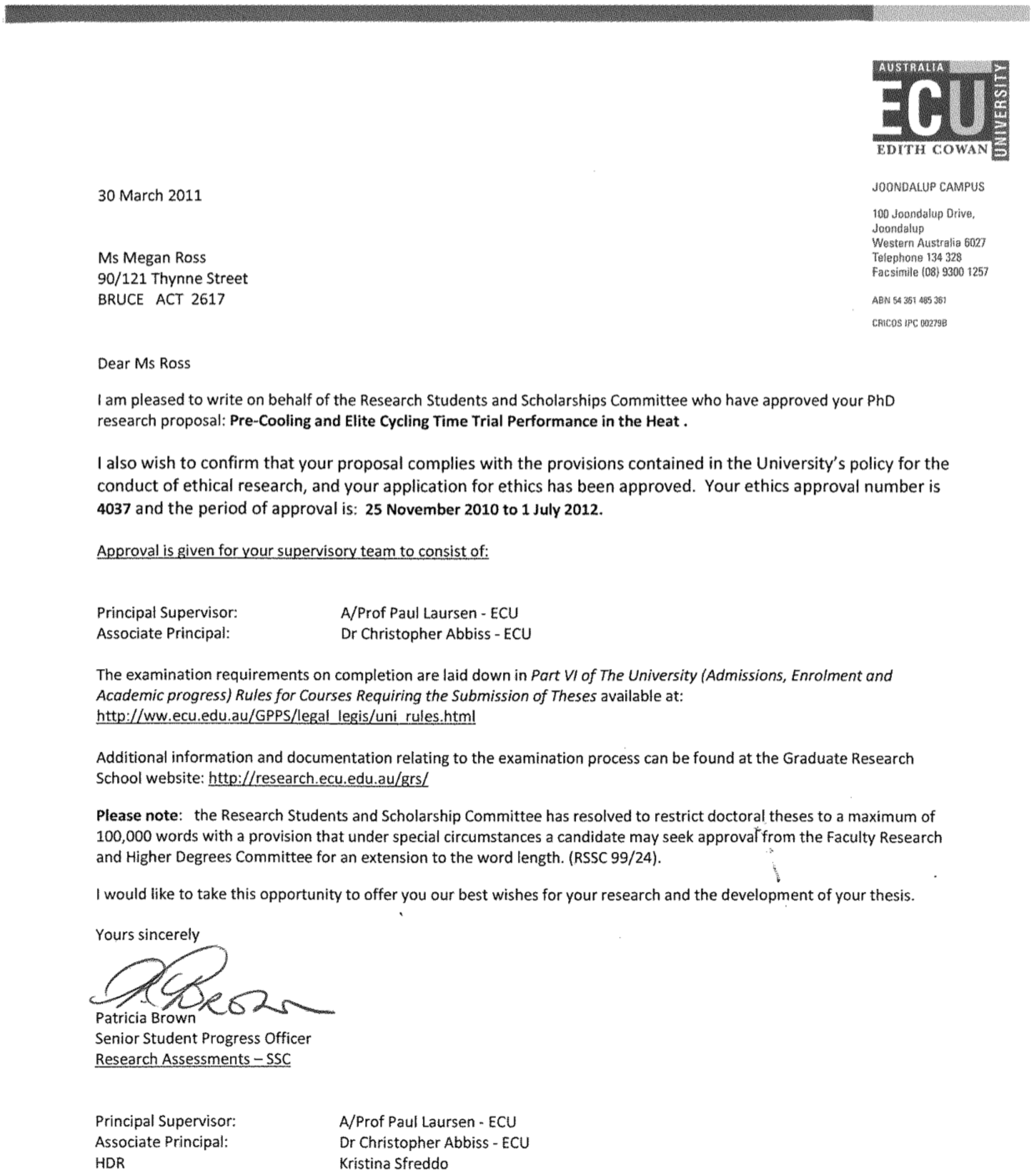
Course Profile		**Treatment**	**Performance Time**			**Power Output**			**Qualitative Inference**
Phase	**Distance** (km)	**Intervention**	**mean ± SD** (h:min:sec.0)	**Mean Δ; ±90% CL** (%)	**P**	**mean ± SD** (W)	**Mean Δ; ±90% CL** (%)	**P**	(% Chance of positive / trivial / negative outcome compared to corresponding CON)
Total	0 – 45.6	CON_{Temp}	1:08:58.4 ± 3:27.3	-	-	313.0 ± 32.4	-	-	-
		PC_{Temp}	1:09:03.4 ± 2:53.7	0.2; ±0.8	0.73	315.6 ± 29.5	0.9; ±1.4	0.27	Unclear (12/59/30)
		CON_{Hot}	1:11:17.6 ± 3:28.9	-	-	290.2 ± 27.8	-	-	-
		PC_{Hot}	1:10:25.6 ± 3:32.0	-1.2; ±1.4	0.13	299.2 ± 28.7	3.1; ±2.8	0.07	Likely benefit (85/12/3); OR>66
		(CON_{Hot} V CON_{Temp})	-	3.3; ±1.2	0.00	-	-7.8; ±3.0	0.00	Almost certain impairment (0.01/0.05/99.95)
Lap 1	0 – 22.8	CON_{Temp}	34:25.4 ± 1:47.3	-	-	312.7 ± 34.9	-	-	-
		PC_{Temp}	34:32.5 ± 1:34.9	0.4; ±0.7	0.39	314.1 ± 31.8	0.6; ±1.4	0.49	Likely trivial (0/91/9)
		CON_{Hot}	35:09.8 ± 1:47.4	-	-	298.4 ± 32.0	-	-	-
		PC_{Hot}	34:57.7 ± 1:53.8	-0.6; ±1.5	0.49	302.6 ± 32.5	1.4; ±3.0	0.43	Unclear (33/63/4); OR<66
		(CON_{Hot} V CON_{Temp})	-	2.1; ±1.1	0.00	-	-4.7; ±2.6	0.01	Very likely impairment (0/4/96)
Lap 2	22.8 – 45.6	CON_{Temp}	34:33.0 ± 1:43.1	-	-	313.3 ± 31.1	-	-	-
		PC_{Temp}	34:30.9 ± 1:21.1	-0.1; ±1.0	0.92	317.1 ± 28.0	1.3; ±1.7	0.19	Likely trivial (9/85/6)
		CON_{Hot}	36:07.8 ± 1:47.7	-	-	282.5 ± 25.2	-	-	-
		PC_{Hot}	35:28.0 ± 1:42.0	-1.8; ±1.4	0.04	296.1 ± 25.9	4.8; ±2.9	0.01	Likely benefit (89/11/0); OR>66
		(CON_{Hot} V CON_{Temp})	-	4.4; ±1.4	0.00	-	-10.8; ±3.4	0.00	Almost certain impairment (0/0/100)
Flat	1) 0-4.6,	CON_{Temp}	51:04.1 ± 2:26.1	-	-	308.1 ± 34.5	-	-	-
	2) 9.6-27.4,	PC_{Temp}	51:08.5 ± 2:00.4	0.2; ±0.8	0.71	310.1 ± 32.0	0.7; ±1.8	0.47	Unclear (2/89/9)
	3) 32.4-45.6	CON_{Hot}	52:46.3 ± 2:19.2	-	-	283.9 ± 29.3	-	-	-
		PC_{Hot}	52:15.2 ± 2:22.5	-1.0; ±1.3	0.20	292.5 ± 30.3	3.0; ±3.0	0.09	Possible benefit (58/40/1); OR>66
		(CON_{Hot} V CON_{Temp})	-	3.2; ±1.3	0.00	-	-8.4; ±3.6	0.00	Almost certain impairment (0/0/100)

