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## Thermoregulatory and exercise performance : responses to cooling with ice slurry ingestion

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**EDITH COWAN UNIVERSITY**

School of Exercise, Biomedical and Health Sciences

**Thermoregulatory and Exercise Performance  
Responses to Cooling with Ice Slurry Ingestion**

**RODNEY SIEGEL BAppSc(Hons)**

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

Principal Supervisor: Professor Paul Laursen

Associate Supervisor: Professor Ken Nosaka

Associate Supervisor: Dr Greig Watson

Date of submission: 7<sup>th</sup> April 2011



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## **ABSTRACT**

The rise in body core, skin and muscle temperatures associated with exercise in hot environments ( $\sim 30^{\circ}\text{C}$  and above) is known to impair performance over a variety of exercise modes and durations. Precooling has become a popular strategy to combat this impairment, as evidence has shown it to be an effective method for lowering pre-exercise core temperature, increasing heat storage capacity and improving exercise performance in the heat. To date, the majority of precooling manoeuvres are achieved via external means, such as cold water immersion and the application of cooling garments; methods which have been criticised for their lack of practicality for use in major sporting competitions. However, recent evidence has shown that internal or endogenous cooling methods, such as drinking cold fluids, are able to lower core temperature and enhance endurance performance in the heat. This method may be more advantageous than current forms of precooling, as ingesting cold fluids is easily implemented in the field and provides the additional benefit of hydrating athletes. Based on the law of enthalpy of fusion, which states that a significantly greater amount of heat absorption is required for water to change phase from solid to liquid (melt), the ingestion of an ice slurry mixture may be a more powerful means for lowering pre-exercise core temperature. Therefore, the primary focus of this PhD thesis was to determine the effectiveness of ice slurry ingestion as a precooling manoeuvre for improving submaximal exercise performance in the heat, as well as investigate the potential mechanisms behind the improvements observed.

Study 1 of this thesis was aimed at determining whether ice slurry ingestion was able to significantly lower pre-exercise core temperature and increase submaximal run time to exhaustion in the heat compared with the ingestion of a cold ( $4^{\circ}\text{C}$ ) fluid. The results showed that ice slurry ingestion significantly reduced rectal

temperature compared with cold water ingestion ( $0.66 \pm 0.14^{\circ}\text{C}$  vs.  $0.25 \pm 0.09^{\circ}\text{C}$ ;  $P = 0.001$ ), and remained lower for the first 30 min of exercise. Running time was longer ( $P = 0.001$ ) after ice slurry ( $50.2 \pm 8.5$  min) versus cold water ( $40.7 \pm 7.2$  min) ingestion. During exercise, mean skin temperature ( $P = 0.992$ ), heart rate ( $P = 0.122$ ) and sweat rate ( $P = 0.242$ ) were all similar between conditions; however, mean ratings of thermal sensation ( $P = 0.001$ ) and perceived exertion ( $P = 0.022$ ) were lower following ice slurry ingestion. An unexpected finding from this study was that at exhaustion, rectal temperature was higher ( $0.31 \pm 0.11^{\circ}\text{C}$ ;  $P = 0.001$ ) with ice slurry versus cold water ingestion. It was speculated that this may have been due to the influence of ice slurry ingestion on lowering brain temperature or in altering thermoreception.

After showing that ice slurry ingestion was an effective precooling manoeuvre for improving endurance performance in the heat, Study 2 was conducted to compare this method with the current “gold standard” method of cold water immersion. Despite rectal ( $P = 0.001$ ) and skin temperatures ( $P = 0.009$ ), as well as heart rate ( $P = 0.018$ ) and sweat rate ( $P = 0.019$ ) being significantly lower following cold water immersion, ratings of thermal sensation ( $P = 0.750$ ) and perceived exertion ( $P = 0.278$ ) were not different, and run times to exhaustion were similar between conditions (CWI:  $56.8 \pm 5.6$  min vs. ICE:  $52.7 \pm 8.4$  min;  $P = 0.355$ ). Additionally, the result of a higher rectal temperature at the point of exercise termination following ice slurry ingestion ( $0.28^{\circ}\text{C}$ ) was replicated. These findings indicate that ice slurry ingestion is a comparable form of precooling to cold water immersion, and provided further evidence that ice slurry ingestion may enhance performance via thermoreceptive/sensory mechanisms.

As a result of the findings showing that the ice slurry precooling method was consistently associated with higher end point rectal temperatures in Studies 1 and 2, Study 3 was performed to determine whether ingesting a small bolus of ice slurry ( $1.25 \text{ g}\cdot\text{kg}^{-1}$ ) was able to increase maximal voluntary isometric contraction (MVC) torque under conditions of heat strain. The results showed that following exercise-induced hyperthermia, ice slurry ingestion significantly increased mean torque production during a 2-min sustained MVC of the elbow flexors, compared with the ingestion of  $40^{\circ}\text{C}$  fluid ( $30.75 \pm 16.40$  vs.  $28.69 \pm 14.88 \text{ Nm}$ ;  $P = 0.001$ ). This was despite run times to exhaustion ( $P = 0.530$ ), end rectal ( $P = 0.934$ ) and skin temperatures ( $P = 0.922$ ) as well as heart rate ( $P = 0.830$ ) being similar between trials. The mechanisms responsible for this improvement with ice slurry ingestion may therefore be an adjustment in afferent feedback relayed from internal thermoreceptors pertaining to the thermal state of the body, and/or activation/suppression of brain regions associated with reward, pleasure, motivation or fatigue.

The main findings from this PhD thesis were that ice slurry ingestion was an effective, practical precooling manoeuvre for prolonging submaximal running time in the heat, and comparable to the current “gold standard” cold water immersion method. Furthermore, ice slurry ingestion was able to prolong running time in the heat by increasing the rectal temperature tolerable before exercise termination. Finally, ice slurry ingestion may enhance exercise performance in conditions of heat strain via thermoreceptive/sensory mechanisms. Due to its’ practicality for use in the field, ice slurry ingestion may be a more preferred form of precooling than traditionally used strategies.

## **SYMBOLS AND ABBREVIATIONS**

°C     Degrees Celsius

MVC   Maximal voluntary contraction

Nm     Newton metres

RPE   Rating of perceived exertion

RH     Relative humidity

T<sub>b</sub>     Mean body temperature

T<sub>c</sub>     Core temperature

T<sub>mu</sub>   Muscle temperature

T<sub>oes</sub>   Oesophageal temperature

T<sub>re</sub>     Rectal temperature

T<sub>sk</sub>     Mean skin temperature

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## LIST OF PUBLICATIONS

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

### **Chapter 3: Study 1**

Siegel, R., Mate, J., Brearley, M. B., Watson, G., Nosaka, K., & Laursen, P. B. (2010). Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat. *Med Sci Sports Exerc*, 42(4), 717-725.

### **Chapter 4: Study 2**

Siegel, R., Mate, J., Watson, G., Nosaka, K., & Laursen, P. B. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. *J Sports Sci*. (In press).

### **Chapter 5: Study 3**

Siegel, R., Mate, J., Watson, G., Nosaka, K., & Laursen, P. B. The influence of ice slurry ingestion on maximal voluntary contraction following exercise-induced hyperthermia. *Eur J Appl Physiol*. (In press).



# **CHAPTER 1**

## **Introduction**

## 1.1 Introduction

Environmental conditions can have a major influence in determining the success of athletic performance. For example, factors such as environmental temperature and humidity (Galloway & Maughan, 1997), wind speed (Saunders et al., 2005), altitude (Rusko et al., 2004), and air pollution (Horvath, 1981) can all adversely affect exercise performance. Arguably one of the greatest stressors to human performance is the environmental temperature and humidity under which sporting events take place, as exemplified by the occurrence of heat illness and reduced exercise performance under conditions of high wet bulb globe temperature (WBGT). While understanding the impact that heat stress has on athlete health is imperative, the world of elite sport is equally interested in practices upon which athletic performance might be improved in these conditions.

Increases in ambient temperature have been consistently shown to impair prolonged exercise performance (Galloway & Maughan, 1997; Parkin et al., 1999). While the precise mechanisms are not entirely clear, the effect of heat stress on exercise performance appears to be multifactorial, and likely due in large part to increases in body core temperature ( $T_c$ ). Major sporting events are often held in hot environments. Most notably, the Summer Olympic Games and Commonwealth Games are typically held during northern hemisphere summer months, and as such, ambient temperatures during these games are generally high. For example, the mean ambient temperature and humidity at the 1996 Atlanta Olympic Games at 1:00 pm was  $29.4 \pm 3.6^\circ\text{C}$ ,  $63 \pm 16\%$  relative humidity (RH) (Sparling, 1997). During the 2000 Sydney Olympic Games, ambient temperature and humidity ranged from  $14.4$  to  $33.8^\circ\text{C}$  and 18 to 90% RH, respectively (Braniš & Větvička, 2010). Furthermore, countless other sporting events take place in warm conditions, such as triathlon,

rowing, cycling and running events, as well as team sports such as soccer, baseball, field hockey and cricket. In addition to competition, pre-season or base training for upcoming competition is often performed in summer months and/or warm climates, where athletes may benefit from interventions to improve the quality of training in these conditions.

The influence of heat stress on exercise performance is also exacerbated in sports where personal protective equipment is required (Taylor, 2006). For example, American football, cricket, cycling, auto and motor sports, rugby and ice hockey require protective equipment in the form of padding and/or helmets. Wearing this additional equipment reduces the ability of the body to dissipate heat (Taylor, 2006), and consequently, athletes become at risk of attaining high core temperatures, resulting in decreased performance and potentially heatstroke.

In addition to sports in which athletes are susceptible to the detrimental effects of heat stress, many occupations place workers in situations where the risk of heat strain is high. Occupations such as mining and fire fighting are performed in hot environments, where metabolic workloads are high and personal protective equipment is essential (Taylor, 2006). As such, the risk of experiencing heat illness is considerable. For example, Donoghue et al. (2000) reported 147 incidences of heat illness per million man hours of work in an underground metalliferous mine in Australia. Putting practical methods in place to reduce these incidences is therefore needed.

The rise in  $T_c$  observed during exercise in the heat is thought to be the primary cause for the reduction in motor output and cessation of exercise in these conditions (Nybo, 2008). It is often noted that voluntary exhaustion coincides with

the attainment of “critically high” internal temperatures (Cheung, 2007). Cooling prior to exercise, commonly referred to as “precooling”, has become a widely used strategy for improving athletic performance in hot environments (Duffield, 2008). This lowering of  $T_c$  prior to exercise has been shown to increase the amount of heat that can be stored during a given exercise bout, which in turn prolongs the onset of hyperthermia-induced fatigue, and improves performance (Gonzalez-Alonso et al., 1999b). The most common forms of precooling occur largely via external means, such as cold air exposure, cold water immersion, and the wearing of cooling garments (Quod et al., 2006). However, these methods are considered impractical for use in field settings, and as such, investigation into more practical precooling manoeuvres is warranted. Recently, examination of the effects of ingesting cool/cold fluids on exercise performance in the heat has become popular (Lee et al., 2008a; Lee & Shirreffs, 2007; Lee et al., 2006, 2008b; Mundel et al., 2006); however, more research is necessary to determine the most powerful and successful strategy. It has been suggested that the ingestion of crushed ice may be a more effective precooling strategy than the use of cold fluids (Brearley & Finn, 2003). Therefore, the first purpose of this thesis was to examine the effects of ice slurry versus cold water ingestion on thermoregulatory responses and prolonged sub-maximal exercise performance in the heat (Study 1).

Cold water immersion is currently considered to be the “gold standard” method of precooling, as it has consistently been proven to be effective at improving prolonged exercise performance in the heat (Quod, et al., 2006). As ice slurry ingestion is likely to be a more practical strategy, comparing this method against cold water immersion is important in order to gauge its’ success as a precooling agent. Additionally, it is possible that different physiological responses may occur



with internal versus external cooling methods, due to differences in skin ( $T_{sk}$ ) and body temperature ( $T_b$ ), and consequently heat storage. Moreover, it is possible that the ingestion of an ice slurry mixture may stimulate potential thermosensitive receptors in the mouth, throat and core, altering thermoregulatory responses during exercise. Therefore, the second purpose of this thesis was to compare the effects of ice slurry ingestion versus cold water immersion on thermoregulatory responses and prolonged sub-maximal exercise performance in the heat (Study 2). As a result of the findings made in Studies 1 and 2 (discussed subsequently in this thesis), the third purpose was to determine whether stimulating potential internal thermoreceptors (e.g. mouth, oesophagus, stomach) via ice slurry ingestion was able to improve neuromuscular function under hyperthermic conditions (Study 3).

## **1.2 Purpose of the Research**

The aims of this PhD thesis were to determine the effectiveness of ice slurry ingestion as a precooling manoeuvre for prolonged sub-maximal running in the heat, as well as compare it to the popular method of cold water immersion and identify potential mechanisms by which internal cooling is able to enhance exercise performance under conditions of heat strain.

## **1.3 Significance of the Research**

Many sporting events are performed in hot climates where athletes become hyperthermic. Therefore, devising and optimising practical precooling strategies that have the potential to improve athletic performance and lower the incidence of heat strain under these conditions is important. As the effect of internal versus external precooling methods on physiological responses and exercise performance is unknown, examination of such potential differences is needed. Finally, limited

research has investigated the influence of internal thermoreceptors on exercise performance. Such information may help to understand the mechanisms responsible for hyperthermic-induced fatigue and why internal precooling manoeuvres may be successful.

#### **1.4 Research Questions**

1. Does ice slurry ingestion prior to exercise in a hot environment increase sub-maximal running time to exhaustion? (Study 1)
2. Do thermoregulatory responses and exercise performance differ between precooling with ice slurry ingestion and cold water immersion during prolonged running in a hot environment? (Study 2)
3. Does ice slurry ingestion improve neuromuscular function following exercise-induced hyperthermia? (Study 3)

#### **1.5 Research Hypotheses**

1. Ice slurry compared with cold water ingestion prior to exercise in hot ambient temperatures will increase sub-maximal running time to exhaustion.
2. Cold water immersion will be a more successful precooling manoeuvre for improving sub-maximal running performance in the heat, and different thermoregulatory responses will be observed between internal and external cooling.
3. Ice slurry ingestion will improve neuromuscular function following exercise-induced hyperthermia compared with the ingestion of body temperature water.

#### **1.6 Limitations**

Individual shivering responses during precooling manoeuvres may have resulted in variances to starting rectal temperatures ( $T_{re}$ ). Individual differences in

the  $T_{re}$  response during exercise may have lead to variances in exercise performance. In Study 2, conditions were not able to be completed in an entirely balanced manner.

## **1.7 Delimitations**

The findings from all studies presented herein are delimited to moderately trained, non-heat-acclimatised males between the ages of 18-40 years. The results of these studies may therefore not be applicable to other populations. Studies 1 and 2 are delimited to prolonged submaximal running performance, and Study 3 to isometric torque production, and therefore may not be applicable to other forms of exercise. Furthermore, the results are delimited to the temperatures used for each intervention; i.e.  $-1^{\circ}\text{C}$  for ice slurry conditions in Studies 1-3;  $4^{\circ}\text{C}$ ,  $37^{\circ}\text{C}$  and  $40^{\circ}\text{C}$  for fluid ingestion in Studies 1, 2 and 3, respectively; and  $\sim 24^{\circ}\text{C}$  for cold water immersion in Study 2.

# **CHAPTER 2**

## **Literature Review:**

**Precooling for exercise in the heat**

## 2.1 Exercise in the heat

Increases in core, body and muscle temperature resulting from exercise in hot environments ( $\sim 30^{\circ}\text{C}$  and above) are associated with decreases in both prolonged exercise ( $\sim 30$  min and above) (Galloway & Maughan, 1997; Parkin, et al., 1999) and intermittent sprint performance (Drust et al., 2005; Morris et al., 2005), as well as some middle distance events (Altareki et al., 2009; Slater et al., 2005). For example, Galloway and Maughan (1997) demonstrated that  $10^{\circ}\text{C}$  increment increases in ambient temperature lead to significant serial reductions in cycling time to exhaustion at  $\sim 70\%$   $\text{VO}_{2\text{max}}$  ( $11^{\circ}\text{C} = 93.5 \pm 6.2$  min;  $21^{\circ}\text{C} = 81.2 \pm 5.7$  min; and  $31^{\circ}\text{C} = 51.6 \pm 3.7$  min). The mechanisms behind these performance decrements remain largely unclear, however both central and peripheral factors appear to be involved (Cheung, 2007). In order to delay hyperthermia-induced fatigue and maintain exercise performance, heat gain must be matched closely by heat dissipation. Heat loss during exercise is achieved through the heat transfer processes of convection, conduction and radiation, but primarily via the evaporation of sweat (Casa, 1999).

Exercise in hot environments results in increases in core, skin and muscle temperatures, as well as skin blood flow, heart rate, sweating rates and glycogen oxidation. Reduced muscle and splanchnic blood flow are also observed during exercise in the heat (Rowell, 1983). Consequently, it was previously thought that peripheral factors, such as reduced muscle blood flow and oxygen delivery, augmented glycogen depletion, increased lactate production, and a rise in muscle temperature ( $T_{\text{mu}}$ ),  $T_{\text{sk}}$  and associated cardiovascular strain were the primary factors impairing prolonged exercise performance in the heat (Casa, 1999; Maxwell et al., 1996; Morris, et al., 2005; Rowell, 1983). Although peripheral factors are altered

during exercise in hot environments, current research indicates that fatigue under these conditions is more associated with central factors. For example, Todd et al. (2005) demonstrated that central activation during sustained maximal voluntary contractions was significantly reduced when  $T_c$  was  $\sim 38.5^\circ\text{C}$  compared to  $\sim 37^\circ\text{C}$ . Thomas et al. (2006) observed that voluntary muscle activation was impaired with increases in  $T_c$ , irrespective of changes in  $T_{mu}$  and  $T_{sk}$ . Additionally, it has been consistently demonstrated that trained subjects exercising at a fixed intensity in the heat reach volitional exhaustion at a  $T_c$  near  $\sim 40^\circ\text{C}$ , despite differences in starting temperature and rates of rise in  $T_c$  (Gonzalez-Alonso et al., 1998, 1999a; Gonzalez-Alonso, et al., 1999b; Morris, et al., 2005; Nielsen et al., 1993; Nielsen et al., 2001; Nielsen et al., 1997). Exhaustion under these conditions has also been shown to occur despite no correlation with factors such as cardiac output, leg blood flow, lactate and potassium accumulation (Nielsen, et al., 1993; Nielsen, et al., 1997), substrate availability and utilisation (Febbraio et al., 1996a), serum concentrations of adrenaline, noradrenaline and cortisol (Morris, et al., 2005), hydration status (Cheung & McLellan, 1998), or  $T_{sk}$  (Gonzalez-Alonso, et al., 1999b). Hunter et al. (2002) showed that exercise in a hot environment ( $35^\circ\text{C}$ ), which did not significantly increase  $T_c$  compared with a cool environment ( $15^\circ\text{C}$ ), resulted in similar muscle recruitment and cycling time to exhaustion despite significantly higher  $T_{sk}$  and heart rate throughout exercise. Thus, termination of exercise in the heat appears to consistently coincide with attainment of a critically high  $T_c$ , giving rise to the term “critical core temperature”. This phenomenon may serve as a protective mechanism aimed at reducing motor output and resulting heat generation before severe heat illness evolves (Cheung & Sleivert, 2004).

Another paradigm offered to explain the decrease in exercise performance observed during self-paced exercise in the heat proposes that exercise intensity is regulated based largely upon afferent input from thermal sensors (Marino, 2004). This feedback is integrated by the brain, which regulates motor output in an anticipatory fashion to reduce metabolic heat production so that a known amount of work can be completed without the development of hyperthermia (Marino, 2004). In support of this theory, Marino et al. (2000) showed that following a 30-min run at 70% peak treadmill running speed, subjects completed a self-paced 8-km run in significantly greater time under conditions of 35°C ( $30.4 \pm 2.9$  min) compared with 15°C ( $27.0 \pm 1.5$  min) and 25°C ( $27.4 \pm 1.5$  min). The similarities in pace during the cooler conditions ( $17.8 \pm 1.0$  km·h<sup>-1</sup> and  $17.5 \pm 1.0$  km·h<sup>-1</sup>, in 15°C and 25°C, respectively) indicates that self-pacing mechanisms become impaired only when heat strain is high (i.e.,  $15.8 \pm 1.5$  km·h<sup>-1</sup> in 35°C).

Further support for this theory was presented by Tucker et al. (2004). They determined that during a self-paced 20-km cycling time trial in the heat (35°C, 60% RH), power output and skeletal muscle recruitment began to decline earlier than in the cool condition (15°C, 60% RH). Interestingly, this occurred before an abnormal rise in  $T_{re}$ , likely as an anticipatory response to maintain body heat content. In a follow up study, Tucker et al. (2006) observed during a cycling trial completed at a set rating of perceived exertion (RPE), the rate of decline in power output was significantly greater in hot (35°C, 65% RH) compared with moderate (25°C, 65% RH) and cool (15°C, 65% RH) conditions. As the rate of heat storage was higher in the first 4 min of the hot condition, the authors concluded that exercise intensity was regulated by afferent feedback responding to the rate of heat storage. This “anticipatory” model may do better to describe scenarios shown during real-life

sporting events, where a set distance must be completed, or in team sports where players compete for a set amount of time. Nevertheless, it is likely that both models play an important role in the development of fatigue and the maintenance of performance during exercise in the heat.

As it is commonly agreed that hyperthermia-induced fatigue is predominantly moderated by the central nervous system (Nybo, 2008), several studies have investigated the effect of hyperthermia on brain activity. Nielsen and colleagues (2001) demonstrated that the ratio of  $\alpha/\beta$  frequencies in the frontal cortex of the brain, used as a measurement of arousal, increased significantly during exercise in hot conditions (42°C), with no change in a cool environment (19°C). These changes were strongly correlated with  $T_{oes}$ , suggesting that changes in electrical activity in the frontal cortex are indicative of hyperthermia-induced fatigue. Moreover, Nybo and Nielsen (2001b) have shown that increases in the ratio of  $\alpha/\beta$  frequencies are strongly correlated with RPE during exercise in the heat. Hence, it is likely that during exercise in a hot environment arousal levels are markedly suppressed, resulting in a reduction in motivation to continue exercise.

Alterations in neurotransmitter levels have also been suggested as a potential cause of fatigue during exercise in the heat. Both serotonin and dopamine have been implicated as possible triggers, as serotonin is associated with levels of arousal, while dopamine is involved in movement initiation and control and may reduce serotonin production (Cheung & Sleivert, 2004). However, Nybo et al. (2003) observed no differences in the cerebral tryptophan (a metabolic precursor to serotonin) balance between exercise in hyperthermic, compared with thermoneutral conditions, suggesting that serotonin is not related to the increase in perceived



exertion during hyperthermia-induced fatigue. While serotonin levels do not appear to be of importance to the development of fatigue during exercise in the heat, the administration of a dopamine reuptake inhibitor has been shown to improve exercise performance in a hot environment (Watson et al., 2004). It is possible that dopamine reuptake inhibition may have improved exercise performance in the heat via lessening/overriding central inhibitory signals to terminate exercise, and thus dopaminergic pathways may be a factor in the evolution of fatigue during exercise hyperthermia.

Cerebral glycogen depletion may also influence central fatigue during exercise in the heat. This suggestion is based on evidence that glucose uptake in the brain was increased following exercise in hyperthermic conditions (Nybo, et al., 2003), and that cerebral blood flow is significantly reduced during hyperthermic exercise (Nybo et al., 2002a). Although oxygen delivery to the brain does not appear to be compromised during exercise in the heat despite a reduction in cerebral blood flow, glucose utilisation has been shown to increase (Nybo, et al., 2002a) and therefore cerebral glycogen depletion as a consequence of this may contribute to fatigue.