Table 6.1 cont.

Course Profile		Treatment	Performance Time			Power Output			Qualitative Inference
Phase	**Distance** (km)	**Intervention**	**mean ± SD** (h:min:sec.0)	**Mean Δ; ±90% CL** (%)	**P**	**mean ± SD** (W)	**Mean Δ; ±90% CL** (%)	**P**	(% Chance of positive / trivial / negative outcome compared to corresponding CON)
Climb	1) 4.6-6.6	CON$_{Temp}$	12:10.0 ± 57.6	-	-	350.7 ± 31.9	-	-	-
	2) 9.1-9.6	PC$_{Temp}$	12:11.2 ± 49.8	0.2; ±1.6	0.80	355.3 ± 30.0	1.3; ±1.3	0.10	Unclear (4/85/10)
	3) 27.4-29.4	CON$_{Hot}$	12:39.8 ± 1:02.5	-	-	333.5 ± 32.7	-	-	-
	4) 31.9-32.4	PC$_{Hot}$	12:21.9 ± 1:04.0	2.4; ±2.1	0.07	344.2 ± 32.3	3.2; ±2.7	0.06	Likely benefit (78/21/0)
		(CON$_{Hot}$ V CON$_{Temp}$)	-	3.9; ±1.6	0.00	-	-5.2; ±2.0	0.00	Almost certain impairment (0/1/99)
Descent	1) 6.6-9.1	PC$_{Temp}$	5:44.3 ± 9.8	-	-	279.9 ± 34.2	-	-	-
	2) 29.4-31.9	CON$_{Temp}$	5:43.8 ± 9.9	-0.1; ±0.6	0.69	280.6 ± 27.1	0.5; ±3.4	0.79	Unclear (11/86/3)
		PC$_{Hot}$	5:51.5 ± 12.3	-	-	256.7 ± 28.6	-	-	-
		CON$_{Hot}$	5:48.6 ± 11.5	-0.8; ±1.0	0.16	263.0 ± 25.8	2.6; ±3.5	0.21	Possible benefit (65/34/1); OR>66
		(CON$_{Hot}$ V CON$_{Temp}$)	-	2.0; ±0.8	0.00	-	-8.9; ±3.6	0.00	Almost certain impairment (0/0/100)

Note: CL = confidence limits, benefit = faster performance time and/or greater power output, impairment = slower performance time and/or lower power output, OR = odds ratio, P = probability; mean Δ ± 90% CL are comparisons of treatment interventions (i.e., PC$_{Temp}$ and PC$_{Hot}$) to their respective controls (i.e., CON$_{Temp}$ and CON$_{Hot}$); The comparison of CON$_{Temp}$-CON$_{Hot}$ is to look at the effect of ambient temperature on cycling time trial performance; Outcomes were assessed by using the following criteria: trivial <0.4%, small 0.4 – 1.1%, moderate 1.2 – 2.0%, large 2.1 – 3.2%, very large 3.3 – 5.1%, and extremely large >5.2% change in performance.

Appendix K



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30 March 2011

Ms Megan Ross
90/121 Thynne Street
BRUCE ACT 2617

Dear Ms Ross

I am pleased to write on behalf of the Research Students and Scholarships Committee who have approved your PhD research proposal: **Pre-Cooling and Elite Cycling Time Trial Performance in the Heat .**

I also wish to confirm that your proposal complies with the provisions contained in the University's policy for the conduct of ethical research, and your application for ethics has been approved. Your ethics approval number is **4037** and the period of approval is: **25 November 2010 to 1 July 2012.**

Approval is given for your supervisory team to consist of:

Principal Supervisor: A/Prof Paul Laursen - ECU
Associate Principal: Dr Christopher Abbiss - ECU

The examination requirements on completion are laid down in *Part VI of The University (Admissions, Enrolment and Academic progress) Rules for Courses Requiring the Submission of Theses* available at: http://ww.ecu.edu.au/GPPS/legal_legis/uni_rules.html

Additional information and documentation relating to the examination process can be found at the Graduate Research School website: http://research.ecu.edu.au/grs/

Please note: the Research Students and Scholarship Committee has resolved to restrict doctoral theses to a maximum of 100,000 words with a provision that under special circumstances a candidate may seek approval from the Faculty Research and Higher Degrees Committee for an extension to the word length. (RSSC 99/24).

I would like to take this opportunity to offer you our best wishes for your research and the development of your thesis.

Yours sincerely

Patricia Brown
Senior Student Progress Officer
Research Assessments – SSC

Principal Supervisor: A/Prof Paul Laursen - ECU
Associate Principal: Dr Christopher Abbiss - ECU
HDR Kristina Sfreddo

Appendix L

AUSTRALIAN INSTITUTE OF SPORT

EDITH COWAN UNIVERSITY

INFORMED CONSENT FORM

Project Title: Pre-cooling strategies and cycling time trial performance in the heat

Principal Researchers: Megan Ross, Nikki Jeacocke, David Martin, Paul Laursen & Chris Abbiss & Louise Burke.

This is to certify that I, ________________________________ hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Institute of Sport (AIS) under the supervision of Megan Ross.

The investigation and my part in the investigation have been defined and fully explained to me by Megan Ross and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my own free will and I have not been coerced in any way to participate.

Signature of Subject: ______________________________Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ____________________________Date: ___/___/___

Appendix M

Participant Information

Project Title: Pre-cooling strategies and cycling time trial performance in the heat

Brief Description of Project

It is well established that endurance cycling performance is impaired in hot and humid conditions. During time trial cycling, a large amount of energy (~75%) is liberated as heat. As air temperature increases, the gradient for heat exchange between the skin and the environment is lowered and body temperature rises. There is evidence to suggest that attainment of a critically high body temperature is the main limiting factor inhibiting exercise intensity in these conditions, as evidenced by increased fatigue causing a reduction in power output.

A number of strategies have emerged to combat the debilitating effects of hyperthermia-induced fatigue for cyclists racing in hot and/or humid conditions. Among these strategies, pre-event cooling has become a popular, legal and effective way to reduce core temperature when performed immediately prior to such exercise. Performance improvements with pre-cooling have been hypothesised to occur as a result of an increased capacity to store heat, thereby increasing the time taken to reach a critical limiting temperature.

Coaches and athletes are interested in strategies that are documented to enhance endurance performance in these conditions. While there is a sound theoretical basis for using a range of strategies, further work is required to examine a variety of popular and novel pre-cooling approaches used to prepare elite cyclists prior to competing in hot and humid conditions. Such a protocol must achieve the best physiological outcomes for the event, but must also be practical to implement within the rules, logistics, and environment of the competition. The aims of the following studies are to determine both the most practical and most effective pre-cooling strategy to apply to an athlete before they perform in a cycling time trial in hot and thermoneutral conditions.

These studies will provide evidence-based guidelines for Australian Cyclists regarding the appropriateness of a pre-cooling procedure to optimise cycling time trial performance under varying environmental conditions. As a participant you will be required to complete the following procedures:

Methodology

Preliminary testing (VO_{2max})

You will perform a national cycling progressive maximal test protocol, in order to identify your maximal power output and corresponding heart rate. You will be required to cycle to exhaustion.

Familiarisation

You will perform at least one familiarisation trial before commencing the experimental trials. This trial is required so that you become familiar with the cycling ergometer, the time trial course and the laboratory conditions.

Heat Acclimatisation

Environmental acclimatisation training will involve you cycling for a minimum of three 60 min self-paced cycling sessions per week, for three weeks prior to the first time trial.

Experimental Trials

<u>Study 1</u> - Comparison of different pre-cooling strategies

You will be required to report to the laboratory on ten separate occasions to perform trials, at the same time each day. Each trial will consist of 90 min, including 30 min stabilisation to hot, humid (32-35ºC; 50-60% r.h.) conditions followed by 30 min pre-cooling. Each trial will assess the effectiveness of ten different pre-cooling strategies on your rectal temperature and thermal comfort.