Notwithstanding the aforementioned alterations observed during prolonged exercise in the heat, the primary cause of fatigue in these conditions is more likely related to the increase in brain temperature (Gonzalez-Alonso et al., 2008; Nybo, 2008). By measuring arterial and venous blood temperature in the internal jugular vein and the aorta, Nybo et al. (2002b) showed that heat removal in the brain was impaired, and heat production increased during hyperthermic exercise. Results also indicated that the average brain temperature is  $\sim 0.2^{\circ}\text{C}$  higher than  $T_{\text{c}}$ , suggesting that

humans are not able to selectively cool the brain. Whilst direct, non-invasive measures of brain temperature are currently unavailable in humans, several animal studies have reported changes in brain temperature during exercise in the heat. Caputa et al. (1986) demonstrated that goats refused to continue exercising once hypothalamic temperatures reached between 42.0-42.9°C. This occurred despite the manipulation of trunk temperature, suggesting that the “critical temperature” may in fact derive from the brain. Since then, Fuller et al. (1998) showed that rats exercising in the heat reached voluntary exhaustion at hypothalamic temperatures between 40.1-40.2°C, which coincided with abdominal temperatures of 39.8-39.9°C. Similarly, Walters et al. (2000) observed that rats terminated exercise in a hot environment at hypothalamic temperatures between 41.9-42.2°C and  $T_{re}$  between 42.2-42.5°C. Clearly, the thermal state of the brain appears to be of great importance to the development of fatigue and exhaustion during exercise in the heat; however, the inability to accurately measure brain temperature in humans presents a challenge in determining the precise mechanisms of how heat strain impacts exercise performance.

A reduced splanchnic blood flow is commonly observed during exercise-induced heat strain, resulting in increased intestinal wall permeability and in turn leakage of endotoxins into the blood stream (Lambert, 2004). This build-up of endotoxins in the blood, known as endotoxemia, may adversely impact exercise performance via increased cytokine release influencing the central nervous system, possibly increasing the perception of effort (Cheung & Sleivert, 2004), and the impairment of skeletal muscle force generation (Supinski et al., 2000). It has also been suggested that the endotoxin-induced increase in nitric oxide production, and subsequent vasodilation in the splanchnic region, may result in hypotension and

augmented cardiovascular strain (Lambert, 2004). However, research investigating the direct influence of endotoxemia on fatigue during exercise in the heat is limited and requires further examination.

Numerous studies have shown that exercising in a hot environment leads to decrements in endurance performance (Cheung, 2007; Hargreaves, 2008). Although the precise mechanisms have yet to be elucidated, and numerous theories have been presented, central fatigue via increases in core and brain temperatures appear to be the major contributors (Nybo, 2008). As such, developing strategies to prevent or prolong the attainment of high  $T_c$  has become a focus for improving endurance performance in the heat.

## **2.2 Hydration, fluid balance and thermoregulation**

The adverse effects of hypohydration on thermoregulation and exercise performance in the heat are well established (Sawka et al., 1998). It has been suggested that hypohydration may impair thermoregulation by decreasing sweating rates, reducing skin blood flow, and shifting fluids from intracellular to extracellular compartments (Sawka, 1992). Consequently, maintaining total body water has been shown to reduce thermal strain by slowing the rate of rise in  $T_c$  during exercise (Gisolfi & Copping, 1974). For example, Greenleaf and Castle (1971) showed that hypohydration (-5.2% body mass) was associated with a significantly greater increase in  $T_{re}$  ( $1.69 \pm 0.11^\circ\text{C}$ ) than hyperhydration (+1.2% body mass) ( $1.05 \pm 0.14^\circ\text{C}$ ) during 70 min of cycling at 49%  $\dot{V}O_{2\text{max}}$  in temperate conditions ( $23.6^\circ\text{C}$ , 51% RH). This significantly faster rise in  $T_{re}$  was attributed to the lower sweat rate observed with hypohydration ( $135 \pm 24$  vs.  $160 \pm 21 \text{ g}\cdot\text{m}^2\cdot\text{h}^{-1}$ ). During 30 min of cycling at 55%  $\dot{V}O_{2\text{max}}$  in  $35^\circ\text{C}$  heat, Nadel et al. (1980) observed an almost 50%

reduction in arm blood flow following hypohydration, compared with euhydration. Hypohydration also resulted in a significantly greater rise in  $T_{oes}$ . More recently, Cheung and McLellan (1998) showed that hypohydration (~2.5% body mass) significantly increased exercising  $T_{re}$  and heart rate and decreased exercise tolerance time compared with euhydration. Clearly, maintaining euhydration prior to exercise is of great importance to athletes competing in hot environments.

### **2.3 Precooling**

Several strategies have been suggested to combat the effects of heat stress during exercise performance, including acclimatisation (Nielsen, et al., 1993), carbohydrate loading (Burke, 2001; Hargreaves, 2008), sodium loading (Sims et al., 2007a; Sims et al., 2007b), ensuring adequate hydration (Burke, 2001; Hargreaves, 2008), and various forms of precooling manoeuvres (Duffield, 2008; Marino, 2002; Quod, et al., 2006). These strategies have all shown varying degrees of success. Precooling is a popular practice amongst researchers and practitioners, based upon evidence that decreasing  $T_c$  prior to exercise increases heat storage capacity and prolongs or even prevents attainment of critical core temperatures, in turn improving endurance performance (Booth et al., 1997; Quod, et al., 2006). For example, Gonzalez-Alonso et al. (1999b) observed that precooling with cold water immersion lowered pre-exercise  $T_{oes}$  to  $35.9 \pm 0.2$  compared with  $37.4 \pm 0.1^\circ\text{C}$  in the control condition of no cooling. Subjects then cycled to exhaustion in the heat ( $40^\circ\text{C}$ , 19% RH) at 60%  $\text{VO}_{2\text{max}}$ , with precooling eliciting significantly greater performance times ( $63 \pm 3$  vs.  $46 \pm 3$  min). The authors speculated that the increased heat storage capacity prolonged the time to reach a critically high  $T_c$ . Heart rate during the trials was strongly correlated with  $T_{es}$ , and as such remained lower in the cooling trials, as did  $T_{sk}$ . Skin blood flow was also lower in the early stages of exercise following

precooling. As precooling also attenuated the decline in stroke volume, this suggests that precooling is able to reduce cardiovascular strain during exercise in hot environments.

Booth et al. (1997) demonstrated that 60 min of cold water immersion (initially at 28-29°C and gradually lowered to 23-24°C) reduced  $T_{re}$  by 0.7°C, which remained lower for the first 20 min of exercise in hot conditions (30°C, 60% RH). This led to a 4% increase in the maximum running distance achieved over 30 min (~300 m) compared with the control condition of no precooling ( $7556 \pm 171$  vs.  $7252 \pm 162$  m). Moreover, a significantly greater rate of heat storage at the end of exercise was shown ( $249 \pm 55$  vs.  $113 \pm 45 \text{ W}\cdot\text{m}^{-2}$ ) and heart rate was lower for the first 10 min of running after the precooling condition. Therefore, it is commonly accepted that precooling is a safe and effective strategy for reducing cardiovascular and thermal strain and improving prolonged exercise performance in the heat.

## **2.4 Potential mechanisms of precooling**

Several theories exist, with no uniform agreement, as to how precooling is able to improve exercise performance in the heat. As precooling lowers skin and core temperatures, perfusion to the skin for heat dissipation is likely reduced, and thus stroke volume is maintained and heart rate lowered. Therefore, it was initially suggested that a reduction in cardiovascular and metabolic strain and increased oxygen supply to the working muscles were responsible for the improvements in exercise performance witnessed following precooling (Hessemer et al., 1984; Lee & Haymes, 1995; Olschewski & Bruck, 1988). However, while augmented cardiovascular strain is clearly apparent during exercise in the heat, evidence suggests that oxygen delivery to the muscle is not compromised during submaximal

exercise (Nielsen et al., 1990). Moreover, significantly elevated heart rate and  $T_{sk}$  alone, without increases in  $T_c$ , have been shown not to decrease muscle recruitment or exercise time to exhaustion in the heat (Hunter, et al., 2002). Thus, increased  $T_{sk}$  and cardiovascular strain are unlikely to be the predominant factor causing fatigue.

Instead, it seems that the reduction in thermal strain, and subsequent attenuation of central fatigue, are the primary factors responsible for the enhanced performance observed following precooling (Duffield, 2008). During exercise which is fixed at a constant intensity, it appears that reducing pre-exercise  $T_c$  leads to a lower  $T_c$  throughout the course of exercise, allowing greater heat storage capacity and prolonging the time taken to achieve critically high internal temperatures. This, in turn, delays the onset of hyperthermia-induced fatigue, resulting in greater endurance capacity (Gonzalez-Alonso, et al., 1999b). However, this theory alone does not appear to explain the improvements seen with precooling during self-paced exercise. Research has proposed that lowering pre-exercise  $T_c$  allows for the selection of higher exercise intensities (Duffield et al., 2010), potentially via attenuating the down-regulation of muscle activation (Kay et al., 1999; Quod, et al., 2006). As self-paced exercise in the heat is thought to be regulated via anticipatory mechanisms pertaining to the rate of heat storage (Marino, 2004), precooling may enhance performance via reducing inhibitory feedback in response to a decreased thermal load and/or rate of heat storage (Duffield, 2008). However, research examining the influence of precooling on pacing during exercise is limited, and requires further investigation.

Other physiological perturbations, such as reduced cerebral blood flow, cerebral glucose depletion, a build-up of branch chain amino acids in cerebral blood,

altered neurotransmitter levels (Nybo, et al., 2003) and endotoxemia (Lambert, 2004) have also been implicated as potential contributors to fatigue during exercise in hot environments. Therefore, in addition to the aforementioned mechanisms proposed, precooling may enhance performance by influencing one or more of these factors. However, the direct effect of precooling on these parameters has not been extensively explored, and therefore, is presently unidentified.

An important outcome of precooling is the lowering of perceived thermal sensation and exertion during exercise (Lee, et al., 2008b). Recent evidence has demonstrated that the perception of thermal comfort is an important factor in the regulation of exercise intensity and fatigue. Schlader et al. (2011b) investigated the effect of  $T_{sk}$  on self-selected exercise intensity by having subjects commence exercise with a cool  $T_{sk}$  which was heated, or a hot  $T_{sk}$  which was cooled during exercise. They showed that although  $T_c$ , as well as the magnitude of change in  $T_{sk}$  were similar between conditions during exercise, subjects completed more work during 60 min of cycling in the cool to hot trial, likely due to the higher initial power output. The same authors (Schlader et al., 2011a) showed that non-thermally cooling and heating the face (application of menthol and capsaicin solutions) without changes in  $T_c$  during exercise, resulted in similar perceptual responses to thermally cooling and heating (forced convection). Additionally, both forms of cooling resulted in higher work output during exercise. These studies show that changes in the perception of thermal comfort, without changes in temperature, are able to alter self-selected exercise intensity. Consequently, simply the perception of cooling may be another factor involved in the enhanced performance seen after precooling.

The combined results of the current available literature clearly highlight the ergogenic benefits of precooling prior to exercise in hot environments. However, to date, the mechanisms by which precooling is able to enhance exercise performance are yet to be fully explained.

## **2.5 Forms of precooling**

Several forms of precooling manoeuvres used throughout the literature have proven to be successful in enhancing exercise performance. Early precooling studies focused largely on cold air exposure as a means of lowering pre-exercise  $T_c$ . For example, Hessemer et al. (1984) observed a  $0.4^{\circ}\text{C}$  reduction in  $T_{oes}$  following precooling with cold air exposure near  $0^{\circ}\text{C}$ , which in turn elicited a 6.8% increase in mean 1 h work rate during exercise in a thermoneutral environment ( $18^{\circ}\text{C}$ ). Additionally, sweat rate was 20.3% lower following precooling compared with the control condition of no cooling. Using a similar precooling manoeuvre, Olschewski and Bruck (1988) subsequently showed that cycling time to exhaustion at 80%  $\text{VO}_{2\text{peak}}$  in thermoneutral conditions ( $18^{\circ}\text{C}$ , 50% RH) was increased by 12%, as  $T_{sk}$  and  $T_{oes}$  were lower for the entire exercise period until the point of exhaustion. However, the method used in both studies required two cold air exposures separated by a rewarming phase, and consequently required  $\sim 130$  min to complete. Lee and Haymes (1995) observed a similar effect using a 30 min cold air exposure at  $5^{\circ}\text{C}$ . In their investigation, precooling lowered  $T_{re}$  by  $0.37^{\circ}\text{C}$ , which remained lower for the first 25 min of running to exhaustion at 82%  $\text{VO}_{2\text{peak}}$  in  $24^{\circ}\text{C}$ . As a result, heat stored during exercise was greater ( $173 \pm 46$  vs.  $143 \pm 38 \text{ W}\cdot\text{m}^{-2}$ ) and running time to exhaustion was extended from  $22.4 \pm 8.5$  min in the control trial (no precooling) to  $26.2 \pm 9.5$  min.



Cold water immersion has since become the more popular precooling strategy, due to its' powerful ability to lower pre-exercise  $T_c$  (Quod, et al., 2006). Initially, Booth et al. (1997) determined that a 60 min whole-body cold water immersion reduced  $T_{re}$  by  $0.7^{\circ}\text{C}$  and increased heat storage and total distance covered in 30 min during running in the heat ( $30^{\circ}\text{C}$ , 60% RH). Wilson et al. (2002) showed that 30 min of lower-body cold water immersion ( $17.7 \pm 0.5^{\circ}\text{C}$ ) significantly reduced  $T_{re}$ ,  $T_{sk}$  and  $T_b$  prior to 60 min of cycling at 60%  $\text{VO}_{2\text{max}}$ . Rectal temperature was lower for the entire exercise period, while  $T_{sk}$  and  $T_b$  were lower until 24 and 34 min, respectively. Precooling increased heat storage, and lowered sweat rate and thermal sensation, despite RPE being unchanged compared with the control condition of  $35.1 \pm 0.3^{\circ}\text{C}$  water immersion.

Thermoregulatory and performance benefits may also occur following precooling by water immersion without lowering pre-exercise  $T_c$ . Kay et al. (1999) demonstrated that a 60-min whole-body water immersion (commencing at  $29.1 \pm 0.2^{\circ}\text{C}$  and gradually lowered to  $25.8 \pm 0.5^{\circ}\text{C}$ ), did not lower  $T_{re}$  prior to a 30-min self-paced cycling trial in the heat ( $31.4 \pm 0.4^{\circ}\text{C}$ ,  $60.2 \pm 0.5\%$  RH), but lead to a significantly lower  $T_{re}$  during exercise. Measurements of  $T_{re}$  may not have been lowered due to the slow cooling method used, and while a classic afterdrop (Romet, 1988) was not witnessed,  $T_{re}$  did not rise in the early stages of exercise. It is, therefore, likely that heat indeed was removed from the body core, however, a reduction in  $T_{re}$  was not observed due to the mild afterdrop effect and slow response time of  $T_{re}$  measurements. Precooling lowered skin temperature by  $\sim 5\text{-}6^{\circ}\text{C}$  and lead to increased heat storage during exercise ( $153.0 \pm 13.1$  vs.  $84.0 \pm 8.8 \text{ W}\cdot\text{m}^{-2}$ ), lowered sweating rate ( $1.2 \pm 0.1$  vs.  $1.7 \pm 0.1 \text{ L}\cdot\text{h}^{-1}$ ) and increased performance ( $15.8 \pm 0.7$  vs.  $14.9 \pm 0.8 \text{ km}$ ).

Following the successful application of water immersion for improving exercise performance (Booth, et al., 1997; Gonzalez-Alonso, et al., 1999b; Kay, et al., 1999), several studies compared various methods in an attempt to optimise this manoeuvre. White et al. (2003) compared the thermoregulatory responses of 30 min of lower-body versus whole-body water immersion at 20°C during subsequent exercise in the heat ( $30.3 \pm 0.2^{\circ}\text{C}$ ,  $31.9 \pm 0.7\%$  RH). They determined that whole-body precooling lead to significantly lower  $T_{\text{sk}}$ ,  $T_{\text{b}}$  and  $T_{\text{re}}$  than lower-body precooling for the first 14, 16 and 24 min of the 30 min cycling bout at 60%  $\text{VO}_{2\text{max}}$ , respectively. Subjects also felt significantly cooler throughout the 30 min trial. Furthermore, heat storage was significantly higher following whole-body precooling. Although no measures of exercise performance were assessed, these results suggest that whole-body versus lower-body precooling is more effective at lowering  $T_{\text{re}}$ ,  $T_{\text{sk}}$  and  $T_{\text{b}}$  and maintaining these changes throughout exercise.

In contrast, Daanen et al. (2006) showed that precooling the upper, lower and whole body increased heat storage capacity compared to no precooling during 40 min of cycling at 60%  $\text{VO}_{2\text{max}}$  in 30°C, 70% RH. However, no significant differences in heat storage were observed between the cooling methods. This may have been due to the fact that  $T_{\text{c}}$  was kept stable between conditions by warming the body parts that were not being cooled. As exercise intensity and duration were kept constant, the effects of each cooling method on exercise performance could not be determined.

Several studies have also investigated the influence of combining multiple forms of precooling protocols in one manoeuvre. For example, Quod et al. (2008) compared two precooling manoeuvres prior to a cycling time trial in the heat (34.38

$\pm 1.18^{\circ}\text{C}$ ,  $41.2 \pm 3.0\%$  RH). When compared to the control condition of no precooling, a combined treatment of 30 min whole-body cold water immersion followed by wearing an ice jacket for 40 min lead to significantly faster cycling time trial performance ( $-42 \pm 25$  s) than ice jacket treatment alone ( $-16 \pm 36$  s), which was not significantly different from the control condition. This was likely due to the fact that following the warm-up,  $T_{\text{re}}$  was  $37.1 \pm 0.2^{\circ}\text{C}$  in the combination treatment; significantly lower than both the jacket and control conditions by  $0.7^{\circ}\text{C}$ . These results suggest that a combination treatment may be effective at lowering  $T_{\text{c}}$ , and in turn improving exercise performance in the heat.

Hasegawa et al. (2006) showed that a combined treatment of precooling (30 min water immersion in  $25^{\circ}\text{C}$  to the torso) and water ingestion during exercise (14- $16^{\circ}\text{C}$ , equal to sweat loss from a previous trial) was most effective at increasing heat storage and reducing thermoregulatory and cardiovascular strain during exercise. Subjects performed 60 min of cycling at  $60\%$   $\text{VO}_{2\text{max}}$ , followed by a time to exhaustion cycling bout at  $80\%$   $\text{VO}_{2\text{max}}$ , in hot conditions ( $32^{\circ}\text{C}$ ,  $80\%$  RH). Immediately following precooling,  $T_{\text{re}}$  fell by  $0.3^{\circ}\text{C}$ , and prior to the commencement of the first exercise bout dropped an additional  $0.3^{\circ}\text{C}$ . Before commencing the second exercise bout,  $T_{\text{re}}$  was significantly lower in the combined treatment ( $38.5 \pm 0.1^{\circ}\text{C}$ ) than the control condition of no water or precooling ( $39.1 \pm 0.1^{\circ}\text{C}$ ), water only ( $38.8 \pm 0.1^{\circ}\text{C}$ ) and precooling only ( $38.7 \pm 0.1^{\circ}\text{C}$ ). Subsequently, time to exhaustion was significantly longer in the combined treatment ( $481 \pm 47$  s) compared with the control ( $152 \pm 16$  s), precooling only ( $317 \pm 50$  s) and water only conditions ( $373 \pm 17$  s). These results suggest that in addition to cold water immersion, water ingestion during exercise has a cooling capacity which can improve exercise performance.

In another study investigating the combination of various precooling modalities, Duffield and Marino (2007) examined the effect of 15 min of precooling, and 10 min halftime cooling on intermittent sprint running performance in hot conditions ( $32 \pm 1^\circ\text{C}$ ,  $30 \pm 3\%$  RH). They compared the use of an ice vest versus the combination of an ice vest and ice bath ( $14.0 \pm 1^\circ\text{C}$ ). Although precooling was unable to reduce  $T_c$  below  $37^\circ\text{C}$  (absolute value not reported),  $T_c$  remained significantly lower for the first 40 min of the 60 min of exercise following the ice bath/vest manoeuvre. No significant improvements in mean, total, or % decline in 15 m sprint time during the  $2 \times 30$  min intermittent sprint test were found as a result of either cooling method. However, a large effect size ( $ES = 0.88$ ) showing an increase in distance covered during self-paced hard running bouts ( $\sim 200$  m) was observed following the ice bath/vest manoeuvre. Thus, while precooling did not improve sprint performance, it did improve submaximal exercise performance. Moreover, much like the majority of the precooling literature that has investigated endurance performance, this study showed that a combination treatment is most effective, likely due to larger reductions in  $T_c$ .

The use of ice vests/jackets is another strategy that has been employed in the hopes of uncovering a more practical means of precooling. Cotter et al. (2001) investigated the combination of an ice vest and cold air exposure ( $3^\circ\text{C}$ ) with and without thigh cooling on cycling performance in the heat ( $35^\circ\text{C}$ ,  $60\%$  RH). Precooling was performed for 45 min, followed by 20 min of fixed paced exercise at  $65\% \text{VO}_{2\text{peak}}$  before subjects completed a 15-min performance trial. Both cooling methods significantly reduced  $T_{re}$  ( $\sim 0.5^\circ\text{C}$ ) compared to the control condition of no cooling, and in turn mean power output was increased by 16% and 17.5% with and without leg cooling, respectively, during the 15-min self-paced trial. As no

significant differences were observed between the two cooling conditions, the authors suggested that cooling the legs provided no additional benefit.

Cooling garments have also been shown to be effective when used during a warm-up (Arngrimsson et al., 2004; Yates et al., 1996). Yates et al. (1996) demonstrated that precooling via the use of an ice jacket during a 30 min warm-up significantly improved 2000-metre rowing performance in the heat (33°C, 60% RH). Whereas the initial 1000 m was performed at a set pace, the final 1000 m was self-paced. Precooling lead to a significantly lower rise in  $T_{re}$  ( $0.51 \pm 0.10$  vs.  $0.85 \pm 0.17^{\circ}\text{C}$ ) and significantly greater reduction in  $T_{sk}$  ( $0.93 \pm 0.25$  vs.  $0.77 \pm 0.23^{\circ}\text{C}$ ) during the warm-up. Thermal sensation was also significantly lower following the warm-up and at the completion of the trial. As a result, the time to complete the final, self-paced 1000 m of the trial was significantly faster ( $226.0 \pm 6.7$  vs.  $233.2 \pm 6.8$  s). Arngrimsson et al. (2004) found that wearing an ice vest during a 38-min warm-up lead to reductions in  $T_{oes}$  and  $T_{re}$  of  $0.28 \pm 0.35^{\circ}\text{C}$  and  $0.21 \pm 0.20^{\circ}\text{C}$  respectively, and significantly improved 5-km running performance in the heat (32°C, 50% RH) by 13 s (1.1%).

Current research has demonstrated that precooling provides clear ergogenic benefits to exercise performance in the heat, and can be achieved successfully via several methods. As such, sport science practitioners are interested in revealing the most optimal and practical strategies for enhancing performance during sporting competition.

## **2.6 Limitations of current precooling methods**

Currently, many of the extensively researched precooling manoeuvres, although shown to be effective in a laboratory setting, are somewhat impractical for

use in major sporting competitions. Early precooling studies focused on cold air exposure (Hessemer, et al., 1984; Lee & Haymes, 1995; Olschewski & Bruck, 1988; Schmidt & Bruck, 1981); however, this treatment can take a great deal of time (100-130 min) to gain a physiologically significant reduction in  $T_c$  ( $> 0.3^\circ\text{C}$ ), can be quite uncomfortable for the subjects/athletes, and usually requires rewarming intervals to reduce shivering and blunt the metabolic response to dramatic changes in ambient temperatures (Schmidt & Bruck, 1981). Additionally, the exposure to such cold air ( $0\text{-}5^\circ\text{C}$ ) is unlikely to be available in the field.

Cold water immersion, the most common form of precooling presently employed in current research, can be difficult due to lack of access to large amounts of water in the field, or lack of electricity to maintain water temperature. Furthermore, although more time efficient than cold air exposure, cold water immersion can still take up to 30-60 min to achieve the desired reduction in  $T_c$ . Whilst shorter durations can certainly be effective (Duffield, et al., 2010), this generally requires considerably lower water temperature which can be uncomfortable for the athlete.

Although considered somewhat more practical, anecdotal reports from practitioners suggests that ice vests and jackets are heavy, bulky, a challenge to transport to competition, uncomfortable for the athlete, and also a concern to some coaches that wearing such garments during a warm-up may adversely affect sport specific mechanics. Moreover, while some studies have shown their use to be effective (Arngrimsson, et al., 2004; Cotter, et al., 2001; Yates, et al., 1996), others have shown no improvements (Castle et al., 2006; Duffield et al., 2003; Duffield & Marino, 2007; Quod, et al., 2008), likely due to minimal reductions in  $T_c$ . For

example, Quod et al. (2008) showed that wearing an ice jacket for 40 min prior to exercise did not significantly lower  $T_{re}$  or improve cycling time trial performance in the heat, and may have actually caused athletes to mis-pace their trial, likely because the ice jacket caused athletes to perceive themselves to be cooler than they actually were (M. Quod, personal communication). Therefore, the development of a more practical and logistical precooling manoeuvre for use in the field is needed.

## **2.7 Internal precooling**

To date, precooling manoeuvres investigated have been achieved primarily via external cooling modalities, such as cold water immersion and cooling garments, with very little investigation into internal cooling methods. This is despite several studies demonstrating the cooling capacity of ingesting cold fluids. Initially, Imms and Lighten (1989) showed that ingesting 1 L of 7°C water reduced  $T_c$  by  $0.61 \pm 0.13^\circ\text{C}$ . Subsequently, Wimer et al. (1997) observed that both cold (0.5°C) and cool (19°C) water ingestion during exercise attenuated the rise in  $T_c$  when subjects cycled at 51%  $\text{VO}_{2\text{peak}}$  in warm conditions (26°C, 40% RH), compared with the ingestion of warm (38°C) water and no fluid intake. In addition to this, cold water ingestion also reduced whole body sweat rate and forearm blood flow. However, no measures of exercise performance were assessed. Hasegawa et al. (2006) demonstrated a performance benefit from ingesting 14-16°C water in the period separating 60 min of cycling at 60%  $\text{VO}_{2\text{max}}$  and cycling to exhaustion at 80%  $\text{VO}_{2\text{max}}$ . Fluid ingestion reduced  $T_{re}$  by  $\sim 0.3^\circ\text{C}$  and improved subsequent performance by 221 s compared with the control condition of no fluid ingestion. Mundel et al. (2006) also observed a performance enhancing effect in response to drinking cold fluids during exercise. They showed that ingesting a cold (4°C) drink increased fluid consumption ( $1.3 \pm 0.3$  vs.  $1.0 \pm 0.2 \text{ L}\cdot\text{h}^{-1}$ ) and cycling time to exhaustion at 65% peak aerobic power in

the heat ( $33.9 \pm 0.2^{\circ}\text{C}$ ;  $27.9 \pm 0.7\%$  RH) by  $11 \pm 5\%$ , compared with a  $19^{\circ}\text{C}$  drink. Consequently, Lee et al. (2008b) investigated the effect of 900 ml of cold ( $4^{\circ}\text{C}$ ) and warm ( $37^{\circ}\text{C}$ ) water ingestion in the 30 min period prior to exercise, as well as 100 ml of the same drink every 10 min during exercise, on cycling performance in hot, humid conditions ( $35.0 \pm 0.2^{\circ}\text{C}$ ,  $60.0 \pm 1.0\%$  RH). Compared with warm water, cold water ingestion reduced  $T_{\text{re}}$  by  $0.5 \pm 0.1^{\circ}\text{C}$ , and significantly increased cycling time to exhaustion at  $66 \pm 2\%$   $\text{VO}_{2\text{peak}}$  ( $63.8 \pm 4.3$  vs.  $52.0 \pm 4.1$  min). It is difficult to ascertain whether the lower mean  $T_{\text{re}}$  shown throughout the trial ( $37.7 \pm 0.4$  vs.  $38.0 \pm 0.4^{\circ}\text{C}$ ) and subsequent improved exercise performance were due to the cooling effect of the cold water consumed before or during exercise; however, it is probable that both factors contributed to such a finding.

A more aggressive internal precooling technique might arise from the ingestion of an ice slurry mixture (Brearley & Finn, 2003). Based on the law of enthalpy of fusion, ice requires significantly greater heat absorption in order to change from solid to liquid (phase change), and thus provides a far greater cooling effect than water of a similar temperature (Merrick et al., 2003). Specific heat capacity ( $C_p$ ) refers to the quantity of energy required to increase 1 g of a substance by  $1^{\circ}\text{K}$ . In a solid form,  $C_p$  of ice is  $2.108 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ , whereas liquid  $\text{H}_2\text{O}$  is  $4.204 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . However, the energy required for  $\text{H}_2\text{O}$  to change phase also requires the introduction of  $334 \text{ kJ}\cdot\text{kg}^{-1}$  of energy. Combining both solid and liquid  $\text{H}_2\text{O}$  into an ice slurry solution has the added heat sink benefit of the  $C_p$  from both the solid and liquid  $\text{H}_2\text{O}$ , as well as the enthalpy of fusion needed for the phase change. Summing these thermodynamic properties in an ice slurry mixture yields a larger heat storing capacity than liquid  $\text{H}_2\text{O}$  alone. Hence, ingestion of an ice slurry drink has the potential to reduce the rate of heat retention in the body. In a study examining the



efficacy of three different ice treatments for lowering  $T_{sk}$  and 1 cm subadipose tissue temperature, Merrick et al. (2003) demonstrated that treatments which undergo a phase change (ice-bag and wet ice) provided a significantly greater cooling effect compared to the treatment that did not undergo a phase change (Flex-i-Cold frozen gel pack). As consumption of an ice slurry drink will reach a location near the body's core (i.e., stomach), it is possible that the ice will absorb a greater amount of internal heat compared with water when it changes phase from solid ice to liquid water. This, in turn, should lower  $T_c$  significantly more than water of a similar temperature, resulting in improvements to prolonged exercise performance in the heat.

Vanden Hoek et al. (2004) investigated the differences in cooling between infusion of a saline ice slurry versus chilled saline in swine. They demonstrated that a  $50 \text{ ml}\cdot\text{kg}^{-1}$  intravenous bolus of saline ice slurry reduced core brain temperature by  $5.3 \pm 0.7^\circ\text{C}$  compared to  $3.4 \pm 0.4^\circ\text{C}$  in the chilled saline condition. This study confirms that ice slurry infusion can reduce core brain temperature to a greater degree than water alone in swine. Thus, ice slurry ingestion could also be effective at significantly reducing  $T_c$  in humans.

In addition to the positive effect of lowering  $T_c$ , internal cooling via ice slurry ingestion may improve exercise performance in the heat by having an effect on internal thermoreceptors. While it has been established that thermosensitive receptors are located in the hypothalamus monitoring the temperature of blood flow through the brain (Benzinger, 1969; Gleeson, 1998), and the skin (Hensel, 1981; Nadel et al., 1971) in humans, it has been hypothesised that thermoreceptors may also be located near, or within the core itself (Gleeson, 1998; Thomas, et al., 2006). This is in fact true in several species, with thermoreceptors being detected in the

mouth, spinal cord (Hensel, 1981), oesophagus (El Ouazzani & Mei, 1982), abdominal viscera (Cottrell, 1984; Gupta et al., 1979; Riedel et al., 1973), abdominal cavity (Rawson & Quick, 1970) and muscle (Benzinger, 1969). In humans, thermoreceptors have been identified in the stomach and small intestine (Villanova et al., 1997), and it is known that the glossopharyngeal (ninth cranial) nerve carries impulses for temperature sensation from the posterior third of the tongue and upper pharynx to the brain (Pallett & O'Brien, 1985). It is therefore possible that ice slurry ingestion may directly affect  $T_c$  afferents and have a significant effect on critical  $T_c$  attainment and thus exercise performance.

Improvements in exercise performance via stimulation of internal receptors have been reported in studies investigating glucose receptors in the mouth. Several studies have shown that simply rinsing the mouth with carbohydrate during exercise is able to improve endurance performance (Carter et al., 2003; Chambers et al., 2009; Pottier et al., 2010; Rollo et al., 2010; Rollo et al., 2008). It is speculated that energy receptors in the mouth convey a message of energy availability, which stimulates regions of the brain associated with central drive and motivation. Consequently, exercise performance is enhanced despite no changes in carbohydrate availability or metabolism. If thermosensitive receptors are present throughout the human core (e.g. mouth, oesophagus, stomach etc.), it is possible that when stimulated, the message of lowered body temperature may stimulate areas in the frontal cortex pertaining to motivation and central drive and in turn improve exercise performance in conditions of heat strain.

Several aspects of ice slurry ingestion must be considered in order to optimise its' use as a successful precooling manoeuvre. For example, both the timing

of consumption prior to exercise, as well as the amount ingested may influence the degree that  $T_c$  is lowered, as well as the gastrointestinal comfort of athletes during exercise. Furthermore, the ingestion of cold foods and beverages may cause sphenopalatine ganglioneuralgia; commonly known as “brain freeze”, which may also cause discomfort to athletes prior to/during competition. Other factors that may confound the application of ice slurry ingestion as a precooling manoeuvre during athletic competition are the accessibility of slushy machines, as well as the associated difficulties with transporting a machine and access to power in the field.

## **2.8 Summary**

Heat stress invariably has a negative effect on prolonged exercise performance. Precooling prior to exercise in hot environments has been consistently shown to enhance performance; however, current practises are largely impractical for use in major sporting competitions. As a result, athletes, coaches and sport science practitioners alike are seeking alternative strategies which are more logistical for use in the field, whilst still being equally successful. Internal precooling techniques, such as cold drink ingestion, have been shown to be effective, are easily implemented during competition and provide the additional benefit of hydrating athletes. Nevertheless, thermodynamic law suggests that more aggressive alternatives exist, and the ingestion of an ice slurry mixture may provide a more efficient manoeuvre for lowering pre-exercise  $T_c$ , and subsequently improving exercise performance in the heat.

# **CHAPTER 3**

## **Study 1:**

**Ice slurry ingestion increases core temperature  
capacity and running time to exhaustion in the heat**

### 3.1 ABSTRACT

The purpose of this study was to investigate the effect of ice slurry ingestion on thermoregulatory responses and sub-maximal running time in the heat. On two separate occasions, in a counterbalanced order, ten males ingested  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of either ice slurry ( $-1^{\circ}\text{C}$ ) or cold water ( $4^{\circ}\text{C}$ ) before running to exhaustion at their first ventilatory threshold in a hot environment ( $34.0 \pm 0.2^{\circ}\text{C}$ ,  $54.9 \pm 5.9\%$  RH). Rectal and skin temperatures, heart rate, sweating rate, and ratings of thermal sensation and perceived exertion were measured. Running time was longer ( $P = 0.001$ ) after ice slurry ( $50.2 \pm 8.5 \text{ min}$ ) versus cold water ( $40.7 \pm 7.2 \text{ min}$ ) ingestion. Prior to running, rectal temperature dropped  $0.66 \pm 0.14^{\circ}\text{C}$  following ice slurry ingestion compared to  $0.25 \pm 0.09^{\circ}\text{C}$  ( $P = 0.001$ ) with cold water, and remained lower for the first 30 min of exercise. At exhaustion however, rectal temperature was higher ( $P = 0.001$ ) with ice slurry ( $39.36 \pm 0.41^{\circ}\text{C}$ ) versus cold water ingestion ( $39.05 \pm 0.37^{\circ}\text{C}$ ). During exercise, mean skin temperature was similar between conditions ( $P = 0.992$ ), as was heart rate ( $P = 0.122$ ) and sweat rate ( $P = 0.242$ ). Following ice slurry ingestion, subjects stored more heat during exercise ( $100.10 \pm 25.00$  vs.  $78.93 \pm 20.52 \text{ W}\cdot\text{m}^{-2}$ ;  $P = 0.005$ ), and mean ratings of thermal sensation ( $P = 0.001$ ) and perceived exertion ( $P = 0.022$ ) were lower. Compared with cold water, ice slurry ingestion lowered pre-exercise rectal temperature, increased sub-maximal endurance running time in the heat ( $+19 \pm 6\%$ ) and allowed rectal temperature to become higher at exhaustion. As such, ice slurry ingestion may be an effective and practical precooling manoeuvre for athletes competing in hot environments.

### 3.2 INTRODUCTION

The rise in  $T_c$  associated with exercise in hot environments is generally thought to be the principle contributing factor causing fatigue and the reduction in motor output observed during prolonged exercise in the heat (Galloway & Maughan, 1997; Parkin, et al., 1999). A fundamental concept in the thermoregulatory literature is that the termination of prolonged exercise in the heat appears to coincide with the attainment of a critically high  $T_c$  (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993). For example, Gonzalez-Alonso et al. (1999b) showed that despite differences in starting  $T_c$ , subjects consistently fatigued at the same  $T_c$ . Such an occurrence may serve as a protective mechanism aimed at reducing motor output and heat production prior to the development of severe heat illness.

As thoroughly reviewed by Marino (2002) and Quod et al. (2006), precooling is a useful strategy for combating the detrimental effects that heat stress has on exercise performance. The main benefit of precooling is the lowering of  $T_c$  prior to exercise in the heat, thereby increasing heat storage capacity and in turn prolonging or even preventing attainment of critical core temperatures. This consequently improves endurance performance in hot conditions. Precooling manoeuvres investigated to date have been achieved almost exclusively via external cooling procedures, such as cold water immersion or wearing ice jackets (Quod, et al., 2008), with limited exploration into the potential benefits of internal cooling modalities. Lee et al. (2008b) investigated the effect of cold (4°C) and warm (37°C) water ingestion prior to, and during exercise, on cycling performance in hot, humid conditions. Compared with warm water, cold water ingestion reduced  $T_{re}$  by  $0.5 \pm 0.1^\circ\text{C}$  prior to exercise and significantly increased cycling time to exhaustion by  $23 \pm 6\%$ . It is

difficult to ascertain whether the lower mean  $T_{re}$  throughout the trial and subsequent improved exercise performance was due to the cooling effect of the cold water before, or during exercise, however, it is probable that both factors contributed.

A more aggressive and practical internal precooling technique might arise from the ingestion of an ice slurry mixture. Ice slurries, commonly referred to as slushies, are icy mixtures that are consumed as a drink. Changing the physical state of water ( $H_2O$ ) from solid to liquid (phase change) requires a large transfer of heat energy into the system. Utilising this 'enthalpy of fusion' of ice as an additional heat sink allows more heat to be transferred into the drink rather than being stored in the body. Hence, solid ice provides a greater cooling effect than liquid water alone. For example, Merrick et al. (2003) showed that cooling treatments that undergo phase change (ice-bag and wet ice) lower  $T_{sk}$  and 1 cm subadipose tissue temperature significantly more than treatments that do not undergo phase change (Flex-i-Cold frozen gel pack). As ice slurry ingestion is an internal cooling modality, it is possible that a greater amount of internal heat might be transferred to the drink as it changes phase from solid ice to liquid water. This effect, in turn, may lower  $T_c$  significantly more than water of a similar temperature, potentially resulting in improvements to prolonged exercise performance in the heat. A lowering of internal temperatures with an ice slurry solution has been shown in swine. Vanden Hoek et al. (2004) showed that a  $50\text{ ml}\cdot\text{kg}^{-1}$  intravenous bolus of saline ice slurry ( $-1$  to  $0^\circ\text{C}$ ) reduced swine brain temperature by  $5.3 \pm 0.7^\circ\text{C}$  compared to  $3.4 \pm 0.4^\circ\text{C}$  with chilled saline ( $0$ - $1^\circ\text{C}$ ). While ice slurry cooling has been shown to reduce internal temperatures to a greater degree than chilled water in swine, limited research has focused on its effect on cooling and subsequent exercise performance in the heat in humans.

The purpose of the present investigation was to examine the effects of ice slurry versus cold water ingestion on thermoregulatory responses and prolonged sub-maximal exercise performance in the heat. We hypothesised that ice slurry ( $-1^{\circ}\text{C}$ ) ingestion would significantly reduce  $T_{\text{c}}$ , and in turn improve run time to exhaustion in the heat, compared with cold water ( $4^{\circ}\text{C}$ ) ingestion.



### **3.3 METHODS**

#### **3.3.1 Participants**

Ten healthy males (age:  $28 \pm 6$  y; height:  $178.9 \pm 6.3$  cm; body mass:  $79.9 \pm 11.2$  kg; body fat %:  $15.7 \pm 4.0\%$ ;  $\text{VO}_{2\text{max}}$ :  $56.4 \pm 4.7$  ml·kg<sup>-1</sup>·min<sup>-1</sup>) volunteered for this study. Subjects were considered moderately active, participating in recreational sport, had no prior history of heat illness and were without injuries. Subjects provided written informed consent prior to study commencement. The study procedures were approved by the Edith Cowan University Human Research Ethics Committee.

#### **3.3.2 Preliminary measurements**

On their first visit to the laboratory, subjects performed a progressive exercise test on a running treadmill (Trackmaster; JAS Fitness Systems, Newton, USA) at room temperature ( $24.6 \pm 1.9^\circ\text{C}$ ,  $44.4 \pm 8.2\%$  RH) for the determination of maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ) and their first ventilatory threshold ( $\text{VT}_1$ ). Prior to the test, the subject's body mass and height were measured to the nearest 10 g and 0.1 cm using a floor scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Skinfold thickness measurements were assessed at 4 sites (triceps, subscapular, biceps and mid iliac crest) in duplicate using skinfold callipers (Model HSK-BI-3; Baty International, West Sussex, UK). Body density was then calculated (Durnin & Womersley, 1974) and body fat per cent estimated using Siri's (1956) equation. For the progressive exercise test, a diagnostic system (ParvoMedics TrueOne 2400, East Sandy, UT) was used to measure minute ventilation, carbon dioxide production and oxygen uptake. The gas analysers were calibrated using 4.01%  $\text{CO}_2$ –16.00%  $\text{O}_2$ –89.99%  $\text{N}_2$  gas

mixture (BOC gases, Surrey, UK), and the volume sensor using a 3 L calibration syringe (Hans Rudolph series 5530, Kansas City MO, USA). The test began with subjects running at  $8 \text{ km}\cdot\text{h}^{-1}$  for 4 min on a zero percent gradient, with  $2 \text{ km}\cdot\text{h}^{-1}$  increases in treadmill speed occurring every 4 min. Once speed reached  $16 \text{ km}\cdot\text{h}^{-1}$ , gradient remained at zero for the first 4 min, and then increased by 2% every 4 min thereafter until volitional fatigue. Heart rate was monitored continuously by telemetry using a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland) and rating of perceived exertion (RPE) was recorded every 4 min using the 6-20 point Borg Scale (Borg, 1982).  $\text{VO}_{2\text{max}}$  was recorded as the highest value obtained in a 30 s period (Millet et al., 2003). Attainment of  $\text{VO}_{2\text{max}}$  was indicated by a plateau in oxygen consumption. Secondary criteria used to confirm  $\text{VO}_{2\text{max}}$  attainment were a respiratory exchange ratio (RER) greater than 1.10, and peak heart rate within  $10 \text{ beats}\cdot\text{min}^{-1}$  of age predicted maximum ( $220 - \text{age}$ ). When  $\text{VO}_{2\text{max}}$  was not achieved, the  $\text{VO}_{2\text{peak}}$  was recorded.  $\text{VT}_1$  was determined by the increase in the ventilatory equivalent for oxygen uptake ( $\text{VE}\cdot\text{VO}_2^{-1}$ ) with no concomitant increase in the ventilatory equivalent for carbon dioxide production ( $\text{VE}\cdot\text{VCO}_2^{-1}$ ) (Lucia et al., 2000).

### **3.3.3 Experimental Design**

Throughout the study, subjects were asked to keep stable their normal lifestyle activities, including physical activity and nutritional habits. On the day before each trial, subjects were asked to eat at least 6 g of carbohydrate per kg of body weight, and the same pre-trial meal on the day of the experimental trials (providing at least 1 g carbohydrate/kg). They were also asked to consume at least 2 litres of fluid on this day, and 400 ml of fluid during the meal consumed just before the experimental trials. In the 24 h period prior to the trials, subjects were asked to

avoid strenuous exercise, as well as the consumption of alcohol, caffeine, non-steroidal anti-inflammatory drugs or nutritional supplements. Before the experimental trials were completed, subjects performed a familiarisation trial involving running to exhaustion at the subject's previously determined  $VT_1$  running speed in the same hot environment as the experimental trials. Within 5-14 days following this familiarisation trial, subjects completed the first of two experimental trials on a treadmill, running to exhaustion at their  $VT_1$  running speed after ingesting either ice slurry ( $-1^{\circ}\text{C}$ ) or cold water ( $4^{\circ}\text{C}$ ). We chose a  $4^{\circ}\text{C}$  temperature for our control drink as this is the typical temperature of drinks found in conventional refrigeration units. Subjects completed their assigned conditions in a counterbalanced and random order, at the same time of day, separated by 5-20 days. For each trial, the subjects wore the same exercise clothing.

### **3.3.4 Experimental Procedures**

On arrival to the laboratory, urine and blood samples were collected before nude body mass was recorded. Approximately 5 ml of blood was drawn using standard venipuncture technique from an antecubital vein. A disposable rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was then self-inserted 120 mm past the anal sphincter. Four re-usable skin thermistors were affixed using hypoallergenic polyacrylate adhesive tape (Fixomull, Smith and Nephew Ltd., Auckland, New Zealand) at the mid belly of the left gastrocnemius, quadriceps, biceps, and chest. A heart rate monitor was then fixed to the subjects' chest before a 15 min rest period to gather baseline resting data. Following this rest period, over the course of the next 30 min, subjects ingested either a  $7.5\text{ g}\cdot\text{kg}^{-1}$  ice slurry ( $-1^{\circ}\text{C}$ ) with added syrup for flavour (Cottee's Foods, NSW, Australia), or  $7.5\text{ g}\cdot\text{kg}^{-1}$  of cold water ( $4^{\circ}\text{C}$ ) with added syrup. Both solutions

were made with the same flavouring for all subjects, and consisted of 5% carbohydrate. Ice slurries were made using a slushy machine (Essential Slush Co., QLD, Australia), and every 5 min, subjects were given  $1.25 \text{ g}\cdot\text{kg}^{-1}$  of either drink to ensure a standardised ingestion rate. In order to establish the possible influence of ice slurry or cold water ingestion on bronchial constriction during the experimental trials, subjects performed a pulmonary function test (MED Graphics CPX/D System, Medical Graphics Corporation, St Paul, Minnesota, USA) to measure forced vital capacity (FVC) and forced expiratory volume in 1 s ( $\text{FEV}_1$ ), immediately before and after drink ingestion. Subjects then commenced running, approximately 5 min after completing drink ingestion. Following exercise, subjects towelled dry and were weighed again for nude body mass prior to the collection of urine and blood samples.

### 3.3.5 Measurements

Throughout the experimental protocol,  $T_{\text{re}}$  and  $T_{\text{sk}}$  were recorded continuously at a sampling rate of 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgeshire UK). From this data 5 min averages were calculated. Mean  $T_{\text{sk}}$  was calculated using Ramanathan's (1964) formula:  $T_{\text{sk}} = 0.3 (T_{\text{chest}} + T_{\text{arm}}) + 0.2 (T_{\text{thigh}} + T_{\text{calf}})$ . Mean body temperature ( $T_{\text{b}}$ ) was calculated using the formula of Colin et al. (1971):  $T_{\text{b}} = 0.66 (T_{\text{re}}) + 0.34 (T_{\text{sk}})$  at rest and during drink ingestion, and  $T_{\text{b}} = 0.79 (T_{\text{re}}) + 0.21 (T_{\text{sk}})$  during exercise. Heat storage was calculated at 5 min increments using the formula of Adams et al. (1992):  $\text{heat storage} = 0.965 \times m \times \Delta T_{\text{b}} / A_{\text{D}}$ , where 0.965 is the specific heat storage capacity of the body ( $\text{W}\cdot\text{kg}^{-1}\cdot^\circ\text{C}$ ),  $m$  the mean body mass (kg) over the duration of the trial, and is  $A_{\text{D}}$  the body surface area ( $\text{m}^2$ ) according to Du Bois and Du Bois (1989):  $A_{\text{D}} = 0.202\text{m}^{0.425} \times \text{height}^{0.725}$ .

Heart rate was monitored continuously throughout the trial and reported as 5 min averages. Rating of thermal sensation (9 point scale ranging from unbearably cold [0] to unbearable hot [8] (Young et al., 1987)) was recorded every 5 min during drink ingestion and exercise, while RPE (Borg, 1982) was recorded every 5 min throughout the course of exercise.

Serum osmolality was measured from blood serum using a freezing point depression osmometer (Model 3250; Advanced Instruments Inc., Norwood, MA, USA) after samples were centrifuged for 15 min at 3,000 rev·min<sup>-1</sup> (1942 g) and 4°C. Urine samples were assessed for urine osmolality using a freezing point depression osmometer (Model 3250; Advanced Instruments Inc., Norwood, MA, USA), and urine specific gravity using a hand held refractometer (No. 503, Nippon Optical Works Co., LTD., Tokyo, Japan). Changes in nude body mass were used to assess fluid loss to the nearest 10 g. For the purpose of this study, 10 g of body mass lost was assumed to equate to 10 ml of fluid lost from sweat. Sweat rate was estimated using the formula: sweat rate (L·h<sup>-1</sup>) = Pre-*m* (kg) + fluid ingested (L) – post-*m* (kg).