The ten experimental pre-cooling treatments will include:

1) A control – No intervention
2) Wearing an RMIT/AIS Jacket (Non-commercial cooling jacket)
3) Wearing an Arctic Heat Vest (Commercially available cooling vest)
4) Wearing iced towels
5) Ingesting a large cold volume of fluid
6) Ingesting a small slushie
7) Ingesting a large slushie
8) Immersion in a cold water plunge
9) A combination of the ‘Best’ internal and external cooling strategies
10) STD COOL – A Combination of Plunge + RMIT/AIS Jacket

Following 30 min of pre-cooling, a 30 min standardised warm-up will be completed.

<u>Study 2</u> - Practical pre-cooling

Results identified in Study 2 will be used to identify the most effective pre-cooling strategy. The influence of this new pre-cooling strategy on thermoregulatory responses and cycling performance will be compared with the industry pre-cooling standard (combination of cold water immersion followed by wearing an ice-jacket; STD COOL) and a control condition.

You will be required to make a total of twelve visits to the laboratory, including nine heat acclimatisation trials, a preliminary testing session (progressive maximal cycling test), at least one familiarisation trial and three experimental sessions.

Each trial is estimated to last ~ 3.5 h and will be conducted in a hot and humid (32-35º C; 50-60% r.h.) environmental chamber. Two hours prior to the commencement of a simulated time trial, you will enter the environmental chamber and stabilise to the conditions for 60 min. You will then complete one of two pre-cooling strategies or a control (no intervention) condition for 30 min, followed by a 20 min standardised warm-up and a 10 min period to make final preparations. You will then complete a 46.4 km time trial on a cycle ergometer.

Each time trial requires a maximal effort so you will be asked to give as much as possible for the total distance. Your times will be compared to all of the other participants.

Study 3 - Pre-cooling and hyperhydration combined
The best pre-cooling strategy identified in Study 3 will be further examined with and without the addition of a hyperhydration ingredient (glycerol), and compared to a control condition (no intervention), for its effect on thermoregulation and performance in a cycling time trial in the heat.

Your involvement will again involve heat acclimatisation, preliminary testing, trial familiarisation and three experimental trials as detailed in Study 3.

In this research phase, each trial will last ~ 3.5 hr and will follow the same schedule as outlined in Study 3, but will be preceded by the ingestion of a large beverage ~3 hr prior to the commencement of each time trial.

Each time trial requires a maximal effort so you will be asked to give as much as possible for the total distance. Your times will be compared to all of the other participants.

Study 5 – Environmental temperature on thermoregulation during pre-cooling and subsequent time trial performance

The best pre-cooling strategy identified in Study 4 will be further examined for its effects on thermoregulation and cycling time trial performance when administered in both hot, humid and thermoneutral conditions.

Your involvement will again involve heat acclimatisation, preliminary testing, trial familiarisation and four experimental trials. Each trial will compare cycling time trial performance after preparing in both hot/humid and thermoneutral environmental conditions when preceded by pre-cooling or a control (no intervention). Again, each trial will last ~ 3.5 hr and will follow the same schedule as outlined in Study 3.

Measurements:
During all parts of this investigation we will monitor the environmental conditions, your urine production, rectal temperature (as measured by a general purpose temperature inserted 12 cm beyond the anal sphincter), body mass, heart rate. You will also be asked to provide ratings of thermal comfort, gastrointestinal comfort and self-perceived rating of cooling effectiveness. Only Studies 3-5 will involve the measurement of cycling performance and blood lactate concentration.

Participation in each of these trials will be terminated if body temperatures exceed 40º C or drop below 36º C.

About the Time Trial
Effort: The time trial is expected to be a maximal performance. Times will be compared to other participants. You will be required to complete the entire duration of the trial regardless

Pacing: You are free to choose your own pacing strategy and feedback will be restricted to distance, velocity, gear ratio, gradient and your location on the course. Best results will likely occur if the second lap is similar or faster than the first lap.

Performance: You will not receive your time for each time trial until you have completed your fourth time trial. This way, you will not be able to compare your performances form trial to trial and will also ensure that you give all that you can on the day of each trial.

Drinking: Drinking will take place at designated areas of the course and will be the same volume and composition for each trial.

Your Rights

Please note that it is your prerogative to withdraw from the study at any time, and that no explanation is required for such withdrawal.

While the data collected during the study will be published in scientific and coaching journals and presented at conferences, your identity will not be disclosed unless prior written approval is provided. Results will be filed securely in a locked filing cabinet for the following 5 years in accordance with the National Health and Medical Research Council Statement of Scientific Practice. After this period results will be destroyed. Access to results will only be made available to principle researchers of the study.

All tests are physically demanding and require maximal effort. You are free to withdraw at any stage if you feel you cannot complete the tests, or do not wish to complete the project.