Environmental conditions in the climate chamber were monitored continuously using a wet bulb globe temperature heat stress monitor (Microtherm; Casella Measurement Ltd., Bedford, UK) and averaged at 5 min intervals.

### **3.3.6 Statistical Analyses**

Data were analysed in two phases; during the drinking period, and during exercise. Differences in time to exhaustion, physiological variables at a single time point, sweat rate, heat storage and hydration status between conditions were analysed using a paired Student's *t*-test. Mean differences in physiological variables between conditions and over time were compared using a two-way (drink × time) repeated

measures analysis of variance (ANOVA). When a significant main effect or interaction effect was identified, differences were delineated using a paired Student's *t*-test with Bonferroni adjustment. For all comparisons, significance was set at  $P < 0.05$ . All data are presented as means  $\pm$  standard deviations. Statistical analyses were performed using SPSS version 17.0 (SPSS Inc., Chicago, USA).

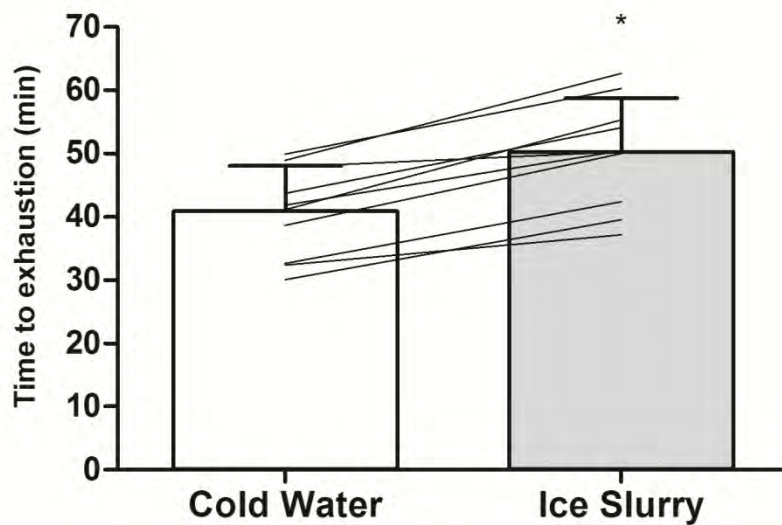
### **3.4 RESULTS**

#### **3.4.1 Environmental conditions and pre-exercise hydration status**

During the drinking period, mean ambient temperature was similar between trials ( $24.4 \pm 0.9^{\circ}\text{C}$  vs.  $24.6 \pm 1.3^{\circ}\text{C}$ ;  $P = 0.809$ ). Similarly, during exercise, there were no significant differences in mean ambient temperature ( $34.1 \pm 0.2$  vs.  $34.0 \pm 0.3^{\circ}\text{C}$ ;  $P = 0.503$ ), and relative humidity ( $55.9 \pm 5.2$  vs.  $53.8 \pm 6.4$  % RH;  $P = 0.075$ ) between conditions. Subjects were considered similarly euhydrated before each trial, as demonstrated by equivalent measures of pre-exercise body mass ( $80.23 \pm 11.04$  vs.  $80.18 \pm 11.26$  kg;  $P = 0.782$ ), urine specific gravity (USG;  $1.015 \pm 0.008$  vs.  $1.013 \pm 0.009$ ;  $P = 0.349$ ), urine osmolality ( $543 \pm 268$  vs.  $465 \pm 328$  mOsm $\cdot\text{kg}^{-1}$ ;  $P = 0.447$ ) and serum osmolality ( $296 \pm 4$  vs.  $296 \pm 6$  mOsm $\cdot\text{kg}^{-1}$ ;  $P = 0.761$ ) (ice slurry vs. cold water ingestion, respectively). During the drinking period, 3 of 10 subjects experienced sphenopalatine ganglioneuralgia (brain freeze) with ice slurry ingestion, whereas no subjects experienced this with cold water ingestion.

#### **3.4.2 Running times to exhaustion**

As shown in Figure 3.1, all ten subjects ran longer (range 2.4–14.2 min) following ice slurry ( $50.2 \pm 8.5$  min) compared with cold water ingestion ( $40.7 \pm 7.2$  min). This equated to a mean running time increase of  $9.5 \pm 3.6$  min ( $19 \pm 6\%$ ;  $P = 0.001$ ).



**Figure 3.1** – Mean ( $\pm$  SD) run time to exhaustion during the two experimental conditions. Lines denote individual data ( $n = 10$ ). Time to exhaustion was longer (\*) after ice slurry compared with cold water ingestion ( $P = 0.001$ ).

### 3.4.3 Rectal temperature ( $T_{re}$ )

Figure 3.2A illustrates mean  $T_{re}$  data recorded over the two trials. Following the 15 min resting period prior to drink ingestion, there were no differences in  $T_{re}$  between conditions ( $37.21 \pm 0.19$  vs.  $37.13 \pm 0.11^{\circ}\text{C}$ ; ice slurry vs. cold water ingestion, respectively;  $P = 0.130$ ). However, ice slurry ingestion resulted in a greater ( $P = 0.001$ ) reduction in  $T_{re}$  ( $0.66 \pm 0.14^{\circ}\text{C}$ ) compared with cold water ingestion ( $0.25 \pm 0.09^{\circ}\text{C}$ ). Consequently,  $T_{re}$  was  $0.32 \pm 0.14^{\circ}\text{C}$  cooler following ice slurry compared with cold water ingestion prior to the start of exercise ( $P = 0.001$ ). During exercise,  $T_{re}$  increased ( $P = 0.001$ ), but remained lower following ice slurry compared with cold water ingestion for the first 30 min of exercise ( $P = 0.001$ ). Subjects achieved a significantly higher ( $0.78 \pm 0.27\%$ )  $T_{re}$  at exhaustion ( $39.36 \pm 0.41$  vs.  $39.05 \pm 0.37^{\circ}\text{C}$ ;  $P = 0.001$ ) following ice slurry compared with cold water ingestion (Figure 3.3). Despite a larger observed rate of change occurring in  $T_{re}$



during ice slurry compared with cold water ingestion ( $0.27 \pm 0.04$  vs.  $0.25 \pm 0.06^{\circ}\text{C}\cdot 5 \text{ min}^{-1}$ ), this comparison did not reach significance ( $P = 0.052$ ).

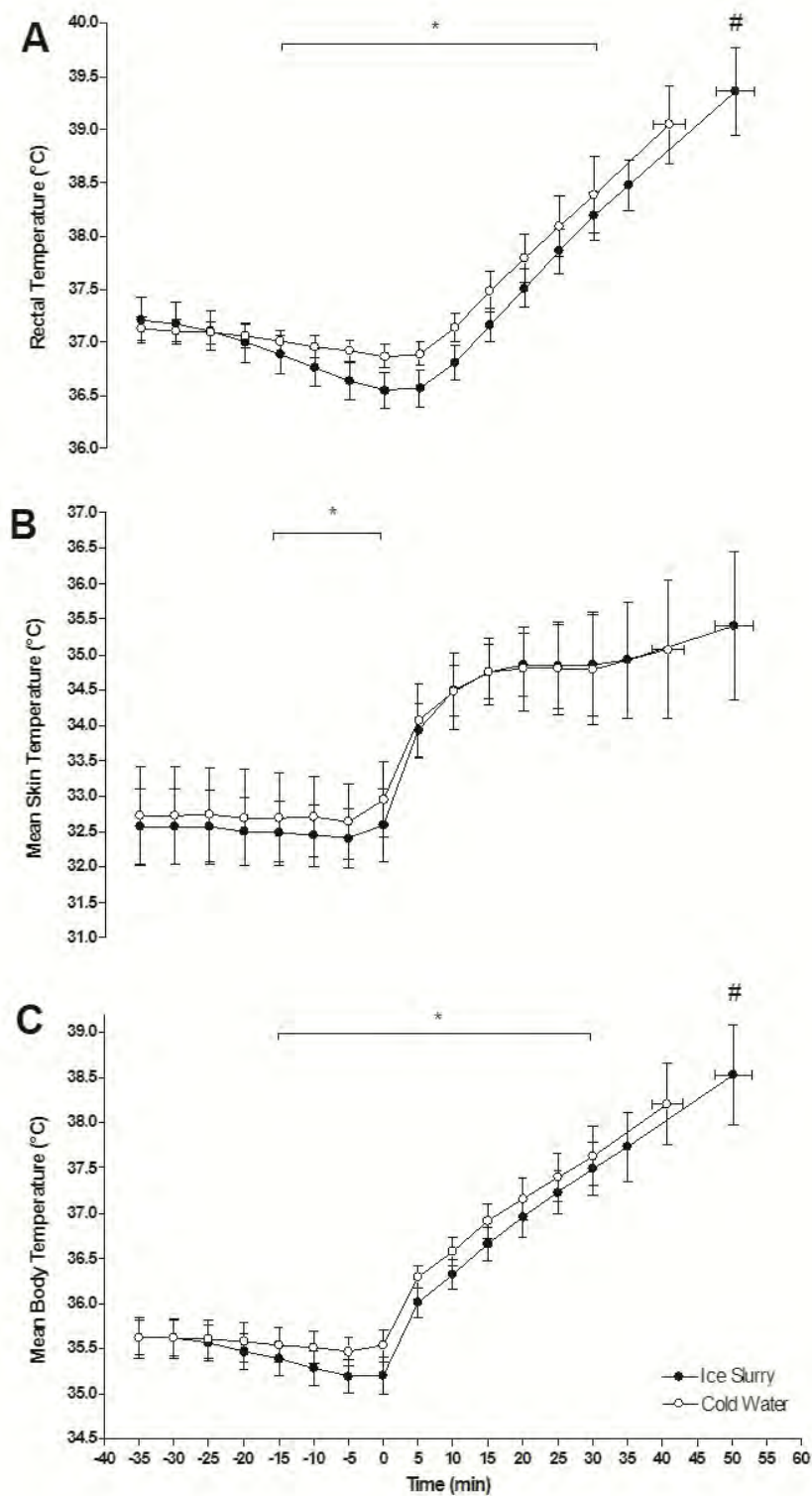
#### **3.4.4 Mean skin temperature ( $T_{\text{sk}}$ )**

Figure 3.2B compares the mean  $T_{\text{sk}}$  over the two conditions. Initially prior to the commencement of drink ingestion, there were no differences in  $T_{\text{sk}}$  between conditions ( $32.57 \pm 0.54$  vs.  $32.73 \pm 0.68^{\circ}\text{C}$ ;  $P = 0.134$ ). During the pre-exercise period, mean  $T_{\text{sk}}$  was significantly lower following ice slurry compared with cold water ingestion ( $P = 0.017$ ); specifically after 20 min ( $32.48 \pm 0.46$  vs.  $32.70 \pm 0.63^{\circ}\text{C}$ ;  $P = 0.038$ ), 25 min ( $32.45 \pm 0.44$  vs.  $32.71 \pm 0.57^{\circ}\text{C}$ ;  $P = 0.014$ ) and 30 min of drinking ( $32.41 \pm 0.42$  vs.  $32.64 \pm 0.53^{\circ}\text{C}$ ;  $P = 0.008$ ), as well as prior to the commencement of exercise ( $32.59 \pm 0.52$  vs.  $32.95 \pm 0.54^{\circ}\text{C}$ ;  $P = 0.001$ ). Once exercise commenced,  $T_{\text{sk}}$  increased continuously ( $P = 0.001$ ), however there were no differences between conditions ( $P = 0.992$ ).

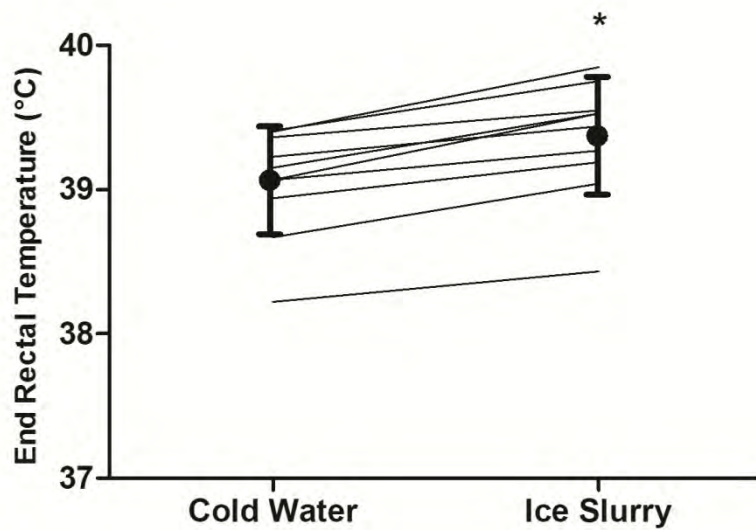
#### **3.4.5 Mean body temperature ( $T_{\text{b}}$ ) and heat storage**

Figure 3.2C shows the mean  $T_{\text{b}}$  over the two conditions.  $T_{\text{b}}$  was similar between conditions following the 15 min resting period ( $35.63 \pm 0.20$  vs.  $35.63 \pm 0.23^{\circ}\text{C}$ ;  $P = 1.000$ ). Ice slurry ingestion lead to a significantly greater drop in  $T_{\text{b}}$  ( $0.43 \pm 0.13^{\circ}\text{C}$ ) compared with cold drink ingestion ( $0.09 \pm 0.10^{\circ}\text{C}$ ;  $P = 0.001$ ).  $T_{\text{b}}$  was  $0.38 \pm 0.22^{\circ}\text{C}$  ( $P = 0.001$ ) cooler prior to the start of exercise, and remained cooler for the first 30 min of exercise ( $P = 0.007$ ).  $T_{\text{b}}$  increased continuously during exercise ( $P = 0.001$ ), and at exhaustion was significantly higher ( $P = 0.001$ ) following ice slurry ( $38.53 \pm 0.48^{\circ}\text{C}$ ) compared with cold water ingestion ( $38.21 \pm 0.45^{\circ}\text{C}$ ). Heat storage during the drinking period was significantly lower ( $P = 0.001$ ) following ice slurry ( $-18.28 \pm 5.68 \text{ W}\cdot\text{m}^{-2}$ ) compared with cold water ingestion (-

$7.84 \pm 3.13 \text{ W}\cdot\text{m}^{-2}$ ). During exercise, subjects stored significantly more heat ( $P = 0.005$ ) following ice slurry ( $100.10 \pm 25.00 \text{ W}\cdot\text{m}^{-2}$ ) compared with cold water ingestion ( $78.93 \pm 20.52 \text{ W}\cdot\text{m}^{-2}$ ). Mean rates of heat storage were similar between trials ( $10.98 \pm 2.95$  vs.  $10.10 \pm 2.72 \text{ W}\cdot\text{m}^{-2}\cdot 5 \text{ min}^{-1}$ ;  $P = 0.234$ ).



**Figure 3.2** – Rectal temperature ( $T_{re}$ ; A), mean skin temperature ( $T_{sk}$ ; B) and mean body temperature ( $T_b$ ; C) during each experimental condition (means  $\pm$  SD). (\*) ice slurry < cold water ( $P < 0.05$ ); (#) ice slurry > cold water ( $P = 0.001$ ).



**Figure 3.3** – Mean ( $\pm$  SD) rectal temperature ( $T_{re}$ ) at exhaustion during the two experimental conditions. Lines denote individual data ( $n = 10$ ).  $T_{re}$  was higher (\*) at exhaustion after ice slurry compared with cold water ingestion ( $P = 0.001$ ).

### 3.4.6 Heart rate

Figure 3.4A shows the mean heart rate response over the two conditions. Heart rate did not differ significantly between conditions prior to drink ingestion ( $65 \pm 8$  vs.  $65 \pm 8$  beats $\cdot$ min $^{-1}$ ;  $P = 0.891$ ). During the drinking period, heart rate decreased ( $P = 0.001$ ), but was not affected by drink type ( $P = 0.625$ ). During exercise, heart rate increased continuously ( $P = 0.001$ ), and remained similar between conditions ( $P = 0.122$ ) including at exhaustion ( $185 \pm 7$  vs.  $183 \pm 6$  beats $\cdot$ min $^{-1}$ ).

### 3.4.7 Sweat rate and post-exercise hydration status

Sweat rate for the ice slurry trial ( $1.89 \pm 0.61$  L $\cdot$ h $^{-1}$ ) was not significantly different ( $P = 0.242$ ) to the cold water trial ( $2.05 \pm 0.43$  L $\cdot$ h $^{-1}$ ). Post-exercise, hydration status was also similar between conditions, as demonstrated by comparable measures of body mass ( $79.29 \pm 10.91$  vs.  $79.40 \pm 11.18$  kg;  $P = 0.621$ ),

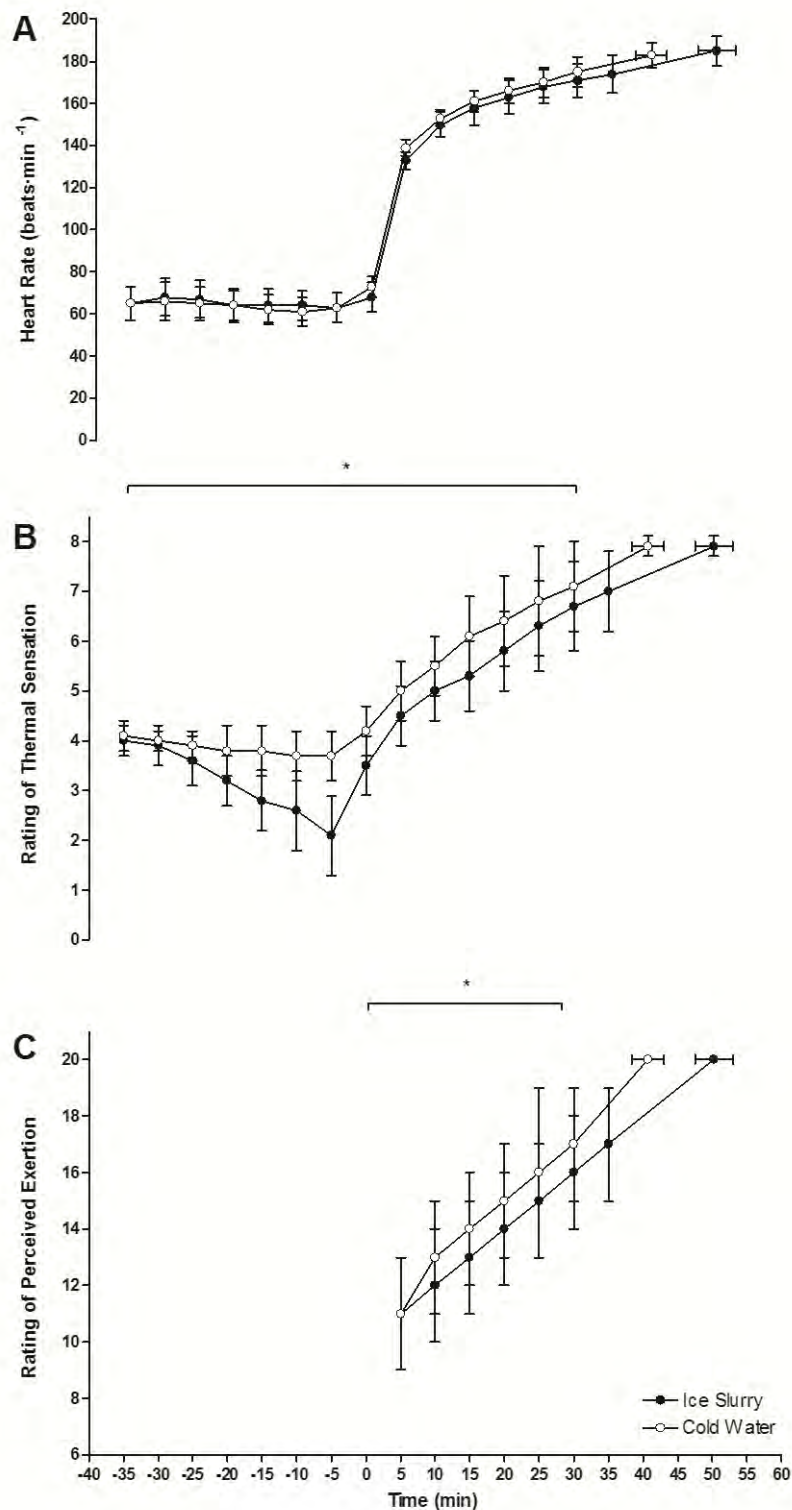
USG ( $1.012 \pm 0.007$  vs.  $1.013 \pm 0.009$ ;  $P = 0.650$ ), urine osmolality ( $395 \pm 236$  vs.  $459 \pm 283$  mOsm·kg<sup>-1</sup>;  $P = 0.444$ ) and serum osmolality ( $294 \pm 3$  vs.  $294 \pm 3$  mOsm·kg<sup>-1</sup>;  $P = 0.720$ ).

#### **3.4.8 Ratings of thermal sensation and perceived exertion**

Figure 3.4 shows the mean ratings of thermal sensation (B) and perceived exertion (C) recorded over the two trials. Prior to drinking, ratings of thermal sensation were similar between trials ( $4.0 \pm 0.3$  vs.  $4.1 \pm 0.3$ ;  $P = 0.168$ ). Thermal sensation was lower following drink ingestion ( $2.1 \pm 0.8$  vs.  $3.7 \pm 0.5$ ;  $P = 0.001$ ), prior to exercise ( $3.5 \pm 0.6$  vs.  $4.2 \pm 0.5$ ;  $P = 0.001$ ), and remained lower for the first 30 min of exercise ( $P = 0.029$ ) for ice slurry versus cold water ingestion respectively. During exercise, mean ratings of thermal sensation ( $P = 0.001$ ) and perceived exertion ( $P = 0.022$ ) were lower following ice slurry ingestion. RPE values were lower at the 10 ( $P = 0.04$ ), 20 ( $P = 0.04$ ), 25 ( $P = 0.024$ ) and 30 min ( $P = 0.012$ ) exercise time points following ice slurry compared with cold water ingestion trials. At exhaustion, thermal sensation ( $7.9 \pm 0.2$  vs.  $7.9 \pm 0.2$ ;  $P = 0.343$ ) and RPE ( $20 \pm 0$  vs.  $20 \pm 0$ ;  $P = 1.000$ ) were similar between trials.

#### **3.4.9 Pulmonary function**

Ice slurry ingestion caused a greater reduction ( $P = 0.038$ ) in FVC ( $0.21 \pm 0.14$  L) compared with cold water ingestion ( $0.07 \pm 0.18$  L). There were no significant changes between conditions in FEV<sub>1</sub> following drink ingestion ( $0.16 \pm 0.16$  vs.  $0.06 \pm 0.18$ ;  $P = 0.278$ ).



**Figure 3.4** – Heart rate (A) and ratings of thermal sensation (B) and perceived exertion (C) during the two experimental conditions (mean  $\pm$  SD). Heart rate was unaltered by drink type. Mean ratings of thermal sensation ( $P = 0.001$ ) and perceived exertion ( $P = 0.022$ ) were lower (\*) following ice slurry, compared with cold water ingestion.

### 3.5 DISCUSSION

The present study has shown at least three novel findings. First, ingestion of  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry ( $-1^{\circ}\text{C}$ ) significantly reduced  $T_{\text{re}}$  compared with cold water ( $4^{\circ}\text{C}$ ) ingestion ( $0.66 \pm 0.14$  vs.  $0.25 \pm 0.09^{\circ}\text{C}$ ) in normothermic individuals. Second, ice slurry ingestion prior to exercise in a hot environment significantly prolonged run time to exhaustion ( $+9.5 \pm 3.6$  min;  $19 \pm 6\%$ ). And last, precooling using ice slurry ingestion resulted in a significantly higher  $T_{\text{re}}$  at exhaustion compared with the cold water ingestion trial ( $39.36 \pm 0.41$  vs.  $39.05 \pm 0.37^{\circ}\text{C}$ ). These results are the first to show the practical effectiveness of ice slurry ingestion as a precooling manoeuvre, not only for delaying the time to reach a critically high  $T_{\text{c}}$  and in turn improving exercise performance, but also for allowing a higher tolerable  $T_{\text{c}}$  prior to exhaustion.

It is generally accepted that the attainment of a critically high  $T_{\text{c}}$  is the primary reason for the termination of prolonged exercise in hot environments (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993). Gonzalez-Alonso et al. (1999b) observed that subjects who cycled in the heat ( $40^{\circ}\text{C}$ , 19% RH) at 60%  $\text{VO}_{2\text{max}}$  reached volitional fatigue at the same  $T_{\text{oes}}$  ( $40.1\text{-}40.2^{\circ}\text{C}$ ), despite a different starting  $T_{\text{es}}$ . In that study (Gonzalez-Alonso, et al., 1999b), pre-exercise  $T_{\text{oes}}$  was lowered using water immersion ( $35.9 \pm 0.2$  vs.  $37.4 \pm 0.1^{\circ}\text{C}$  in the control condition of no cooling), which elicited a significantly longer cycling time to exhaustion ( $63 \pm 3$  vs.  $46 \pm 3$  min). This was thought to be due to the increased heat storage capacity that prolonged the time to reach a critically high  $T_{\text{c}}$  (Gonzalez-Alonso, et al., 1999b). Similar mechanisms were likely involved in the current study. Decreasing  $T_{\text{re}}$  via ice slurry ingestion likely elicited a larger heat sink ( $-18.28 \pm 5.68$  vs.  $-7.84 \pm 3.13 \text{ W}\cdot\text{m}^{-1}$

<sup>2</sup>), which increased the body's capacity to store heat ( $100.10 \pm 25.00$  vs.  $78.93 \pm 20.52 \text{ W}\cdot\text{m}^{-2}$ ). The delayed attainment of a high  $T_c$  and the increased running time found with ice slurry ingestion are both likely due to the ice slurry's capacity to create an expanded heat sink compared with cold water ingestion.

The larger heat sink created by the ingestion of the ice slurry is the result of the unique thermodynamic characteristics of  $\text{H}_2\text{O}$  and the changing of physical states. Specific heat capacity ( $C_p$ ) refers to the quantity of energy required to increase 1 g of a substance by  $1^\circ\text{K}$ . In a solid form,  $C_p$  of ice is  $2.108 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ , whereas liquid  $\text{H}_2\text{O}$  is  $4.204 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . However, the energy required for  $\text{H}_2\text{O}$  to change phase also requires the introduction of  $334 \text{ kJ}\cdot\text{kg}^{-1}$  of energy. Combining both solid and liquid  $\text{H}_2\text{O}$  into an ice slurry solution has the added heat sink benefit of the  $C_p$  from both the solid and liquid  $\text{H}_2\text{O}$ , as well as the enthalpy of fusion needed for the phase change. Summing these thermodynamic properties in an ice slurry mixture yields a larger heat storing capacity than liquid  $\text{H}_2\text{O}$  alone. Hence, ingestion of an ice slurry drink has the potential to reduce the rate of heat retention in the body. It is important to note, that although there was  $\sim 5^\circ\text{C}$  difference in drink temperatures, the large difference in  $T_{re}$  observed between conditions was predominantly due to the enthalpy of fusion, rather than the difference in drink temperature *per se*. Using the equation  $Q = m \cdot C_p \cdot \Delta T$  (where  $Q$  is the quantity of heat gained/lost (kJ),  $m$  is the mass of the substance (kg), and  $\Delta T$  is the change in temperature ( $^\circ\text{K}$ )), the expected change in  $T_c$  from drinking  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of cold water and ice slurry can be calculated. For the subjects in the current investigation, a reduction in  $T_c$  of  $\sim 0.30^\circ\text{C}$  and  $\sim 1.07^\circ\text{C}$  would be expected from drinking equal volumes of cold water and ice slurry drinks, respectively. This substantial difference is due almost entirely to the



additional energy required for the phase change, as if subjects were to ingest 0°C water, the expected reduction in  $T_c$  would only be ~0.34°C.

In the present investigation, subjects achieved a significantly higher  $T_{re}$  at exhaustion following the ingestion of ice slurry versus cold water ( $39.36 \pm 0.41$  vs.  $39.05 \pm 0.37^\circ\text{C}$ ;  $P = 0.001$ ; Figure 3.3). This does not concur with current literature, which suggests that subjects exercising in hot environments will reach volitional exhaustion at similar  $T_c$  (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993). This also holds true in studies where a precooling manoeuvre has been performed (Gonzalez-Alonso, et al., 1999b; Hasegawa, et al., 2006; Lee, et al., 2008b). Although it is difficult to discount the possibility of a placebo effect, this is unlikely, as ratings of thermal sensation ( $7.9 \pm 0.2$  vs.  $7.9 \pm 0.2$ ) and perceived exertion ( $20 \pm 0$  vs.  $20 \pm 0$ ) were similar at the point of exhaustion. It is possible that differences in  $T_{re}$  observed between conditions at the point of exhaustion may be explained by increased brain cooling achieved by ice slurry ingestion. As the ice slurry was ingested through the mouth, it is reasonable to suggest that its' consumption caused a physiologically meaningful reduction in brain temperature; hence delaying the attainment of critically high brain temperature. This may have allowed subjects to run longer, generate and store more metabolic heat in their core, all of which could account for the observed increase in  $T_{re}$  at the point of exhaustion. A similar effect has been shown in canines, whereby brain cooling via cold water (~8°C) nasal irrigation significantly increased the  $T_c$  tolerated by the dogs by 0.5-1.0°C, while being heated in a hot water bath (Carithers & Seagrave, 1976). The importance of brain temperature during prolonged exercise in the heat was shown in goats by Caputa et al. (1986). They showed that goats reached the point of exhaustion at hypothalamic temperatures between 42.0-42.9°C, irrespective of trunk temperature.

In humans, Ansley et al. (2008) showed that head cooling during exercise in warm conditions increased cycling time to exhaustion by 51% (45 vs. 24 min), despite similarities in  $T_{re}$  throughout exercise. The authors postulated that the increased performance was due to lower brain temperatures throughout the cooling trial.

Another possible explanation for the differences in  $T_{re}$  observed at exhaustion in the present study might be due to differences in thermoreception. While it has been established that thermoreceptors are located in both the hypothalamus monitoring the temperature of blood flow through the brain (Gleeson, 1998), and the skin in humans (Hensel, 1981), it has been hypothesised that thermoreceptors might also be located near, or within the core itself (Gleeson, 1998). This is in fact true in other species, with thermoreceptors located in the mouth, oesophagus, spinal cord, abdominal viscera (Hensel, 1981), abdominal cavity (Rawson & Quick, 1970) and the muscle (Benzinger, 1969). If this is also true in humans, ice slurry ingestion could have directly affected  $T_c$  afferents and had a significant effect on critical  $T_c$  attainment. Additionally, the glossopharyngeal (ninth cranial) nerve carries impulses for temperature sensation from the posterior third of the tongue and upper pharynx to the brain (Pallett & O'Brien, 1985). As such, subjects may have perceived exercise at a given  $T_{re}$  as easier during the ice slurry trial, in turn prolonging running time, thus increasing metabolic heat production and  $T_{re}$  at exhaustion. In the present investigation, attainment of a higher  $T_{re}$  was associated with the positive effect of further extending running time before volitional exhaustion occurred. However, it is important to note that this could also be considered as a negative consequence, as increasing  $T_{re}$  above the normal tolerable limits could result in heat illness.

Mean  $T_{re}$  at exhaustion for both trials was  $39.21 \pm 0.41^{\circ}\text{C}$ ; values lower than those normally considered to be 'critical'. This is likely due to the fact that subjects

in the current study were not highly trained. Selkirk and McLellan (2001) established that trained subjects were able to tolerate higher  $T_{re}$  during exercise in the heat than untrained subjects. The authors suggested this was due to the familiarisation of achieving high  $T_c$  during training, rather than increased aerobic capacity *per se*, as they found no correlation between  $T_{re}$  at exhaustion and  $VO_{2peak}$ .

Ice slurry ingestion caused a small, yet statistically significant reduction in  $T_{sk}$  for the final 15 min of drinking, so that upon commencement of running it was  $0.36 \pm 0.25^{\circ}\text{C}$  lower than following cold water ingestion. This reduction in  $T_{sk}$  is much smaller than that witnessed with external cooling methods. For example, Quod et al. (2008) found that a combination treatment of cold water immersion followed by wearing an ice jacket reduced  $T_{sk}$  by  $8.1^{\circ}\text{C}$  compared to the control condition of no cooling. The drop in  $T_{sk}$  shown in the present study is unlikely to be physiologically significant, as once exercise began, differences were no longer seen between conditions. The similarity in  $T_{sk}$  between conditions may have been due to similar rates of evaporative sweat loss between trials (sweat rate  $1.89 \pm 0.61 \text{ L}\cdot\text{h}^{-1}$  vs.  $2.05 \pm 0.43 \text{ L}\cdot\text{h}^{-1}$ ) (Johnson et al., 1984). These findings do not correspond with a number of studies that have demonstrated reduced sweat rates following an external precooling manoeuvre (Hessemer, et al., 1984; Olschewski & Bruck, 1988). The increased running time to exhaustion observed despite similarities in  $T_{sk}$  between trials lends support to the study by Morrison et al. (2004), who showed that changes in  $T_c$ , rather than  $T_{sk}$ , are the primary cause for reductions in exercise performance in the heat, likely due to central impairment of neuromuscular activation.

Heart rate in the present study was also unaltered by ice slurry ingestion, a finding which conflicts with the majority of studies investigating the effect of precooling on thermoregulatory responses during exercise. This finding also may be

explained by the similarities in  $T_{sk}$  shown during exercise, as skin blood flow was likely similar between conditions (Johnson, et al., 1984). Other studies which have shown a reduction in heart rate during exercise following precooling have also shown reductions in  $T_{sk}$  (Hasegawa, et al., 2006; Lee & Haymes, 1995; Wilson, et al., 2002).

Subjects reported feeling cooler throughout the drinking and exercise periods following ice slurry ingestion. Sweat rate and  $T_{sk}$ , both previously shown to influence ratings of thermal sensation (Gagge et al., 1967), were similar between conditions. Therefore, the lower ratings of thermal sensation were likely due to the reduced  $T_{re}$  and  $T_b$ , as feelings of heat-related fatigue have been shown to be a result of both increased  $T_{sk}$  and  $T_{re}$  (Simmons et al., 2008b). Subjects' ratings of perceived exertion were also lower throughout the exercising period after consuming the ice slurry. It is likely that subjects perceived exercise after ice slurry ingestion to be easier at each time point due to the lower thermal strain and  $T_{re}$ . Indeed, it has previously been shown that increases in RPE during exercise in the heat are predominantly due to increases in  $T_{re}$  (Simmons et al., 2008a).

Costill and Saltin (1974) showed that fluid volume remaining in the stomach was less following the ingestion of colder ( $5^{\circ}\text{C}$ ), compared with warmer fluids ( $35^{\circ}\text{C}$ ). This might suggest differences in blood volume and cardiovascular strain between conditions in the current study as a result of the different drink temperatures. Moreover, a faster gastric emptying rate could lead to a greater availability of carbohydrate, which paradoxically has been shown to increase endurance performance in the heat (Carter, et al., 2003). However, more recent studies have shown no differences in gastric emptying rates between drinks of different temperatures ranging from  $4$  to  $58^{\circ}\text{C}$  (Lambert & Maughan, 1992;

McArthur & Feldman, 1989). As gastric emptying rates are only slowed until drink temperature becomes neutral, and considering the total length of time for emptying, the minor difference in temperature between drinks in the present investigation ( $\sim 5^{\circ}\text{C}$ ) would be physiologically insignificant (Brouns, 1998). Consequently, the improvements in exercise performance observed following ice slurry ingestion can be attributed to the reduction in  $T_c$  that it elicited, rather than changes in blood volume or carbohydrate availability.

Due to the temperature ( $-1^{\circ}\text{C}$ ) of the ice slurry mixture, we investigated the effects of ingestion on bronchial constriction. Ice slurry ingestion caused a significantly greater reduction in FVC compared with cold water ingestion ( $0.21 \pm 0.14$  vs.  $0.07 \pm 0.18$  L); however, it is unlikely that such a small reduction would have had any influence on exercise performance at the relatively low intensity selected ( $VT_1$ ).

Currently, many of the extensively researched precooling manoeuvres, while shown to be effective in a laboratory setting, are somewhat impractical for use in major sporting competitions. Cold water immersion can be uncomfortable for the athlete, and can take up to 30-60 min to gain a physiologically significant reduction in  $T_c$  (Quod, et al., 2006). Furthermore, access to large amounts of water, as well as electricity to maintain desired water temperature, may be an issue in the field. Although considered somewhat more practical, anecdotal evidence suggests that ice vests/jackets are heavy and uncomfortable, and it is also a concern to some coaches and practitioners that wearing such garments during a warm up may adversely affect sport specific mechanics. Moreover, Quod et al. (2008) showed that wearing an ice jacket for 40 min prior to exercise did not significantly lower  $T_{re}$  or improve cycling time trial performance in the heat. Ice slurry ingestion provides a practical

precooling manoeuvre that can easily be employed in a field setting. What's more, in addition to its cooling benefits, ice slurry consumption can also be used to hydrate athletes before competition.

In conclusion, the present study has shown that ice slurry ingestion prior to exercise in the heat was able to significantly reduce pre-exercise  $T_{re}$  and prolong run time to exhaustion at  $VT_1$  running speed compared with cold water ingestion. Additionally, ice slurry ingestion resulted in a higher  $T_{re}$  at the point of exercise termination. Ice slurry ingestion may serve as a practical precooling manoeuvre for improving endurance exercise performance in the heat compared with some of the more traditionally proven strategies, such as using ice jackets or cold water immersion baths.

# **CHAPTER 4**

## **Study 2:**

**Precooling with ice slurry ingestion leads to similar  
run times to exhaustion in the heat as cold water  
immersion**

## 4.1 ABSTRACT

The purpose of this study was to compare the effects of pre-exercise ice slurry ingestion versus cold water immersion on submaximal running time in the heat. On three separate occasions, eight males ran to exhaustion at their first ventilatory threshold in the heat ( $34.0 \pm 0.1^{\circ}\text{C}$ ,  $53.9 \pm 2.5\%$  RH) following one of three 30 min manoeuvres conducted prior to exercise: 1) ice slurry ingestion (ICE;  $-1^{\circ}\text{C}$ ); 2) cold water immersion (CWI;  $24.1 \pm 0.9^{\circ}\text{C}$ ); or 3) warm fluid ingestion (CON;  $37^{\circ}\text{C}$ ). Running time was longer following CWI ( $56.8 \pm 5.6$  min;  $P = 0.008$ ) and ICE ( $52.7 \pm 8.4$  min;  $P = 0.005$ ) compared with CON ( $46.7 \pm 7.2$  min), but not significantly different between CWI and ICE ( $P = 0.335$ ). During exercise, rectal temperature was lower with CWI from 15 and 20 min into exercise compared with CON and ICE, respectively, and remained lower until 40 min ( $P = 0.001$ ). At exhaustion rectal temperature was significantly higher with ICE ( $39.76 \pm 0.36^{\circ}\text{C}$ ) compared with CON ( $39.48 \pm 0.36^{\circ}\text{C}$ ;  $P = 0.042$ ) and tended to be higher than CWI ( $39.48 \pm 0.34^{\circ}\text{C}$ ;  $P = 0.065$ ). Mean skin temperature, heart rate and sweating rate were significantly lower during exercise following CWI compared with ICE and CON ( $P < 0.05$ ), however, were similar between ICE and CON ( $P > 0.05$ ). During exercise, ratings of thermal sensation and perceived exertion were lower with CWI and ICE compared with CON ( $P < 0.05$ ), but were not different between cooling trials ( $P > 0.05$ ). As run times were similar between conditions, ICE may be a comparable form of precooling to CWI, despite clear differences in thermoregulatory and perceptual responses.



## 4.2 INTRODUCTION

The rise in  $T_c$  observed during exercise in hot ambient conditions is associated with reduced motor output during self-paced exercise (Marino, et al., 2000; Tucker, et al., 2006), as well as the termination of exercise during time to exhaustion protocols (Cheung & McLellan, 1998; Gonzalez-Alonso, et al., 1999b). The central nervous system is thought to reduce motor output with elevations in  $T_c$  and terminate exercise once critically high internal temperatures are attained, in an attempt to limit the development of catastrophic heat illness (Cheung, 2007).

Pre-exercise cooling is a popular strategy for improving prolonged exercise performance in the heat. This is based on evidence that reducing pre-exercise  $T_c$  allows for greater heat storage capacity during exercise, in turn prolonging the onset of hyperthermia-induced fatigue (Marino, 2002; Quod, et al., 2006). Effective precooling strategies have been achieved via external cooling modalities, such as cold water immersion (Gonzalez-Alonso, et al., 1999b), the wearing of ice jackets (Arngrimsson, et al., 2004) and by combining the two methods (Quod, et al., 2008). For example, Booth, Marino & Ward (1997) showed that 60 min of cold water immersion significantly reduced rectal temperature ( $T_{re}$ ) by  $0.7^{\circ}\text{C}$  and increased the distance covered during 30 min of self-paced treadmill running by  $\sim 300$  m. However, there has recently been a focus on the investigation of internal precooling modalities, due to their practicality for use in the field. For example, Lee, Shirreffs, & Maughan (2008b) showed that the ingestion of cold ( $4^{\circ}\text{C}$ ) versus warm ( $37^{\circ}\text{C}$ ) fluid prior to and during exercise in the heat prolonged cycling time to exhaustion by  $23 \pm 6\%$ . Subsequently, we have shown that the ingestion of an ice slurry mixture ( $-1^{\circ}\text{C}$ ) was able to significantly reduce  $T_{re}$  by  $0.66 \pm 0.14^{\circ}\text{C}$ , which was associated with prolonged run time to exhaustion by  $19 \pm 6\%$  when compared with cold ( $4^{\circ}\text{C}$ )

fluid ingestion (Siegel et al., 2010). The large reduction in  $T_{re}$  observed with ice slurry ingestion was due primarily to the additional energy required to change the physical state of the drink solution from solid ice to liquid water, known as the “enthalpy of fusion.”

An unexpected finding from our previous work (Siegel, et al., 2010) was a significantly higher  $T_{re}$  ( $0.31 \pm 0.11^{\circ}\text{C}$ ) at the point of exhaustion following ice slurry ingestion. This finding does not correspond with numerous studies showing individuals will terminate exercise at a similar  $T_c$  (Cheung, 2007). We speculated that ice ingestion was responsible for the difference in  $T_{re}$  at exhaustion due either to its effect on reducing brain temperature and/or some direct effect on internal thermoreceptors (Siegel, et al., 2010).

The few studies which have investigated internal cooling modalities have mostly compared solutions of different temperatures and/or physical states (Burdon et al., 2010a; Ihsan et al., 2010; Lee, et al., 2008b; Siegel, et al., 2010; Stanley et al., 2010), with limited exploration into the comparison of internal versus external cooling manoeuvres (Hasegawa, et al., 2006; Ross et al., 2011). It is possible that differences in skin temperature ( $\bar{T}_{sk}$ ), and thus body temperature ( $\bar{T}_b$ ) and heat storage, may lead to differences in exercise performance when comparing internal and external precooling manoeuvres. As ice slurry ingestion is an effective, practical precooling strategy for use in the field (Ross, et al., 2011), we wanted to determine its’ success relative to cold water immersion, currently considered the gold standard of cooling techniques (Casa et al., 2007). Moreover, we wanted to confirm the finding from our previous work of a higher  $T_{re}$  at exhaustion following ice slurry ingestion (Siegel, et al., 2010). Therefore, the purpose of the present investigation

was to compare the effects of ice slurry ingestion (ICE) versus cold water immersion (CWI) on thermoregulatory responses and prolonged submaximal exercise performance in the heat.

## **4.3 METHODS**

### **4.3.1 Participants**

Eight healthy non-heat-acclimatised males (age:  $26 \pm 4$  y; height:  $179.9 \pm 6.7$  cm; body mass:  $78.1 \pm 5.9$  kg; body fat %:  $14.8 \pm 3.6\%$ ;  $\text{VO}_{2\text{peak}}$ :  $54.2 \pm 2.5$  ml·kg<sup>-1</sup>·min<sup>-1</sup>) volunteered for this study. Participants were considered moderately active, participating in recreational sport, had no prior history of heat illness and were without injuries. Participants provided written informed consent prior to study commencement. The study procedures were approved by the Edith Cowan University Human Research Ethics Committee.

### **4.3.2 Preliminary measurements**

On their first visit to the laboratory, participants performed a progressive exercise test on a running treadmill (Trackmaster; JAS Fitness Systems, Newton, USA) at room temperature ( $23.5 \pm 1.8^\circ\text{C}$ ,  $42 \pm 10\%$  RH) for the determination of peak aerobic capacity ( $\text{VO}_{2\text{peak}}$ ) and their first ventilatory threshold ( $\text{VT}_1$ ). Prior to the test, the subject's body mass and height were measured to the nearest 10 g and 0.1 cm using a floor scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Skinfold thickness measurements were assessed at 4 sites (triceps, subscapular, biceps and mid iliac crest) in duplicate using skinfold callipers (Model HSK-BI-3; Baty International, West Sussex, UK). Body density was then calculated (Durnin & Womersley, 1974) and body fat per cent estimated using Siri's (1956) equation. For the progressive exercise test, a diagnostic system (TrueOne 2400; ParvoMedics, East Sandy, UT) was used to measure minute ventilation, carbon dioxide production and oxygen uptake. The gas analysers were calibrated using 4.01%  $\text{CO}_2$ –16.00%  $\text{O}_2$ –89.99%  $\text{N}_2$

gas mixture (BOC gases, Surrey, UK), and the volume sensor using a 3 L calibration syringe (Hans Rudolph series 5530, Kansas City MO, USA). The test began with participants running at  $8 \text{ km}\cdot\text{h}^{-1}$  for 4 min on a 0% gradient, with  $2 \text{ km}\cdot\text{h}^{-1}$  increases in treadmill speed every 4 min. Once speed reached  $16 \text{ km}\cdot\text{h}^{-1}$ , gradient remained at 0 for the first 4 min, and then increased by 2% every 4 min thereafter until volitional fatigue. Heart rate was monitored continuously by telemetry using a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland) and rating of perceived exertion (RPE) was recorded every 4 min using the 6-20 point Borg Scale (Borg, 1982).  $\text{VO}_{2\text{peak}}$  was recorded as the highest value obtained in a 30 s period (Millet, et al., 2003).  $\text{VT}_1$  was determined by the increase in the ventilatory equivalent for oxygen uptake ( $\text{VE}\cdot\text{VO}_2^{-1}$ ) with no concomitant increase in the ventilatory equivalent for carbon dioxide production ( $\text{VE}\cdot\text{VCO}_2^{-1}$ ) (Lucia, et al., 2000).

#### **4.3.3 Experimental Design**

Throughout the study, participants were asked to keep stable their normal lifestyle activities, including physical activity and nutritional habits. On the day before each trial, participants were asked to eat at least 6 g of carbohydrate per kg of body weight, and the same pre-trial meal on the day of the experimental trials (providing at least  $1 \text{ g carbohydrate}\cdot\text{kg}^{-1}$ ). In order to ensure participants adhered to these guidelines, they were provided with a comprehensive list of common foods and drinks with their approximate carbohydrate content. Participants were also asked to consume at least 2 liters of fluid on this day, with 400 ml of fluid also ingested with the meal consumed just before the experimental trials. In the 24 h period prior to the trials, participants were asked to avoid strenuous exercise, as well as the consumption of alcohol, caffeine, non-steroidal anti-inflammatory drugs or nutritional supplements. Before the experimental trials were completed, participants

performed a familiarisation trial, involving running to exhaustion at the subject's previously determined  $VT_1$  running speed in the same hot environment as the experimental trials. Within 4-14 days following this trial, participants completed the first of three experimental trials on a treadmill, running to exhaustion at their  $VT_1$  running speed after one of three 30 min pre-exercise manoeuvres: 1) ice slurry ingestion ( $-1^{\circ}\text{C}$ ; ICE); 2) cold water immersion ( $24^{\circ}\text{C}$ ; CWI); or 3) warm fluid ingestion ( $37^{\circ}\text{C}$ ; CON). We chose  $24^{\circ}\text{C}$  for CWI as pilot testing suggested this temperature would result in a similar reduction in  $T_{re}$  between cooling trials once the afterdrop from CWI was taken into account. Participants completed their assigned conditions in a randomised order, at the same time of day, separated by 4-21 days.