For more information, please contact the Principal Researcher:
Megan Ross
megan.ross@ausport.gov.au
[ph] 02 6214 1137
[mob] 0408 668 573

If you have any concerns with respect to the conduct of this study, you may wish to contact:

- Ms. Helene Kaye – Secretary, Ethics Committee, Australian Institute of Sport: (02) 6214 1816
- Ms. Kim Gifkins – Research Ethics Officer, Edith Cowan University: (08) 6304 2170

Appendix N

[SUBJECT NAME]

71 kg Standardised Diet Checklist

- Eat all the foods and drinks provided to you over the day. Eat and drink only what is provided or allowed
- Try to eat the food on the day specified.
- Do not consume drinks which contain caffeine - coffee, tea, caffeine-containing soft drinks (i.e. Pepsi Max, Diet Coke, Mountain Dew)
- No alcohol is to be consumed
- You may add a salad to your evening meal – lettuce, tomato, cucumber, capsicum and low oil dressing. This must be recorded and repeated exactly on each occasion.
- You can drink water (low cal cordial can be added) over the day, but this must be recorded and repeated exactly.

Lunch:

☐ Lean Cuisine Sundried Tomato Chicken with Pasta – 370g
☐ 20 Starburst Jelly Babies – 50g

Dinner

☐ Lean Cuisine Sundried Tomato Chicken with Pasta – 370g
☐ Garlic Bread – 110g
☐ Apple juice – 250ml popper

Snacks (afternoon tea and supper)

☐ White bread – 2 slices
☐ Margarine – 3 sachets
☐ Vegemite – 1 sachet
☐ Honey – 1 sachet
☐ Up and Go – 250ml (banana)
☐☐ 2 x 20 Starburst Jelly Babies – 100g

Breakfast: suggested time = 8 – 9am

☐ Weet bix– 4 biscuits
☐ Milk – 200ml tetrapack reduced fat
☐ Apple Juice – 250ml popper
☐ Goulburn Valley Tinned Fruit – 1 tub
☐ Yoghurt – 200g tub

Lunch: 2 hours prior to start of trial = 11am

☐ Fruit bread – 3 slices
☐ Margarine – 2 sachets
☐ Jam – 3 sachets
☐ Honey – 2 sachets
☐ Apple juice – 250ml

Do not eat before you come to the lab on your trial day. You may drink water

Extra food or drinks consumed: ______________________________

____

____

____

PLEASE TICK OFF ALL FOODS AS YOU CONSUME THEM AND BRING THIS SHEET TO YOUR TRIAL.
IF YOU HAVE ANY PROBLEMS, PLEASE CALL MEG (0408 668 573) OR NIKKI (0409 223 811) IMMEDIATELY

Recommendations for Pacing the Simulated Beijing Time Trial
(46.4km; 32-34 C; 50-60%r.h.)

MAXIMAL EFFORT

- This is a maximal performance trial (give as much as possible for total distance)
- Your times will be compared to all the other participants (there are incentives!)

PLAN TO FINISH THIS EFFORT REGARDLESS

- You will complete the entire duration of the trial regardless

PACING STRATEGY

- You are free to choose your own pacing strategy
- Feedback will be restricted to distance, velocity, road gradient and your gearing
- Exercise intensity in hot conditions will be lower than normal (5-10% reduction)
- Going out too hard for a 46km TT in the heat can severely compromise performance
- Best results will likely occur if the second lap is similar or faster to the first lap
- If you are feeling good save the “big effort” for the second lap

WHAT HAPPENS IF YOU GO OUT TOO HARD

- You will be in pain for a long time.
- You will be asked to repeat the trial if your second lap power output is less than 90% of your average power output for the first lap (~30-40W reduction)

HOW SHOULD THE FIRST LAP FEEL?

- Your perceptions during for the first lap should be “under control” and “on top of the gear”

DRINKING

- Drinking will take place at the top of the climb before the descent (~350ml per lap)

Appendix P

Novel Precooling Strategy Enhances Time Trial Cycling in the Heat

MEGAN L. R. ROSS[1,2], LAURA A. GARVICAN[1], NIKKI A. JEACOCKE[1], PAUL B. LAURSEN[2], CHRIS R. ABBISS[1,2,3], DAVID T. MARTIN[1], and LOUISE M. BURKE[1]

[1]*Australian Institute of Sport, Belconnen, Australian Capital Territory, AUSTRALIA;* [2]*School of Exercise Biomedical and Health Science, Edith Cowan University, Joondalup, Western Australia, AUSTRALIA; and* [3]*Division of Materials Science and Engineering, Commonwealth Scientific and Industrial Research Organisation, Belmont, Victoria, AUSTRALIA*

ABSTRACT

ROSS, M. L. R., L. A. GARVICAN, N. A. JEACOCKE, P. B. LAURSEN, C. R. ABBISS, D. T. MARTIN, and L. M. BURKE. Novel Precooling Strategy Enhances Time Trial Cycling in the Heat. *Med. Sci. Sports Exerc.*, Vol. 43, No. 1, pp. 123–133, 2011. **Purpose**: To develop and investigate the efficacy of a new precooling strategy combining external and internal techniques on the performance of a cycling time trial (TT) in a hot and humid environment. **Methods**: Eleven well-trained male cyclists undertook three trials of a laboratory-based cycling TT simulating the course characteristics of the Beijing Olympic Games event in a controlled hot and humid environment (32°C–35°C at 50%–60% relative humidity). The trials, separated by 3–7 d, were undertaken in a randomized crossover design and consisted of the following: 1) CON—no treatment apart from the *ad libitum* consumption of cold water (4°C), 2) STD COOL—whole-body immersion in cold (10°C) water for 10 min followed by wearing a cooling jacket, or 3) NEW COOL—combination of consumption of 14 g of ice slurry ("slushie") per kilogram body mass made from a commercial sports drink while applying iced towels. **Results**: There was an observable effect on rectal temperature (T_{rec}) before the commencement of the TT after both precooling techniques (STD COOL < NEW COOL < CON, $P < 0.05$), but pacing of the TT resulted in similar T_{rec}, HR, and RPE throughout the cycling protocol in all trials. NEW COOL was associated with a 3.0% increase in power (~8 W) and a 1.3% improvement in performance time (~1:06 min) compared with the CON trial, with the true likely effects ranging from a trivial to a large benefit. The effect of the STD COOL trial compared with the CON trial was "unclear." **Conclusions**: This new precooling strategy represents a practical and effective technique that could be used by athletes in preparation for endurance events undertaken in hot and humid conditions. **Key Words**: ICE INGESTION, INTERNAL COOLING, EXTERNAL COOLING, COLD WATER IMMERSION, COOLING JACKET