#### **4.3.4 Experimental Procedures**

On arrival to the laboratory, a urine sample was collected before nude body mass was recorded. A disposable rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was then self-inserted approximately 120 mm past the anal sphincter. Participants then entered the climate chamber. Four re-usable skin thermistors were affixed using hypoallergenic polyacrylate adhesive tape (Fixomull, Smith and Nephew Ltd., Auckland, New Zealand) at the midpoint of the left gastrocnemius lateral head, rectus femoris, biceps brachii, and pectoralis major. A heart rate monitor was then fixed to the participants' chest before a 30 min rest period to gather baseline data. Participants then performed one of three pre-exercise manoeuvres, within the climate chamber: 1) the ingestion of  $7.5\text{ g}\cdot\text{kg}^{-1}$  of an ice slurry mixture ( $-1^{\circ}\text{C}$ ) with added syrup for flavour (Cottee's Foods, NSW, Australia); 2) cold water immersion at  $24^{\circ}\text{C}$  in a water tank attached to a portable cooling unit (iCool Portacover; iCool, Queensland, Australia) to the level of the mid-sternum; or 3) the ingestion of  $7.5\text{ g}\cdot\text{kg}^{-1}$  of warm fluid ( $37^{\circ}\text{C}$ ) with added

syrup. During CWI, participants consumed  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of warm fluid ( $37^\circ\text{C}$ ) to ensure similar hydration status between trials. All drinks were made with the same flavouring (orange) and consisted of 5% carbohydrate. Ice slurries were made using a slushy machine (Essential Slush Co., QLD, Australia), and participants were given  $1.25 \text{ g}\cdot\text{kg}^{-1}$  of either drink every 5 min to ensure a standardised ingestion rate. During CWI, participants entered the bath at  $24.8 \pm 0.8^\circ\text{C}$  and water temperature was gradually lowered ( $\sim 0.05^\circ\text{C}\cdot\text{min}^{-1}$ ), so that at the completion of cooling it was  $23.4 \pm 0.7^\circ\text{C}$ . Participants then provided another urine sample and commenced running 10 min following the completion of cooling. Following exercise, participants towelled dry and were weighed again for nude body mass prior to the collection of a final urine sample.

#### 4.3.5 Measurements

$T_{\text{re}}$  and  $T_{\text{sk}}$  were recorded continuously at a sampling rate of 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgeshire UK) and reported as 5 min averages.  $T_{\text{sk}}$  was calculated using Ramanathan's (1964) formula:  $T_{\text{sk}} = 0.3 (T_{\text{chest}} + T_{\text{arm}}) + 0.2 (T_{\text{thigh}} + T_{\text{calf}})$ .  $T_{\text{b}}$  was calculated using the formula of Colin et al. (1971):  $T_{\text{b}} = 0.79 (T_{\text{re}}) + 0.21 (T_{\text{sk}})$  at rest; Webb (1993):  $T_{\text{b}} = 0.75 (T_{\text{re}}) + 0.25 (T_{\text{sk}})$  during CWI; and Burton (1935):  $T_{\text{b}} = 0.87 (T_{\text{re}}) + 0.13 (T_{\text{sk}})$  during exercise. Heat storage was calculated at 5 min increments using the formula of Adams et al. (1992): heat storage =  $0.965 \times m \times \Delta T_{\text{b}} / A_{\text{D}}$ , where 0.965 is the specific heat storage capacity of the body ( $\text{W}\cdot\text{kg}^{-1}\cdot^\circ\text{C}$ ),  $m$  is the mean body mass (kg) over the duration of the trial, and  $A_{\text{D}}$  is the body surface area ( $\text{m}^2$ ):  $A_{\text{D}} = 0.202m^{0.425} \times \text{height}^{0.725}$  (Du Bois & Du Bois, 1989).

Heart rate was monitored continuously throughout the trial and reported as 5 min averages. Rating of thermal sensation (9 point scale ranging from unbearably cold [0] to unbearable hot [8] (Young, et al., 1987)) was recorded every 5 min during the pre-exercise and exercise periods, while RPE (Borg, 1982) was recorded every 5 min during exercise.

Urine samples were measured for volume and assessed for urine osmolality using a freezing point depression osmometer (Model 3250; Advanced Instruments Inc., Norwood, MA, USA), and urine specific gravity using a handheld refractometer (No. 503, Nippon Optical Works Co., LTD., Tokyo, Japan). Changes in nude body mass were used to assess fluid loss to the nearest 10 g. For the purpose of this study, 10 g of body mass lost was assumed to equate to 10 ml of fluid lost from sweat. Sweat rate was estimated using the formula:  $\text{sweat rate (L}\cdot\text{h}^{-1}) = \text{Pre-}m \text{ (kg)} + \text{fluid ingested (L)} - \text{urine excreted} - \text{post-}m \text{ (kg)}$ .

Environmental conditions in the climate chamber were monitored continuously using a wet bulb globe temperature heat stress monitor (Microtherm; Casella Measurement Ltd., Bedford, UK). Water temperature was measured continuously with 4 re-usable thermistors and the mean values were used to calculate mean water temperature.

#### **4.3.6 Statistical Analyses**

Data were analysed in two phases; during the pre-exercise, and exercise periods. Differences in time to exhaustion, physiological variables at a single time point, sweat rate, heat storage and hydration status between conditions were analysed using a one-way repeated measures analysis of variance (ANOVA) with Bonferroni adjustment. Mean differences in physiological variables between conditions and over



time were compared using a two-way (condition  $\times$  time) repeated measures ANOVA. When a significant main effect or interaction effect was identified, differences were delineated using a one-way repeated measures analysis of variance with Bonferroni adjustment. For all comparisons, significance was set at  $P < 0.05$ . All data are presented as means  $\pm$  standard deviations, and all analyses were performed using SPSS version 17.0 (SPSS Inc., Chicago, USA). Differences in run time to exhaustion were also analysed using a magnitude-based inference approach used to indicate the likely benefit of each manoeuvre (Batterham & Hopkins, 2006; Hopkins et al., 2009).

## 4.4 RESULTS

### 4.4.1 Environmental conditions and pre-exercise hydration status

Mean ambient temperature ( $34.0 \pm 0.1$  vs.  $34.1 \pm 0.1$  vs.  $34.0 \pm 0.1^\circ\text{C}$ ;  $P = 0.193$ ) and relative humidity ( $51.9 \pm 2.8$  vs.  $52.1 \pm 2.5$  vs.  $51.8 \pm 3.0\%$  RH;  $P = 0.966$ ) were similar between trials. Participants were considered similarly euhydrated before each trial, as demonstrated by equivalent measures of pre-exercise body mass ( $77.47 \pm 6.48$  vs.  $77.33 \pm 6.66$  vs.  $77.88 \pm 6.43$  kg;  $P = 0.322$ ), urine specific gravity ( $1.010 \pm 0.005$  vs.  $1.013 \pm 0.008$  vs.  $1.011 \pm 0.009$ ;  $P = 0.727$ ) and urine osmolality ( $378 \pm 185$  vs.  $429 \pm 297$  vs.  $399 \pm 313$  mOsm $\cdot\text{kg}^{-1}$ ;  $P = 0.834$ ). During the treatment period, 6 of 8 participants experienced sphenopalatine ganglioneuralgia (brain freeze) with ice slurry ingestion, whereas none experienced this with warm fluid ingestion. No participants reported any gastrointestinal discomfort during/following ice slurry ingestion.

### 4.4.2 Running times to exhaustion

There was no trial order effect for running time to exhaustion ( $P = 0.671$ ). Participants ran significantly longer following both CWI ( $56.8 \pm 5.6$  min;  $P = 0.008$ ) and ICE ( $52.7 \pm 8.4$  min;  $P = 0.005$ ) compared with CON ( $46.7 \pm 7.2$  min); however, the ~4 min run time difference between ICE and CWI was not statistically different ( $P = 0.355$ ). The likely effect of CWI versus CON ranged from a “moderate to large benefit” (22%, 90% CI 10, 37%), and the likely benefit of ICE compared with CON was “trivial to large” (13%, 90% CI -1, 29%). The effect of CWI compared with ICE was “unclear” (9%, 90% CI: -3, 22%).

#### 4.4.3 Rectal temperature ( $T_{re}$ )

At rest  $T_{re}$  was similar between conditions ( $P = 0.204$ ; Figure 4.1A). ICE reduced  $T_{re}$  by  $0.43 \pm 0.14^{\circ}\text{C}$  ( $P = 0.001$ ) immediately prior to the commencement of exercise, whereas CWI ( $P = 0.060$ ) and CON ( $P = 0.588$ ) showed no significant change from resting values. During the treatment period,  $T_{re}$  tended to be higher with CWI compared with CON ( $P = 0.053$ ). Following ICE,  $T_{re}$  was significantly lower compared with CWI after 15 min of cooling until immediately prior to running ( $P = 0.012$ ) and was similar between these conditions for the first 15 min of exercise ( $P = 0.129$ ). In CWI,  $T_{re}$  began to drop shortly following immersion, reaching its lowest point after 5 min of running;  $0.25 \pm 0.20^{\circ}\text{C}$  lower than resting levels ( $P = 0.009$ ). From 20 to 40 min of exercise,  $T_{re}$  was lower in CWI compared with ICE ( $0.51 \pm 0.21^{\circ}\text{C}$  lower at 40 min;  $P = 0.001$ ). Compared with CON,  $T_{re}$  was significantly lower with ICE from 25 min of the treatment period until 5 min of exercise ( $0.41 \pm 0.28^{\circ}\text{C}$  lower at 5 min;  $P = 0.017$ ). Following CWI,  $T_{re}$  was lower compared with CON from 15 to 40 min ( $0.50 \pm 0.25^{\circ}\text{C}$  lower at 40 min;  $P = 0.001$ ). During running,  $T_{re}$  increased continuously ( $P = 0.001$ ), however, at different rates between treatments ( $P = 0.001$ ).  $T_{re}$  during exercise rose fastest with ICE ( $0.30 \pm 0.10^{\circ}\text{C} \cdot 5 \text{ min}^{-1}$ ), followed by CON ( $0.24 \pm 0.08^{\circ}\text{C} \cdot 5 \text{ min}^{-1}$ ) and CWI ( $0.19 \pm 0.13^{\circ}\text{C} \cdot 5 \text{ min}^{-1}$ ). Although  $T_{re}$  at exhaustion was similar between CWI and CON trials ( $39.48 \pm 0.34$  vs.  $39.48 \pm 0.36^{\circ}\text{C}$ ;  $P = 1.000$ ), it was significantly higher with ICE ( $39.76 \pm 0.36^{\circ}\text{C}$ ) compared to CON ( $P = 0.042$ ), and tended to be higher compared with CWI ( $P = 0.065$ ).

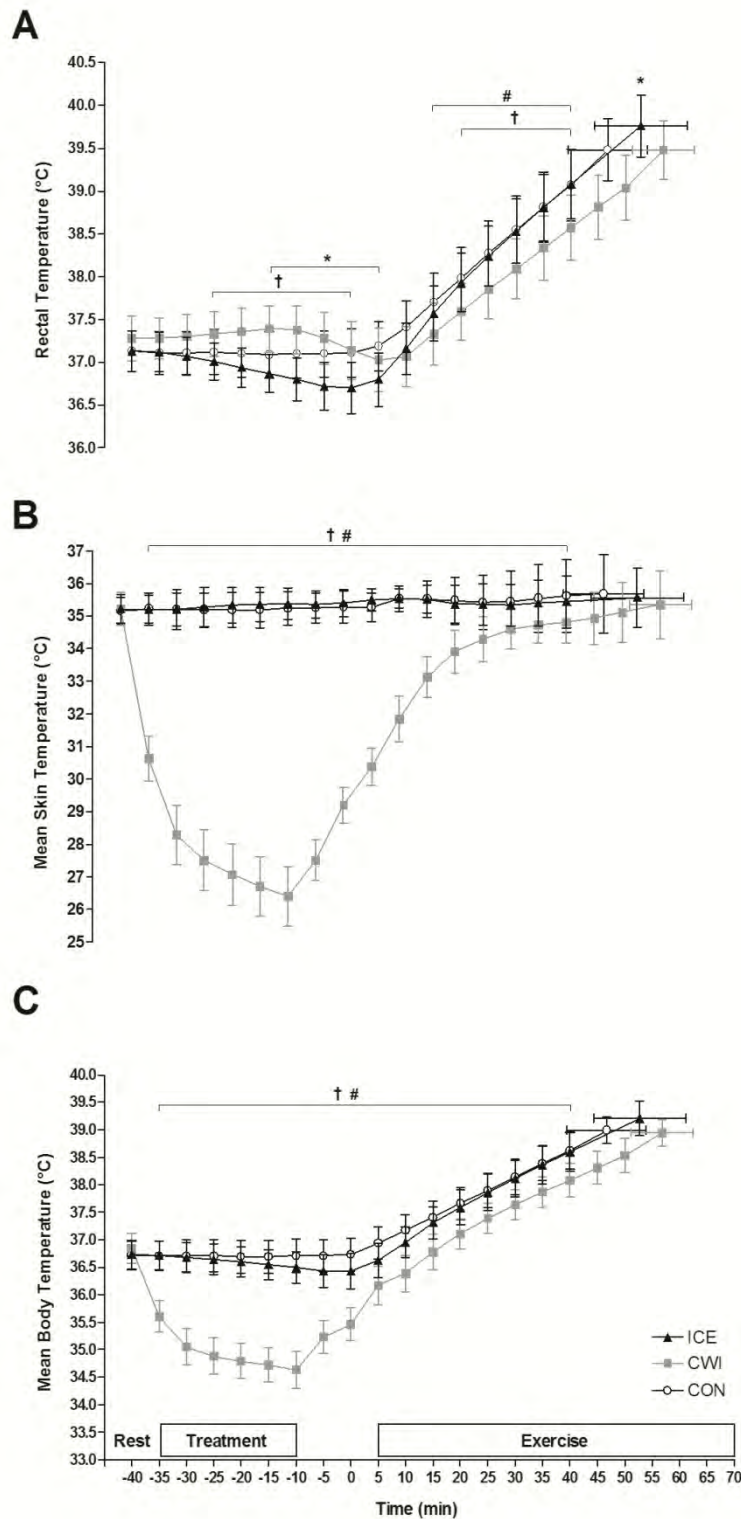
#### 4.4.4 Mean skin temperature ( $T_{sk}$ )

At rest there were no differences in  $T_{sk}$  between conditions ( $P = 0.728$ ; Figure 4.1B). During the pre-exercise period  $T_{sk}$  was not different between ICE and

CON ( $P = 0.453$ ), however, was  $6.03 \pm 0.72^{\circ}\text{C}$  lower than resting values with CWI prior to the commencement of exercise ( $P = 0.001$ ). Consequently,  $T_{\text{sk}}$  remained significantly lower for the first 40 min of exercise following CWI compared with both ICE ( $P = 0.009$ ) and CON ( $P = 0.017$ ) trials.  $T_{\text{sk}}$  remained similar between ICE and CON during exercise ( $P = 0.839$ ). At exhaustion, there were no differences in  $T_{\text{sk}}$  between conditions ( $P = 0.345$ ).

#### **4.4.5 Mean body temperature ( $T_b$ ) and heat storage**

No significant differences in  $T_b$  were observed between conditions at rest ( $P = 0.155$ ; Figure 4.1C).  $T_b$  was lower with CWI from 5 min into the treatment period, and remained lower until 40 min of exercise, compared with both ICE ( $P = 0.001$ ) and CON ( $P = 0.002$ ). In the pre-exercise period,  $T_b$  remained relatively unchanged with CON ( $P = 0.674$ ), and was not significantly different to ICE during the treatment ( $P = 0.121$ ), or exercise periods ( $P = 0.286$ ).  $T_b$  increased continuously during exercise ( $P = 0.001$ ), and at exhaustion was similar between conditions ( $P = 0.101$ ). During the treatment period, heat storage in CWI ( $-80.52 \pm 12.40 \text{ W}\cdot\text{m}^{-2}$ ) was lower than ICE ( $-11.94 \pm 4.70 \text{ W}\cdot\text{m}^{-2}$ ;  $P = 0.001$ ) and CON ( $+0.14 \pm 2.34 \text{ W}\cdot\text{m}^{-2}$ ;  $P = 0.001$ ). Similarly, ICE resulted in less heat storage than CON ( $P = 0.001$ ). During exercise, participants stored significantly more heat in CWI ( $103.74 \pm 15.37 \text{ W}\cdot\text{m}^{-2}$ ;  $P = 0.004$ ) and ICE ( $99.97 \pm 10.73 \text{ W}\cdot\text{m}^{-2}$ ;  $P = 0.001$ ) compared with CON ( $73.55 \pm 7.49 \text{ W}\cdot\text{m}^{-2}$ ). However, heat storage was not different between ICE and CWI ( $P = 0.478$ ). Mean rate of heat storage was higher in ICE ( $10.22 \pm 0.98 \text{ W}\cdot\text{m}^{-2}\cdot 5 \text{ min}^{-1}$ ) compared with CWI ( $9.38 \pm 0.86 \text{ W}\cdot\text{m}^{-2}\cdot 5 \text{ min}^{-1}$ ;  $P = 0.032$ ) and CON ( $8.84 \pm 1.09 \text{ W}\cdot\text{m}^{-2}\cdot 5 \text{ min}^{-1}$ ;  $P = 0.002$ ), but not different between CWI and CON ( $P = 0.223$ ).



**Figure 4.1** – Rectal temperature ( $T_{re}$ ; A), mean skin temperature ( $T_{sk}$ ; B) and mean body temperature ( $T_b$ ; C) during the experimental conditions (means  $\pm$  SD). (\*) ICE significantly different from CON, (†) ICE significantly different from CWI, (#) CWI significantly different from CON ( $P < 0.05$ ).

#### **4.4.6 Heart rate**

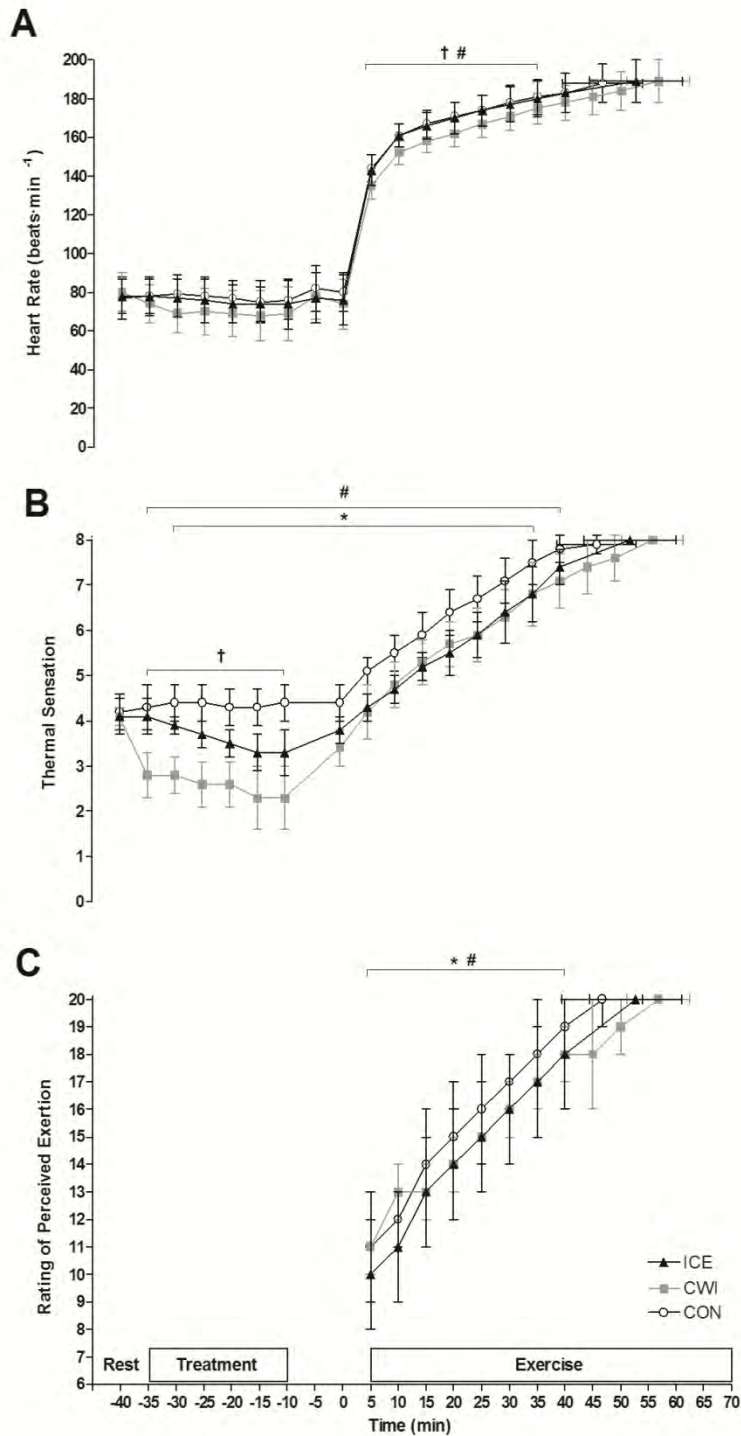
Heart rate did not differ significantly between conditions prior to the treatment period ( $P = 0.264$ ; Figure 4.2A). During the treatment period, heart rate decreased ( $P = 0.001$ ), but was unaffected by treatment type ( $P = 0.115$ ). During exercise, heart rate increased continuously ( $P = 0.001$ ), and remained lower with CWI for the first 35 min compared with ICE ( $P = 0.018$ ) and CON ( $P = 0.045$ ). Conversely, no differences were observed between ICE and CON ( $P = 0.488$ ). At exhaustion heart rate was similar between all conditions ( $P = 0.682$ ).

#### **4.4.7 Sweat rate**

Sweat rate during exercise was lower in CWI ( $1.84 \pm 0.51 \text{ L}\cdot\text{h}^{-1}$ ) compared with both ICE ( $2.06 \pm 0.49 \text{ L}\cdot\text{h}^{-1}$ ;  $P = 0.019$ ) and CON ( $2.28 \pm 0.61 \text{ L}\cdot\text{h}^{-1}$ ;  $P = 0.010$ ). Additionally, sweat rate tended to be lower in ICE compared with CON ( $P = 0.056$ ).

#### **4.4.8 Ratings of thermal sensation and perceived exertion**

Prior to each treatment, ratings of thermal sensation were similar between trials ( $P = 0.863$ ; Figure 4.2B). Following CWI, thermal sensation was lower than CON from 5 min of the treatment until 40 min of exercise ( $P = 0.034$ ). Mean thermal sensation was also lower in CWI compared with ICE during the treatment period ( $P = 0.001$ ). However, once exercise commenced, no differences were observed between CWI and ICE ( $P = 0.750$ ). Compared with CON, thermal sensation was lower in ICE from 10 min cooling until 35 min of exercise ( $P = 0.002$ ). Mean RPE (Figure 4.2C) was lower in both ICE ( $P = 0.035$ ) and CWI ( $P = 0.022$ ) compared with CON, however, no differences were observed between ICE and CWI ( $P = 0.278$ ). At exhaustion, thermal sensation ( $P = 0.133$ ) and RPE ( $P = 0.101$ ) were similar between trials.



**Figure 4.2** – Heart rate (A), ratings of thermal sensation (B) and perceived exertion (C) during the experimental conditions (mean  $\pm$  SD). (\*) ICE significantly different from CON, (†) ICE significantly different from CWI, (#) CWI significantly different from CON ( $P < 0.05$ ).

## 4.5 DISCUSSION

The present study has shown that similar improvements in submaximal running performance in the heat were achieved when precooling with a 30 min cold water immersion ( $\sim 24^{\circ}\text{C}$ ) and ingesting  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry ( $-1^{\circ}\text{C}$ ), compared with a control condition of warm fluid ( $37^{\circ}\text{C}$ ) ingestion. The second important finding was that participants terminated exercise at a higher  $T_{\text{re}}$  following ice slurry ingestion.

The effectiveness of precooling for improving prolonged exercise performance in hot environments is well established (Marino, 2002; Quod, et al., 2006). The principal mechanism thought to elicit these improvements is the creation of a significantly larger heat sink allowing for greater heat storage during exercise, thus delaying or prolonging the attainment of critically high internal temperatures. This was evident in the current study, whereby precooling created a larger heat sink prior to exercise, in turn allowing for greater heat storage whilst running. Consequently, both forms of precooling prolonged run time to exhaustion compared with the control condition. Although participants ran for  $\sim 4$  min longer when precooled with cold water immersion compared with ice slurry ingestion, this difference was not statistically significant. Furthermore, the likely effects of cold water immersion versus ice slurry ingestion using magnitude-based inferences were “unclear”, further suggesting the two methods result in similar benefits. A possible reason for this comparison not reaching statistical significance may be that 2 of 8 participants ran for longer in the ice slurry condition compared with the cold water immersion trial. It is also possible that similar run times between ice slurry and cold water immersion treatments could be explained by the fact that heat stored during exercise was not different between conditions. As precooling is thought to enhance performance by creating a larger heat sink, allowing an equivalent amount of heat



storage may have resulted in similar run times to exhaustion. Comparable run times between the two precooling treatments suggests that ice slurry ingestion may be a more preferred strategy for lowering pre-exercise  $T_{c}$ , due to the logistical demands associated with cold water immersion. Additionally, the discomfort which accompanies cold water immersion, as well as the peripheral vasoconstriction, which may impair muscle function and exercise performance in some situations (Peiffer et al., 2009), can be avoided.