Preparations for the 2008 Beijing Olympic Games were dominated by concerns of coaches and athletes as to how to achieve optimal performance of sustained high-intensity exercise in a hot and humid weather (7,36). Thorough reviews of the literature show that techniques that reduce core temperature immediately before a prolonged endurance exercise carried out under high thermal stress can enhance exercise capacity and performance (24,32). Effective techniques involving external cooling include immersion in cold water (5,21), direct application of cold materials to the skin (28,33), including the use of commercially available ice jackets (9,14,19), or combinations of these strategies (33).

Recently, the ingestion of large volumes of cold water has been investigated as a precooling strategy (22). This was based on calculations that ingestion of 1 L of water at 7°C by a 70-kg subject would reduce core temperature by ~0.5°C if negative heat load was equally distributed through the body and the specific heat of the body was assumed to be 0.85 (20). When tested, the actual reduction in core temperature was observed to be 0.61°C ± 0.13°C at its maximum point, 20–25 min after ingestion, and remained 0.31°C ± 0.13°C lower than a control trial 55 min after drinking the cold water (20). Furthermore, Lee and Shirreffs (22) reported that the consumption of 1 L of cold (10°C) fluid during exercise in mild conditions attenuated the rise in rectal temperature (T_{rec}) during steady-state cycling compared with ingestion of equal volumes of warm (37°C) and hot (50°C) fluids. Of course, the ingestion of large volumes of fluid before or during exercise is impractical in many sports, particularly those involving a high-intensity exercise because of the high risk of causing gastrointestinal upset or discomfort. A variation of this strategy, involving the ingestion of ice slurries, offers the potential for equal dissipation of heat from a smaller volume of "beverage." On the basis of the theory of enthalpy of fusion, ice requires substantially larger heat energy to cause a phase change from a solid to a liquid state (at 0°C) compared with the energy required to increase the temperature of liquid water (26).

Although there is a sound theoretical basis for using precooling strategies, "in-the-field" application during sporting competition requires identification of an ideal protocol for

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Evidence of High Body Temperature During Men's Stage-Race Cycling in Temperate Environmental Conditions

Ross MLR[1], Stephens B[1], Abbiss CR[2], Martin DT[1], Laursen PB[2], Burke LM[1]
[1]Australian Institute of Sport, [2]Edith Cowan University

Introduction

Hyperthermia, hypohydration and carbohydrate (CHO) depletion are contributing factors to fatigue during prolonged exercise[1] especially when performed in high ambient temperatures. However, there is currently limited field-based research examining the occurrence of hyperthermia and real-life fluid and fuel practices of athletes, especially during exercise in temperate conditions.

To observe thermoregulatory stress, fluid balance and voluntary CHO intake of highly competitive road cyclists during a multiday multiple-stage race in temperate conditions.

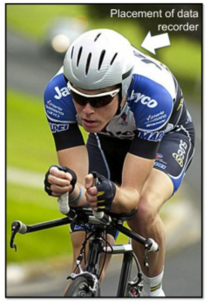
Table 1. Nutrient consumption rate during racing.

	TOUR 1		TOUR 2	
	Mean of all cyclists	**Mean of cyclists who consumed nutrients during stage**	**Mean of all cyclists**	**Mean of cyclists who consumed nutrients during stage**
Fluid Consumption				
Road Race	410 ± 189 ml.h^{-1} (n=25)	410 ± 189 ml.h^{-1} (n=25)	558 ± 145 ml.h^{-1} (n=10)	558 ± 145 ml.h^{-1} (n=10)
Criterium	181 ± 198 ml.h^{-1} (n=20)	241 ± 195 ml.h^{-1} (n=15)	237 ± 220 ml.h^{-1} (n=15)	274 ± 214 ml.h^{-1} (n=13)
Individual time trial	-	-	360 ± 501 ml.h^{-1} (n=5)	899 ± 188 ml.h^{-1} (n=2)
CHO Consumption				
Road Race	40.5 ± 24.2 g.h^{-1} (n=25)	44.0 ± 21.9 g.h^{-1} (n=23); 60%	64.2 ± 23.7 g.h^{-1} (n=10)	64.2 ± 23.7 g.h^{-1} (n=10); 58%
Criterium	11.1 ± 14.9 g.h^{-1} (n=20)	27.7 ± 8.6 g.h^{-1} (n=8); 48%	27.5 ± 25.0 g.h^{-1} (n=15)	29.4 ± 24.7 g.h^{-1} (n=14); 48%
Individual time trial	-	-	46.0 ± 46.5 g.h^{-1} (n=5)	76.7 ± 28.2 g.h^{-1} (n=3); 86%

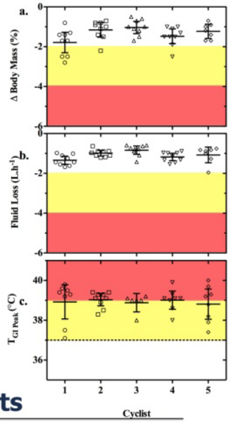
Data presented as mean ± SD (n); % CHO as solid.

Methods

Subjects: Ten internationally competitive male cyclists (19.7 ± 0.8 y, 72.0 ± 6.1 kg, 180 ± 5 cm). **Races:** 2009 Tour of Gippsland (*Tour 1*, n=5) and 2010 Tour of Geelong, (*Tour 2*, n=5). *Tour 1* involved 9 stages (55 ± 21; 71 sprints, 20 hill climbs) over 5 d and included 5 road races and 4 criteriums. *Tour 2* involved 6 stages (66 ± 42 km; 49 sprints, 15 hill climbs) over 5 d and included 3 criteriums, 2 road races and an individual time trial. **Environmental conditions:** *Temperate* (13.2-15.8˚C; 54-80% r.h.). **Observations:** 'First-waking' urine samples collected for determination of specific gravity (USG). Body mass (BM) and thermal comfort (TC) recorded immediately before and after each stage. Peak gastrointestinal temperature ($T_{GI\ peak}$) monitored throughout racing (see Fig. 1). Types and volumes of fluid and food consumed during racing were recalled.



^**Figure 1.** Cyclist racing while T_{GI} was continuously monitored.



>**Figure 2.** %ΔBM (a), fluid loss (b) and $T_{GI\ peak}$ (c) during Tour 1.

Results

Body temperature and thermal comfort

T_{GI} peak during racing were 38.9 ± 0.7˚C, with 67% of observations bein >39˚C in *Tour 1* (Fig. 2a) and 39.3 ± 0.4˚C, with 73% of observations bein >39˚C during *Tour 2* (Fig 3). Thermal comfort during each stage were 4.7 0.9 (where 5 = *warm*) during *Tour 1*, and 3.4 ± 1.5 (where 3 = *cool* and 4 – *comfortable*) during each stage of *Tour 2*.

Hydration and body mass

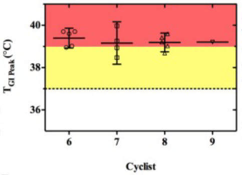
USG on days 1-4 of *Tour 1* were 1.023 ± 0.006, with 12 of 20 samples > 1.020, and days 1-5 of *Tour 2* were 1.017 ± 0.005 with 6 of 25 > 1.020. Change in body mass from pre- to post-race was -1.3 ± 0.2% BM (range: -0.5 to -2.8%, P<0.001; Fig. 2b), with an estimated fluid loss of 1.1 ± 0.3 L.h^{-1} (range: -0.6 to -2.0 L.h^{-1}; Fig. 2c). The change in BM was -1.5 ± 0.3% (P<0.001; n=19) for road stages and -1.1 ± 0.2% BM (P<0.001; n=24) for criterium stages.

Fluid balance and carbohydrate intake

Table 1 summarises nutrient consumption during both tours. There were strong correlations between fluid intake and distance across all formats of racing (r=0.82, *very large* and r=0.92, *almost perfect*), and mean fluid intake during road stages and individual race time (r=0.64, *large* and r=0.90, *almost perfect*).

Discussion

- Mean changes in BM, from pre- to post-race during stages were small (1.3%), with deficits >2% BM occurring on only five of 43 measured occasions.
- Some cyclists chose to consume no fluid during stages involving criterium or individual time trial formats, but fluid intake always occurred during road racing.
- During most races, cyclists consumed CHO at rates which met the new guidelines[2], although cyclists did not consume CHO during some race formats (23% of all stages, predominately criteriums).
- Consistent observations of $T_{GI\ peak}$ >39˚C during stages of *Tour 1* (67%) and *Tour 2* (73%) despite temperate environmental conditions.



<Figure 3.
$T_{GI\ peak}$ during Tour 2. Note: due to technical malfunctions, data were collected on only 15 out of 30 possible occasions.

>Figure 4. Subjects and members of a single team.

Summary

- Mild mismatches between fluid intake and sweat rates observed.
- Recommended CHO consumption during racing voluntarily achieved.
- Differences in feeding strategies according to racing format detected.
- High $T_{GI\ peak}$ at magnitudes typically associated with heat stress-induced fatigue consistently observed.
- Future research on impact of elevated body temperature on cycling performance is warranted.