Few other studies have investigated the influence of ice ingestion on thermoregulatory responses and exercise performance in the heat. Ihsan et al. (2010) determined that pre-exercise ingestion of  $6.8 \text{ g}\cdot\text{kg}^{-1}$  of crushed ice reduced gastrointestinal temperature by  $1.1 \pm 0.59^{\circ}\text{C}$  and was associated with a 6.5% improvement in 40 km cycling time trial performance compared with tap water ( $26.8 \pm 1.3^{\circ}\text{C}$ ) ingestion. The large reduction in  $T_{c}$  witnessed may reflect the influence of ice consumption on the temperature of ingestible  $T_{c}$  measurement pills (Wilkinson et al., 2008). Ross et al. (2011) showed that a combined cooling procedure of ingesting  $14 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry plus ice towel treatment was associated with faster (1.3%) 46-km cycling time trial performance in the heat ( $32\text{-}35^{\circ}\text{C}$ , 50-60% RH) than the control condition of no cooling. Conversely, the effect of precooling with 10 min of cold water immersion followed by 20 min of wearing an ice jacket was deemed to be “unclear”.

Not all studies, however, have shown enhanced performance following ice slurry ingestion. Both Stanley et al. (2010) and Burdon et al. (2010a) found no improvements in exercise performance following ice slurry ingestion. Stanely et al. (2010) investigated whether ingesting 1 L of ice slurry ( $-0.8 \pm 0.1^{\circ}\text{C}$ ) following 75 min of cycling at  $58 \pm 6\%$  of peak power output would enhance performance during

a subsequent ~30 min performance trial in the heat ( $33.7 \pm 0.8^{\circ}\text{C}$ ,  $60.3 \pm 2.0\%$  RH), compared with the ingestion of cool liquid ( $18.4 \pm 0.5^{\circ}\text{C}$ ). Despite ice slurry ingestion lowering  $T_{\text{re}}$   $0.4^{\circ}\text{C}$  more than the cold fluid, performance was similar between trials. The authors suggested that the lowered core-skin temperature gradient following ice slurry ingestion lead to the faster rate of rise in  $T_{\text{re}}$  observed during exercise, possibly explaining the lack of differences in performance between conditions. Burdon et al. (2010a) examined whether ingesting 30 ml of ice slurry every 5 min during 90 min of cycling at 65%  $\text{VO}_{2\text{peak}}$  in the heat ( $28^{\circ}\text{C}$ , 70% RH), without reducing in  $T_{\text{c}}$ , was able to improve performance during the subsequent 15 min performance test. As performance was not enhanced following ice slurry ingestion, the authors suggested that a sensory response did not occur. In light of these results, further research surrounding the volume and timing of ice slurry ingestion is needed in order understand how to optimise its' success.

In the present investigation, ice slurry ingestion reduced  $T_{\text{re}}$  by  $0.43 \pm 0.14^{\circ}\text{C}$ . This is a smaller reduction than shown in our previous work (Siegel, et al., 2010), where a  $0.66 \pm 0.14^{\circ}\text{C}$  reduction was observed. In our previous work, participants ingested ice slurries in conditions close to thermal neutrality ( $\sim 24.5^{\circ}\text{C}$ ). It was, therefore, assumed that individuals were thermoneutral and any temperature changes observed were due to the ingestion of either solution. In the current study, ingestion occurred within the climate chamber ( $34.0 \pm 0.1^{\circ}\text{C}$ ). With the thermal gradient being different (hot environment), the rate of heat exchange would also be different, potentially leading to a smaller reduction in  $T_{\text{re}}$  with ice slurry ingestion as a result of greater heat absorption from the environment. As drinking ice slurries in a warm environment may have somewhat blunted the cooling effect, ingestion in a cooler environment, such as in a change room, may be advantageous for optimising

the success of using ice slurries as a precooling agent. In the absence of such an option, drinking larger volumes of ice slurries may be required.

Differences in the rate of rise in  $T_{re}$  between conditions may have influenced the time it took to attain critically high internal temperatures, and in turn, the end point of exercise. The rate of rise in  $T_{re}$  was significantly higher following ice slurry ingestion compared with the cold water immersion and control conditions for the first 20 min of exercise. This may be a result of ice slurry ingestion altering the temperature gradient between the body core and skin. Ice slurry ingestion reduced  $T_{re}$  without a concurrent reduction in  $T_{sk}$ , thus resulting in a lowered core-to-skin temperature gradient. This may have resulted in a decreased ability to transfer heat to the environment, leading to a faster rise in  $T_{re}$  during exercise. Indeed, the rate of rise in  $T_{re}$  tended to be higher following ice slurry compared with cold fluid ingestion in our previous work (Siegel, et al., 2010), and was shown to be significantly higher by Stanley et al. (2010) following ice slurry ingestion. In the present investigation, compared with the ice slurry trial, the core-to-skin temperature gradient remained either relatively unchanged (CON) or was increased considerably (CWI). The rate of rise in  $T_{re}$  was also slower in the cold water immersion compared with the control trial. In addition to the vast differences in the core-to-skin temperature gradient between these conditions, it is also possible that commencing exercise with a significantly lower  $T_{sk}$  allowed heat to be stored in the periphery as well as the core, slowing the rise in  $T_{re}$  following cold water immersion (Kay, et al., 1999).

It has been consistently shown that individuals terminate exercise in the heat at similar  $T_c$ . This is true in both trained (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993) and untrained (Cheung & McLellan, 1998; Hasegawa, et al., 2006; Lee, et al., 2008b) populations, as well as when a precooling manoeuvre has been performed

(Gonzalez-Alonso, et al., 1999b; Hasegawa, et al., 2006; Lee, et al., 2008b). This was not the case in the present investigation. Although  $T_{re}$  was similar at exhaustion between cold water immersion and control conditions, it was  $0.28^{\circ}\text{C}$  higher following ice slurry ingestion. These results concur with our previous work showing significantly higher  $T_{re}$  at the point of exhaustion after pre-exercise ice slurry compared with cold water ingestion (Siegel, et al., 2010). This finding lead us to suggest that ice ingestion may have lowered brain temperature more so than  $T_{re}$ . Rectal temperature was in turn higher at exhaustion as the critical temperature may instead originate in the brain more so than the core (Caputa, et al., 1986; Carithers & Seagrave, 1976).

The means by which ice slurry ingestion may cause a physiologically meaningful reduction in brain temperature is not clear, however, several possibilities exist. Due to the close proximity of the esophagus to the carotid arteries, ice slurry ingestion may have resulted in the cooling of blood flowing to the brain. Additionally, as ice slurries were ingested through the mouth, it is possible that consumption resulted in conductive cooling of the facial skin and blood. While it has been suggested that cool facial blood returning to the brain is a means by which brain temperature may be lowered with face cooling (Cabanac & Caputa, 1979), recent evidence suggests that this is unlikely (Nybo, et al., 2002b). Although increased  $T_c$  capacity following ice slurry ingestion in the current study was associated with improved performance via extending running time to exhaustion compared to no cooling intervention, it is possible that this effect may be dangerous to the athlete when exercising under conditions of high heat strain. Comparable run times were observed between precooling trials in the absence of an elevated  $T_{re}$  at

exhaustion with cold water immersion. This is likely due to the slower rate of rise in  $T_{re}$  observed during this condition.

While lowered brain temperature may be a plausible explanation for the increased  $T_{re}$  tolerated by participants at the point of exhaustion after ice slurry ingestion, alterations to thermoreception could be another potential contributor. It is possible that ice ingestion may have had a direct effect on internal thermoreceptors in the mouth (Hensel, 1981; Pallett & O'Brien, 1985), oesophagus (El Ouazzani & Mei, 1982), and stomach regions (Villanova, et al., 1997), altering afferent feedback pertaining to the thermal state of the body. This may have, in turn, allowed participants to perceive exercise as easier at a given  $T_{re}$ , thus permitting higher  $T_{re}$  at exhaustion. This theory is supported by data from the present study regarding ratings of thermal sensation and perceived exertion. As expected, mean ratings of each measure were significantly lower following both forms of precooling compared with the control trial. While  $T_{re}$ ,  $T_{sk}$  and  $T_b$  were lower with cold water immersion for the majority exercise, no differences were observed in ratings of thermal sensation or perceived exertion between ice slurry ingestion and cold water immersion protocols. Conversely, ratings of thermal sensation and perceived exertion were lower following ice slurry ingestion compared with the control condition, although all thermoregulatory measures were similar for the majority of exercise. Although speculative, it is possible that this anomaly may have been due to the effect that ice ingestion had on stimulating internal thermoreceptors, which potentially conveyed a “false” sense of the body’s thermal state, in turn eliciting the perception of exercise as being easier at a given thermal load. As mentioned, this effect has the potential to be dangerous to hyperthermic athletes, as the masking of true body temperature could lead to the development of heat illness.

Cold water immersion caused a significant reduction in  $T_{sk}$ , so that immediately prior to the commencement of exercise it was  $6.03 \pm 0.72^{\circ}\text{C}$  lower than resting values. Similar to our previous research,  $T_{sk}$  was not changed in either pre-exercise periods during the ice slurry or control trials (Siegel, et al., 2010), and as such, remained significantly lower following cold water immersion trials for the first 40 min of exercise. This considerable reduction in  $T_{sk}$  was the primary cause of the larger heat sink created by the cold water immersion protocol compared with both the ice slurry and control conditions. The reduction in  $T_{sk}$  may also explain the lower sweat rate observed during exercise, as skin blood flow was likely lower following cold water immersion (Johnson, et al., 1984). Moreover, lower  $T_{sk}$  may explain the reduction in heart rate observed with cold water immersion, as less skin perfusion would have likely occurred. The reductions in sweat rate and heart rate in the current study following cold water immersion are consistent with reduced thermoregulatory and cardiovascular strain as a result of successful precooling interventions (Wilson, et al., 2002).

In conclusion, findings from this study suggest that the ingestion of  $7.5 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry ( $-1^{\circ}\text{C}$ ) may be a comparable precooling manoeuvre to 30 min of cold water immersion at  $\sim 24^{\circ}\text{C}$  for prolonging submaximal running time in the heat, despite clear differences in thermoregulatory and perceptual responses. Due to the practicality of ice slurry ingestion, this strategy may be more realistic for use in the field. Additionally, results from the present study confirm previous work from our laboratory demonstrating that ice slurry ingestion increases core temperature capacity at the point of exhaustion.

# **CHAPTER 5**

## **Study 3:**

**The influence of ice slurry ingestion on maximal  
voluntary contraction following exercise-induced  
hyperthermia**

## 5.1 ABSTRACT

The purpose of this study was to determine whether ingestion of a small bolus of ice slurry ( $1.25 \text{ g}\cdot\text{kg}^{-1}$ ) could attenuate the reduction in maximal voluntary isometric contraction (MVC) torque output during a 2-min sustained task following exercise-induced hyperthermia. On two separate occasions, 10 males (age:  $24 \pm 3 \text{ y}$ ,  $\dot{V}\text{O}_{2\text{peak}}$ :  $49.8 \pm 4.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) ran to exhaustion at their first ventilatory threshold in a hot environment ( $34.1 \pm 0.1^\circ\text{C}$ ,  $49.5 \pm 3.6\% \text{ RH}$ ). Prior to and after exercise, subjects performed a 2-min sustained MVC of the right elbow flexors in a thermoneutral environment ( $24.6 \pm 0.8^\circ\text{C}$ ,  $37.2 \pm 4.5\% \text{ RH}$ ). The post exercise MVC was performed immediately following the ingestion of either  $1.25 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry ( $-1^\circ\text{C}$ ; ICE) or warm fluid ( $40^\circ\text{C}$ ; CON), in a counterbalanced and randomised order. Run time to exhaustion ( $42.4 \pm 9.5$  vs.  $41.7 \pm 8.7 \text{ min}$ ;  $P = 0.530$ ), and rectal ( $39.08 \pm 0.30$  vs.  $39.08 \pm 0.30^\circ\text{C}$ ;  $P = 0.934$ ) and skin temperatures ( $35.26 \pm 0.65$  vs.  $35.28 \pm 0.67^\circ\text{C}$ ;  $P = 0.922$ ) and heart rate ( $189 \pm 5$  vs.  $189 \pm 6 \text{ beats}\cdot\text{min}^{-1}$ ;  $P = 0.830$ ) at the end of the run were similar between trials. Torque output during the post-exercise 2-min sustained MVC was significantly higher ( $P = 0.001$ ) following ICE ( $30.75 \pm 16.40 \text{ Nm}$ ) compared with CON ( $28.69 \pm 14.88 \text{ Nm}$ ). These results suggest that ice slurry ingestion attenuated the effects of exercise-induced hyperthermia on MVC, possibly via internal thermoreceptive and/or temperature-related sensory mechanisms.



## 5.2 INTRODUCTION

Fatigue during exercise in the heat is in large part caused by central mechanisms pertaining to the increase in  $T_c$  (Nybo, 2008). This theory is based on evidence that trained subjects exercising in hot environments terminate exercise at a  $T_c$  of  $\sim 40^\circ\text{C}$  regardless of starting temperature, or rate of rise in  $T_c$  (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993). Additionally, several studies have shown the independent effects of  $T_c$  on maximal voluntary force production and voluntary activation using passive heating methods (Morrison, et al., 2004; Thomas, et al., 2006; Todd, et al., 2005). For example, under passive resting conditions, Thomas et al. (2006) observed reductions in maximal voluntary contraction (MVC) and central activation with  $0.5^\circ\text{C}$  incremental increases in  $T_c$  from  $37.2$  to  $39.5^\circ\text{C}$  using a liquid conditioning garment. Once  $T_c$  was lowered back to resting levels, force production and central activation were restored (Thomas, et al., 2006). Moreover, in a study using exercise in the heat to induce hyperthermia, Nybo and Nielsen (2001a) showed that neuromuscular function of both the exercised (legs) as well as non-exercised (arms) muscle groups were impaired during a sustained 2-min MVC following cycling in hot ( $40^\circ\text{C}$ ) compared with a cool environment ( $18^\circ\text{C}$ ). These combined results highlight the independent influence of high body core temperatures on neuromuscular function.

Precooling is a popular strategy for improving exercise performance in the heat, and it has been shown extensively that reducing pre-exercise  $T_c$  can delay the onset of high  $T_c$  and in turn hyperthermia-induced fatigue (Olschewski & Bruck, 1988; Quod, et al., 2006). Although most studies focusing on precooling have used external means of lowering  $T_c$ , such as cold water immersion or ice jackets, several

recent studies have demonstrated that internal means of cooling, such as the ingestion of cold fluids (Lee, et al., 2008b) or an ice slurry mixture (Siegel, et al., 2010), are also extremely effective. The successful use of endogenous cooling procedures have lead to the suggestion that in addition to reducing  $T_c$ , a sensory effect associated with the ingestion of a cold solution may be another mechanism responsible for the improvements in exercise performance witnessed (Burdon et al., 2010b; Siegel, et al., 2010). As well as observing a performance improvement following ice slurry ingestion, we have shown that subjects were able to tolerate higher rectal temperatures ( $T_{re}$ ) at the point of exhaustion with ice slurry compared with cold water ingestion (Siegel, et al., 2010). We hypothesised this may have been due partially to the influence that the cold ice had on internal thermoreceptors and their subsequent adjustment of afferent feedback relating to the thermal state of the body. As such, participants may have perceived exercise to be easier at a given thermal load, thereby permitting a longer exercise time and higher  $T_{re}$  at exhaustion. This finding was confirmed in our subsequent study (Siegel et al., In press), whereby subjects fatigued at a higher  $T_{re}$  following precooling with ice slurry ingestion compared with cold water immersion and a control condition of warm fluid (37°C) ingestion.

Thermoreceptors sense the temperature of blood running through the hypothalamus (Gleeson, 1998) and the skin in humans (Hensel, 1981). The presence of other internal thermoreceptors have been described in several animal studies, shown to be located in the mouth and spinal cord (Hensel, 1981), oesophagus (El Ouazzani & Mei, 1982), abdominal viscera (Cottrell, 1984; Gupta, et al., 1979; Riedel, et al., 1973), abdominal cavity (Rawson & Quick, 1970) and skeletal muscle (Benzinger, 1969). In humans, Villanova et al. (1997) presented evidence of

thermosensitive receptors in the stomach and small intestine. It is therefore possible that when the body is in a hyperthermic state, cold stimulation of internal thermoreceptors in the mouth, throat and stomach regions via ice ingestion may improve neuromuscular function by way of lowering central inhibition of higher brain regions.

In light of our recent findings showing increases in  $T_c$  at exhaustion with ice slurry ingestion, the purpose of the present investigation was to determine whether the ingestion of a small bolus ( $1.25 \text{ g}\cdot\text{kg}^{-1}$ ) of ice slurry ( $-1^\circ\text{C}$ ), without causing a reduction in  $T_c$ , would attenuate the reduction in torque development during a 2-min sustained MVC in a hyperthermic state, compared with ingestion of the same volume of a  $40^\circ\text{C}$  solution.

## **5.3 METHODS**

### **5.3.1 Participants**

Ten healthy males (age:  $24 \pm 3$  y; height:  $179.3 \pm 6.7$  cm; body mass:  $79.5 \pm 13.1$  kg; body fat %:  $15.8 \pm 4.1\%$ ;  $\dot{V}O_{2\text{peak}}$ :  $49.8 \pm 4.7$  ml·kg<sup>-1</sup>·min<sup>-1</sup>) volunteered for this study. Subjects were considered moderately active, participating in recreational sport, had no prior history of heat illness and were without injuries. Subjects provided written informed consent before participating in the study. The study design and procedures were approved by the Edith Cowan University Human Research Ethics Committee.

### **5.3.2 Preliminary measurements**

On their first visit to the laboratory, subjects performed a progressive exercise test on a running treadmill (Trackmaster; JAS Fitness Systems, Newton, USA) at room temperature ( $25.1 \pm 1.3^{\circ}\text{C}$ ,  $37.5 \pm 6.2\%$  RH) for the determination of peak aerobic capacity ( $\dot{V}O_{2\text{peak}}$ ) and their first ventilatory threshold ( $VT_1$ ). Before the test, the subject's body mass and height were measured to the nearest 10 g and 0.1 cm using a floor scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Skinfold thickness measurements were assessed at 4 sites (triceps, subscapular, biceps and mid iliac crest) in duplicate using skinfold callipers (Model HSK-BI-3; Baty International, West Sussex, UK). Body density was then calculated (Durnin & Womersley, 1974) and body fat per cent estimated using Siri's (1956) equation. For the progressive exercise test, a diagnostic system (TrueOne 2400; ParvoMedics, East Sandy, UT) was used to measure minute ventilation, carbon dioxide production and oxygen uptake. The gas analysers were calibrated using 4.01% CO<sub>2</sub>–16.00% O<sub>2</sub>–89.99% N<sub>2</sub>

gas mixture (BOC gases, Surrey, UK), and the volume sensor using a 3 L calibration syringe (Hans Rudolph series 5530, Kansas City MO, USA). The test began with subjects running at  $8 \text{ km}\cdot\text{h}^{-1}$  for 4 min on a zero percent gradient, with  $2 \text{ km}\cdot\text{h}^{-1}$  increases in treadmill speed occurring every 4 min. Once speed reached  $16 \text{ km}\cdot\text{h}^{-1}$ , gradient remained at zero for the first 4 min, and then increased by 2% every 4 min thereafter until volitional fatigue. Heart rate was monitored continuously by telemetry using a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland) and rating of perceived exertion (RPE) was recorded every 4 min using the 6-20 point Borg Scale (Borg, 1982).  $\dot{V}\text{O}_{2\text{peak}}$  was recorded as the highest value obtained in a 30 s period (Millet, et al., 2003).  $\text{VT}_1$  was determined by the increase in the ventilatory equivalent for oxygen uptake ( $\dot{V}\text{E}\cdot\dot{V}\text{O}_2^{-1}$ ) with no concomitant increase in the ventilatory equivalent for carbon dioxide production ( $\dot{V}\text{E}\cdot\dot{V}\text{CO}_2^{-1}$ ) (Lucia, et al., 2000).

### 5.3.3 Study Design

Throughout the study, subjects were asked to maintain their normal lifestyle, including physical activity and nutritional habits. Food diaries were analysed to ensure a similar diet was consumed in the 24-h period prior to each trial. Subjects were asked to avoid strenuous exercise, as well as the consumption of alcohol, caffeine, non-steroidal anti-inflammatory drugs or nutritional supplements in the 24-h period prior to the trials. During the experimental trials, subjects ran to exhaustion at their  $\text{VT}_1$  running speed on a treadmill in a hot environment ( $34.1 \pm 0.1^\circ\text{C}$ ,  $49.5 \pm 3.6\%$  RH). Prior to, and within  $\sim 5$  min following exercise, a 2-min sustained isometric MVC of the right elbow flexors was performed at room temperature ( $24.6 \pm 0.8^\circ\text{C}$ ,  $37.2 \pm 4.5\%$  RH) to assess neuromuscular function. Post exercise, the 2-min MVC was completed immediately after the ingestion of either  $1.25 \text{ g}\cdot\text{kg}^{-1}$  of ice

slurry (-1°C; ICE), or warm fluid (40°C; CON). A sustained 2-min MVC was utilised as it has been previously shown that this length of contraction is able to detect changes in neuromuscular function with hyperthermia (Nybo & Nielsen, 2001a), whereas shorter contractions are not (Nybo & Nielsen, 2001a; Saboisky et al., 2003). The elbow flexors were selected as opposed to the knee extensors to minimise the effects of fatigue from running on the MVC. The volume of solution ingested was chosen based on pilot testing which suggested that 1.25 g·kg<sup>-1</sup> of ingested ice would not result in a  $T_{re}$  reduction compared to warm fluid ingestion. The control solution (40°C) was chosen as it was assumed participants would reach volitional exhaustion between ~39-40°C and thus this temperature would not cause a cooling effect. All drinks were made with the same flavouring (orange) and consisted of 5% carbohydrate. Ice slurries were made using a slushy machine (Essential Slush Co., QLD, Australia). Subjects performed their assigned conditions in a counterbalanced and random order, at the same time of day, separated by 4-14 days. For each trial, the subjects wore the same exercise clothing. Prior to the experimental sessions (3-14 days), subjects underwent a familiarisation trial, identical to that of the ICE condition, to familiarise themselves with the exercise and testing procedures. Subjects also completed familiarisation of the MVC protocol prior to and after completion of their progressive exercise test. Environmental conditions were monitored continuously using a wet bulb globe temperature heat stress monitor (Microtherm; Casella Measurement Ltd., Bedford, UK).

On arrival to the laboratory, urine samples were collected before nude body mass was recorded. A disposable rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was then self-inserted ~12 cm past the external anal sphincter. Re-usable skin thermistors were affixed using

hypoallergenic polyacrylate adhesive tape (Fixomull, Smith and Nephew Ltd., Auckland, New Zealand) at the midpoint of the left gastrocnemius lateral head, rectus femoris, biceps brachii, and pectoralis major. A heart rate monitor was then fixed to the subjects' chest before a 15-min rest period to gather baseline resting data. Following this rest period, subjects performed a 2-min sustained MVC, and then commenced running to exhaustion at their  $VT_1$  running speed. Approximately 5 min following exhaustion, and after drink ingestion (drinks took ~1 min to consume) and measurement of thermal sensation (Young, et al., 1987), subjects completed another 2-min sustained MVC.

#### **5.3.4 Maximal voluntary contraction torque**

Subjects were secured to a preacher arm curl bench with shoulder angle at  $45^\circ$ , and MVC of the right elbow flexors was measured at an elbow joint angle of  $90^\circ$ , using an isokinetic dynamometer (Cybex 6000, Lumex Inc. Ronkonkoma, USA) with HUMAC2004 software (Computer Sports Medicine, Inc., MA, USA). A 2-min sustained MVC was assessed immediately before the run, and approximately 5 min after voluntary exhaustion (post drink ingestion), at room temperature. Torque signals were collected at a sampling rate of 200 Hz (PowerLab16, ADInstruments, Bella Vista, Australia) and 5 s averages were calculated. Throughout the 2-min contraction, visual feedback of the MVC and verbal encouragement were given to the subject.