References

1. Jeukendrup, AE. J Sports Sci. 2011; 29 Suppl 1: S91-9.
2. Burke LM, et al. J Sports Sci. 2011; 29 Suppl 1: S17-27.

Photos: Courtesy of cyclingnews.com and M.Ross

Appendix R

2012 AUSTRALIAN OLYMPIC TEAM
GAMES OF THE XXXTH OLYMPIAD LONDON

Chef de Mission:
Nicholas Green OAM

Deputy Chefs de Mission:
Kitty Chiller
Christopher Fydler OAM

Team Chief Operating Officer:
Craig Phillips

21 June 2011

Megan Ross
C/- Physiology
Australian Institute of Sport
Leverrier Crescent
BRUCE ACT 2617

By email: megan.ross@ausport.gov.au

Dear Megan,

RE: 2012 AUSTRALIAN OLYMPIC TEAM APPOINTMENT

It is my great pleasure to advise you that the 2012 Team Executive has approved a recommendation for you to be appointed to the 2012 Australian Olympic Team Medical Headquarters in the role of Assistant Recovery Physiologist. Your appointment to the Team is subject to the following:

- ongoing satisfactory work performance with sports;
- you signing and complying with the Team Agreement – Officials which will be available in the near future;
- overall Team size and the availability of accreditations; and
- the number of athletes in sections without dedicated medical support.

Other appointments to the Team which have now been confirmed are detailed on the attached Team Headquarters Management Structure together with a Medical Headquarters Structure diagram. Also attached for your reference is the agreed certification statement to be used ***at the conclusion of the Games*** in recognition of your provision of sports-related personal services to the 2012 Australian Olympic Team.

You're appointment to the Team is on an honorary basis. Should your personal circumstances prevent you from being available for the Games period, please advise us at the earliest opportunity so that a suitable replacement can be found.

London promises to be a great Games and I know your contribution will do us proud.

Yours sincerely

NICHOLAS GREEN OAM
2012 Chef de Mission

cc Dr Peter Baquie – 2012 Australian Olympic Team Medical Director
Shona Halson – Recovery Physiologist, 2012 Australian Olympic Team
Lauren Fitzgerald – AOC Manager, Sport Services

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Active Voice: Precooling Strategies and Improvements in Cycling Performance in the Heat

By Megan Ross, B.S.

Viewpoints presented in SMB commentaries reflect opinions of the authors and do not necessarily reflect positions or policies of ACSM.

Megan Ross, B.S., is completing her Ph.D. through Edith Cowan University in Joondalup, Western Australia. Based out of the Australian Institute of Sport (AIS) in Canberra, she travels with an AIS competitive cycling team and conducts performance-related studies with these athletes. Ross is interested in developing strategies for reducing risks of heat injury in cycling competitions. This commentary presents her views associated with the research article she and her colleagues published in the Jan. 2011 Medicine & Science in Sports & Exercise®.

January is the month when cyclists travel “Down Under” to compete in the first event on the UCI Pro Tour calendar – an event held in the extreme heat of the Australian summer. With the stage-race covering ~850 km over six days, in temperatures that often reach over 40°C/104°F, it is important that riders manage their heat stress. As such, research into practical means of cooling, either before, during or after exercise in hot temperatures continues to grow.

Generally, cooling interventions applied directly prior to exercise (or “precooling”) are the most practical and beneficial to performance. Indeed, a wide range of precooling methods, which involve exposure to cool air, cool water and ice, have been shown to reduce deep body and skin temperatures, increase heat storage capacity and improve exercise performance in hot conditions. Although there are logistical limitations that have restricted the use of precooling techniques prior to actual competition, cooling is quickly becoming an important part of cyclists’ pre-event routines at major competitions. With the emergence of more practical choices for precooling – including ice towel application, cold water immersion and ice ingestion – precooling has become more accessible for cyclists to employ in the field. Professional teams now install ice-slurry machines on team buses, travel with portable plunge baths or warm up wearing ice-jackets. This way, sport scientists can individualize cooling strategies with cyclists using various modes, timings and combinations of cooling options for specific event disciplines and the individual roles that cyclists play.

The practice of consuming an ice slurry beverage (14 g.kg-1 BM of a crushed ice beverage made from sports drink consumed 30-60 min before exercise) prior to endurance performance makes practical and logical sense, as it has the potential to not only lower core temperature but also enhance fluid intake. This may be important during exercise in heat, such as in an international cycling time trial in which athletes compete against the clock to secure the fastest time (~50 min, or speeds of ~48 km.h-1) over a set distance (~40 km). A new cooling strategy, which involves the combination of ingesting an ice slurry and applying iced towels, was assessed using a laboratory-based cycling time trial simulating the course characteristics of the Beijing Olympic Games (see Ross et al. 2011). Compared to the control condition where no cooling was used, the treatment strategy achieved the desired reduction in rectal temperature (-0.3°C), which persisted throughout a warm-up. Although pacing during the time trial resulted in similar rectal temperatures, heart rates and ratings of perceived exertion, cycling performance following the combined cooling strategy was associated with a three-percent increase in power output and a 1.3-percent improvement in performance time. Therefore, we believe this strategy represents a practical and effective precooling option for cyclists in preparation for races in hot and humid conditions.

In summary, precooling is now emerging from the laboratory and being used in competitions. With a targeted approach for use within cycling, practical precooling is fast becoming popular among professionals. Reinforced by the benefits of improved safety, perceived comfort and endurance performance, as well as the practical ease of cooling prior to a race, interest in this area of research is mounting. Further research into individualized precooling practices will assist practitioners on how to best prepare cyclists for future events contested in hot conditions.