#### **5.3.5 Thermoregulatory, heart rate and hydration measurements**

Throughout the experimental protocol,  $T_{re}$  and  $T_{sk}$  were recorded continuously at a sampling rate of 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgeshire UK). Mean  $T_{sk}$  was calculated using Ramanathan's (1964)

formula:  $T_{sk} = 0.3 (T_{chest} + T_{arm}) + 0.2 (T_{thigh} + T_{calf})$ . Mean body temperature ( $T_b$ ) was calculated using the formula of Burton (1935):  $T_b = 0.87 (T_{re}) + 0.13 (T_{sk})$ . Heart rate was monitored continuously during exercise at a sampling rate of 5 s. Urine samples were assessed for urine osmolality using a freezing point depression osmometer (Model 3250; Advanced Instruments Inc., Norwood, MA, USA) and urine specific gravity using a hand held refractometer (No. 503, Nippon Optical Works Co., LTD., Tokyo, Japan).

### 5.3.6 Statistical Analyses

Paired Students *t*-tests were used to detect differences between conditions for pre-exercise measures of hydration status, environmental conditions, run times to exhaustion, and post exercise  $T_{re}$ ,  $T_{sk}$ ,  $T_b$  and heart rate. Two-way (condition  $\times$  time) repeated-measures analyses of variance (ANOVA) were performed to compare the changes in MVC prior to versus post running, as well as over 2 min between conditions. When the ANOVA showed a significant interaction effect, differences between conditions for each time point were identified using paired Student's *t*-tests with Bonferroni adjustment for multiple comparisons. For all analyses, the significance level was set at  $P < 0.05$ . All analyses were performed using SPSS version 17.0 (SPSS Inc., Chicago, USA), and data herein are presented as means  $\pm$  standard deviations.



## **5.4 RESULTS**

### **5.4.1 Environmental conditions and pre-exercise hydration status**

During exercise, there were no significant differences in mean ambient temperature ( $34.1 \pm 0.1$  vs.  $34.0 \pm 0.1^{\circ}\text{C}$ ;  $P = 0.153$ ), and relative humidity ( $50.2 \pm 5.2$  vs.  $48.7 \pm 3.7\%$  RH;  $P = 0.341$ ) between ICE and CON. Similarly, environmental conditions were similar between trials during the MVC tests ( $24.7 \pm 0.8$  vs.  $24.5 \pm 0.8^{\circ}\text{C}$ ;  $P = 0.443$ ;  $37.0 \pm 5.6$  vs.  $37.4 \pm 6.3\%$  RH;  $P = 0.861$ ). Subjects were considered to be in a similar state of hydration before each trial, as demonstrated by equivalent measures of pre-exercise body mass ( $79.50 \pm 13.04$  vs.  $79.82 \pm 13.28$ ;  $P = 0.219$ ), urine specific gravity ( $1.009 \pm 0.008$  vs.  $1.008 \pm 0.007$ ;  $P = 0.669$ ) and urine osmolality ( $313 \pm 269$  vs.  $306 \pm 252$  mOsm $\cdot\text{kg}^{-1}$ ;  $P = 0.866$ ).

### **5.4.2 Running time, thermoregulatory and heart rate responses**

Run times to exhaustion were similar between conditions (Table 5.1). At exhaustion, no differences were observed between conditions for  $T_{\text{re}}$ ,  $T_{\text{sk}}$ ,  $T_{\text{b}}$ , or heart rate (Table 5.1). Similarly,  $T_{\text{re}}$ ,  $T_{\text{sk}}$ ,  $T_{\text{b}}$ , heart rate and rating of thermal sensation were similar between conditions following drink ingestion, as well as after the completion of the post-exercise 2-min MVC (Table 5.2), confirming that ice slurry ingestion did not influence thermoregulatory, heart rate or perceptual responses.

**Table 5.1** – Run time to exhaustion and thermoregulatory and heart rate responses to running in ice slurry (ICE) and control (CON) conditions (mean  $\pm$  SD).

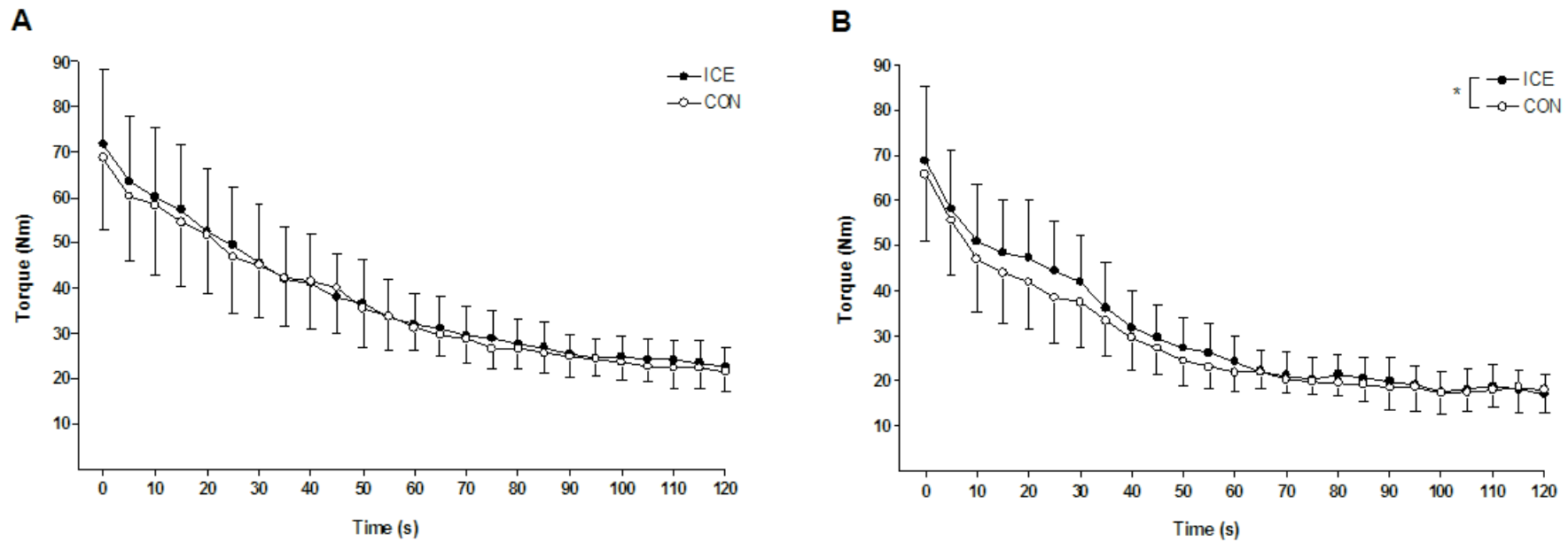
Measure	ICE	CON	<i>P</i> value
Run time to exhaustion (min)	42.4 $\pm$ 9.5	41.7 $\pm$ 8.7	0.530
Rectal temperature at exhaustion ( $^{\circ}$ C)	39.08 $\pm$ 0.30	39.08 $\pm$ 0.30	0.934
Mean skin temperature at exhaustion ( $^{\circ}$ C)	35.26 $\pm$ 0.65	35.28 $\pm$ 0.67	0.922
Mean body temperature at exhaustion ( $^{\circ}$ C)	38.58 $\pm$ 0.30	38.59 $\pm$ 0.29	0.877
Heart rate at exhaustion (beats $\cdot$ min $^{-1}$ )	189 $\pm$ 5	189 $\pm$ 6	0.830

**Table 5.2** – Thermoregulatory, heart rate and perceptual responses to drink ingestion and 2-min sustained MVC task in ice slurry (ICE) and control (CON) conditions (mean  $\pm$  SD).

Measure	ICE	CON	<i>P</i> value
Rectal temperature post drink ingestion ( $^{\circ}\text{C}$ )	39.01 $\pm$ 0.23	39.04 $\pm$ 0.30	0.700
Rectal temperature post 2-min MVC task ( $^{\circ}\text{C}$ )	39.01 $\pm$ 0.27	39.01 $\pm$ 0.32	1.000
Mean skin temperature post drink ingestion ( $^{\circ}\text{C}$ )	35.46 $\pm$ 0.58	35.49 $\pm$ 0.62	0.894
Mean skin temperature post 2-min MVC task ( $^{\circ}\text{C}$ )	35.20 $\pm$ 0.44	35.52 $\pm$ 0.54	0.062
Mean body temperature post drink ingestion ( $^{\circ}\text{C}$ )	38.54 $\pm$ 0.26	38.58 $\pm$ 0.29	0.695
Mean body temperature post 2-min MVC task ( $^{\circ}\text{C}$ )	38.49 $\pm$ 0.24	38.56 $\pm$ 0.21	0.367
Heart rate post drink ingestion (beats $\cdot\text{min}^{-1}$ )	144 $\pm$ 13	145 $\pm$ 11	0.885
Heart rate post 2-min MVC task (beats $\cdot\text{min}^{-1}$ )	164 $\pm$ 14	162 $\pm$ 12	0.578
Thermal sensation post drink ingestion	6.2 $\pm$ 0.7	6.3 $\pm$ 0.7	0.619

### 5.4.3 Maximal voluntary contraction torque

During the pre-exercise 2-min sustained MVC, torque decreased significantly ( $P = 0.001$ ), but no condition ( $P = 0.143$ ) or interaction (condition  $\times$  time;  $P = 0.563$ ) effects were observed for the changes over the 2 min (Figure 5.1A). Following running, mean torque during the MVC decreased significantly in both ICE ( $18 \pm 5\%$ ;  $P = 0.001$ ) and CON ( $21 \pm 3\%$ ;  $P = 0.001$ ) compared with pre-exercise values. A significant interaction effect was observed post running ( $P = 0.001$ ), with torque production being significantly higher in ICE ( $30.75 \pm 16.40$  Nm) compared with CON ( $28.69 \pm 14.88$  Nm; Figure 5.1B). Comparisons between conditions for each individual time point were not significantly different ( $P > 0.05$ ). Main effects for condition ( $P = 0.008$ ) and time ( $P = 0.001$ ) were also observed.



**Figure 5.1** – Changes in maximal voluntary isometric contraction torque of the elbow flexors during 2-min sustained task before (A) and after (B) run to exhaustion, for ice slurry (ICE) and control (CON) conditions (mean  $\pm$  SD). (\*) Significant condition ( $P = 0.008$ ) and interaction ( $P = 0.001$ ) effects.

## 5.5 DISCUSSION

The novel finding of the present study was that the ingestion of a small bolus ( $1.25 \text{ g}\cdot\text{kg}^{-1}$ ) of ice slurry ( $-1^{\circ}\text{C}$ ) was able to attenuate the reduction in maximal voluntary contraction torque of the elbow flexors following exercise-induced hyperthermia, compared with ingesting the same volume of a warm ( $40^{\circ}\text{C}$ ) solution. We propose that the mechanisms responsible for this improvement may be an adjustment in afferent feedback relayed from internal thermoreceptors relating to the thermal state of the body, and/or activation/suppression of brain regions associated with reward, pleasure, motivation or fatigue.

Exercise-induced hyperthermia resulted in a significant reduction in torque output during the 2-min sustained MVC, in both ICE ( $18 \pm 5\%$ ) and CON ( $21 \pm 3\%$ ) trials. This is consistent with research showing that an elevated  $T_c$  is responsible for the reduction in voluntary force development observed under conditions of heat strain (Morrison, et al., 2004; Nybo & Nielsen, 2001a; Saboisky, et al., 2003; Thomas, et al., 2006). The magnitude of reduction in MVC torque observed is greater than that seen following passive heating protocols ( $\sim 2.4\text{-}13\%$ ) (Morrison, et al., 2004; Thomas, et al., 2006; Todd, et al., 2005), and as such, may reflect the additional fatigue from exercise itself on torque production. Moreover, these studies involved mostly brief (2-5 s) contractions. Saboisky et al. (2003) reported a  $\sim 14\%$  decrease in MVC torque following exercise-induced hyperthermia, whereas Nybo and Nielsen (2001a) showed that torque output in the final 60 s of a 2-min contraction was 60% of control values during the hyperthermic trial. The disparities in the magnitude of change in MVC torque may be due to differences in contraction length and/or muscle groups utilised. In the current work, ice slurry ingestion was

able to attenuate this reduction during the post-exercise MVC compared with ingesting warm fluid. These differences, although likely to be physiologically significant, were not large (~7%), and a placebo effect cannot be entirely discounted. However, it should be noted that ratings of thermal sensation were similar between conditions following drink ingestion, suggesting that participants did not perceive a cooling sensation from the small amount of ice slurry ingested. Additionally, although comparisons between conditions for each individual time point were not statistically significant, the effect that ice may have had on internal thermoreceptors appears to have only been apparent in the first minute of the effort (Figure 5.1B). This may have been due to the relatively small amount of ice slurry ingested, or the duration that thermoreceptors were stimulated.

Cooling prior to and during exercise is an effective strategy for improving exercise performance in hot conditions (Marino, 2002; Quod, et al., 2006). The primary mechanism proposed to enable these performance enhancements is the lowered, or attenuated rise in  $T_{c}$ , and associated increase in heat storage. As researchers and practitioners strive towards achieving more practical field-based cooling procedures, the use of endogenous cooling strategies have become popular, such as the ingestion of cold fluids (Lee, et al., 2008b) or ice slurries (Siegel, et al., 2010). The unique findings from these studies, and in particular the higher  $T_{c}$  observed after running to exhaustion in the heat (Siegel, et al., 2010), have lead to the suggestion that a sensory effect associated with ingesting a cold solution may enhance performance via thermoreceptive mechanisms and/or by increasing central drive (Burdon, et al., 2010b; Siegel, et al., 2010). To test this theory, Burdon et al. (2010a) had subjects ingest 30 ml of ice puree every 5 min during 90 min of steady state cycling, but found that it did not improve performance during a subsequent 15-

min performance test in a warm environment (28°C, 70% RH). However, subjects did not ingest the ice puree during the actual performance trial, and the volume ingested might not have been enough to induce a performance benefit.

In the present investigation, the ingestion of a single bolus of 1.25 g·kg<sup>-1</sup> of ice slurry attenuated the reduction in 2-min sustained MVC torque of the elbow flexors following exercise-induced hyperthermia, without reducing  $T_{re}$  (Table 5.1). These results suggest that a sensory effect resulting in an improvement in neuromuscular function in response to a cold stimulus may in fact exist. It is possible that the stimulation of internal thermoreceptors in the mouth, oesophagus and stomach regions altered afferent feedback pertaining to the thermal state of the body, in turn allowing greater torque production during the 2-min effort compared with the control fluid. As it is believed that the brain reduces muscle activation and motor output in an attempt to reduce heat production and the development of severe heat illness (Cheung, 2007), stimulating internal thermoreceptors with a cold solution may have attenuated such inhibitory afferent feedback, leading eventually to the increased MVC torque observed.

Another possibility for the higher MVC torque observed in the ICE condition is that ice slurry ingestion may have stimulated the reward/pleasure centres of the brain, leading to an increase in central drive and/or motivation. A similar effect has been shown in several studies investigating the influence of a carbohydrate mouth-rinse on endurance performance (Carter et al., 2004; Chambers, et al., 2009; Pottier, et al., 2010; Rollo, et al., 2010; Rollo, et al., 2008). These studies have shown an improvement in exercise performance despite no changes in carbohydrate metabolism. Additionally, Chambers et al. (2009) observed increased stimulation in



regions of the brain associated with reward and motor control in response to oral carbohydrate exposure in a rested state. The authors hypothesised that this stimulation lead to increased central drive, arousal and motivation, resulting in enhanced exercise performance. Moreover, Gant et al. (2010) showed that maximal voluntary force and motor evoked potentials of the biceps brachii were significantly increased immediately after carbohydrate ingestion. The authors proposed that oral receptors might have signalled for energy availability, possibly via nuclei in the brainstem. Such mechanisms may also apply to the sensation of a cold stimulus, especially in a hyperthermic state. In support of this theory, Guest et al. (2007) have shown that the temperature of an ingested liquid can influence the activity of brain regions associated with reward and pleasantness. Additionally, Pottier et al. (2010) have suggested that carbohydrate mouth rinsing may act to improve performance by suppressing afferent fatigue signals from working muscles. A similar mechanism may have been at play with ice slurry ingestion in the present study, especially with the fatiguing task of a 2-min sustained MVC in a hyperthermic state.

Unlike the carbohydrate mouth-rinse studies, participants in the present investigation swallowed the ice slurry. The act of simply swallowing might also play an important role in the sensory effect proposed with endogenous cooling. Arnoutis et al. (2010) demonstrated that ingestion of, but not mouth rinsing 25 ml of plain water at the beginning and every 5 min during exercise tended to increase cycling time to exhaustion at 75% of subjects' maximum power output in a hypohydrated (2%) state. The authors suggested that the enhanced performance was due to the activation of pharyngeal receptors. Seckl et al. (1986) also observed a pharyngeal response to water ingestion, showing that a rapid decline in plasma arginine vasopressin occurs prior to any alterations in plasma osmolality or electrolyte levels.

The authors theorised that a swallowing-mediated neuroendocrine reflex may have caused this change. Further results from this study showed that simply gargling water was able to reduce the sensation of thirst (Seckl, et al., 1986). Work in monkeys has also shown that swallowing a solution can significantly increase supraoptic nucleus firing rate well before absorption takes place (Vincent et al., 1972). Therefore, in addition to the potential for ice slurry ingestion to improve performance in the current study via temperature-related sensory pathways, the act of swallowing itself may have also been a factor.

Research has shown that an elevated  $T_c$  is responsible for the reduction in voluntary muscle activation observed with hyperthermia, regardless of changes in  $T_{sk}$  and muscle temperature ( $T_{mu}$ ). Both Thomas et al. (2006) and Morrison et al. (2004) showed that the reduction in maximal torque production and voluntary activation observed with passive heating were similar between heated and thermoneutral legs. These findings, in conjunction with the results from the current work whereby  $T_{re}$ ,  $T_{sk}$  and presumably  $T_{mu}$  were similar between conditions, indicate that impulses from more central internal thermoreceptors may be more influential than those present in the skin and muscle.

Cooling for the purpose of improving exercise performance has been researched extensively (Marino, 2002; Quod, et al., 2006). The principal mechanisms thought to be responsible for the improvements in performance observed following cooling is the lowered or attenuated rise in  $T_c$ , as well as potentially the reduction in cardiovascular strain. Evidence from the present study suggests that in addition to these mechanisms, sensory factors in response to cooling may also influence exercise performance in a hyperthermic state.

In conclusion, results from the present study have shown, for the first time, that the sensory effects associated with the ingestion of a small bolus of ice slurry are able to attenuate the reduction in MVC torque development following exercise-induced hyperthermia, compared with the ingestion of the same volume of a warm solution. These findings suggest that sensory mechanisms related to the temperature of the mouth-throat region may have had a positive influence on the body's perceptual responses, which in turn elicited the enhancement of exercise performance shown. Future research should examine whether such sensory effects are witnessed during more dynamic, prolonged exercise.

# **CHAPTER 6**

## **Discussion**

## 6.1 Introduction

Many major sporting competitions are held in the summer months, and as such, the ambient temperature is often high. The deleterious effects of heat stress on exercise performance are well described (Cheung, 2007; Hargreaves, 2008; Nybo, 2008), and thus, the challenge of developing strategies for combating these effects is of great importance to athletes, coaches and exercise scientists alike. While precooling has been shown to be an effective strategy for improving performance in the heat over a variety of exercise modes and durations (Marino, 2002; Quod, et al., 2006), the precise mechanisms responsible remain elusive. Furthermore, the most common forms of precooling currently adopted, such as cold water immersion and the application of cooling garments, have been criticised as impractical for use in the field. Therefore, the purpose of this PhD thesis was to examine the effectiveness of ice slurry ingestion, a practical precooling manoeuvre which is logistical for use in major sporting competition (Ross, et al., 2011), for improving endurance performance in the heat (Study 1). The subsequent aims were to compare ice slurry ingestion with the current “gold standard” precooling method of cold water immersion (Study 2), as well as identify potential mechanisms by which internal cooling is able to enhance exercise performance under conditions of heat strain (Study 3).

Currently, the most common forms of precooling utilised in both competitive sport and laboratory trials have been via external means that act by cooling a person from the periphery. In spite of this, there is evidence that endogenous cooling modalities, such as the ingestion of cold fluids, are able to significantly reduce  $T_{c}$  (Imms & Lighten, 1989; Wimer, et al., 1997) and in turn enhance exercise performance in the heat (Hasegawa, et al., 2006; Lee, et al., 2008b; Mundel, et al.,

2006). However, the simple laws of thermodynamics suggest that more aggressive strategies are available. The law of enthalpy of fusion states that  $334 \text{ kJ}\cdot\text{kg}^{-1}$  of energy is required in order for ice to melt (phase change from solid to liquid). This fact alone indicates that the ingestion of ice is able to reduce  $T_c$  significantly more than ingesting water of a similar temperature, providing a powerful means by which to lower pre-exercise  $T_c$ . This was indeed shown to be the case in swine, whereby ice slurry saline (0 to  $-1^\circ\text{C}$ ) infusion caused a significantly greater reduction in core brain temperature ( $\sim 2^\circ\text{C}$ ) than chilled saline ( $0-1^\circ\text{C}$ ) (Vanden Hoek, et al., 2004).

Consequently, Study 1 of this PhD thesis (Siegel, et al., 2010) demonstrated that ice slurry ( $-1^\circ\text{C}$ ) ingestion was able to reduce pre-exercise  $T_{re}$  ( $0.66 \pm 0.14^\circ\text{C}$ ) significantly more than the ingestion of  $4^\circ\text{C}$  water ( $0.25 \pm 0.09^\circ\text{C}$ ) in humans. Subjects then ran to exhaustion at their  $VT_1$  running speed in a hot environment ( $34.0 \pm 0.2^\circ\text{C}$ ,  $54.9 \pm 5.9\%$  RH), with ice slurry ingestion increasing endurance capacity by  $19 \pm 6\%$  compared with the cold water trial. This improvement was attributed to the ability of ice slurry ingestion to generate a significantly larger heat sink, prolonging the time taken to reach critically high internal temperatures. However, an additional and unexpected finding from this study was that  $T_{re}$  at the point of exhaustion was significantly higher ( $0.31 \pm 0.11^\circ\text{C}$ ) following ice slurry compared with cold water ingestion; a finding that does not concur with the majority of thermoregulatory literature, which suggest subjects will terminate exercise at similar a  $T_c$  (Cheung, 2007).

In an attempt to confirm the finding of a higher  $T_{re}$  at exhaustion following ice slurry ingestion, Study 2 compared thermoregulatory responses and exercise capacity between ice slurry ingestion and cold water immersion. The occurrence of a higher  $T_{re}$  at exercise termination was replicated, with ice slurry ingestion resulting

in a higher  $T_{re}$  ( $0.28^{\circ}\text{C}$ ) compared with both the cold water immersion and control ( $37^{\circ}\text{C}$  fluid ingestion) conditions. Both ice slurry ingestion ( $P = 0.005$ ) and cold water immersion ( $P = 0.008$ ) resulted in longer run time to exhaustion compared with the control condition. Conversely, cold water immersion and ice slurry ingestion resulted in similar run times ( $P = 0.335$ ), with the likely differences between the conditions using magnitude-based inferences being “unclear.”

Following evidence from both Studies 1 and 2 suggesting that sensory mechanisms may play an important role in the performance improvements observed following ice slurry ingestion, Study 3 (Siegel et al., 2011) was performed to determine whether ice slurry ingestion was able to attenuate the reduction in neuromuscular function observed with heat strain. Results from this study showed that the ingestion of a small bolus of ice slurry ( $1.25\text{ kg}^{-1}$ ) lead to higher torque production of the elbow flexors following exercise-induced hyperthermia, compared with  $40^{\circ}\text{C}$  water ingestion. These results contributed further evidence to support the idea that endogenous cooling is able to enhance exercise performance via thermoreceptive/sensory mechanisms.

## **6.2 Internal cooling mechanisms**

The primary mechanism proposed to explain the improvement in exercise performance in the heat commonly witnessed following precooling is the reduction in starting  $T_c$ , which allows greater heat storage capacity during exercise (Marino, 2002; Quod, et al., 2006). During fixed-intensity exercise to exhaustion in the heat, as with the current work, it is thought that commencing exercise with a lower  $T_c$  allows participants to exercise for longer before attaining critically high internal temperatures, thus prolonging endurance time (Gonzalez-Alonso, et al., 1999b).

Therefore, significantly lowering  $T_c$  prior to endurance exercise in the heat, by any method, should theoretically increase exercise capacity at a set intensity. During self-paced exercise, the mechanisms by which precooling improves performance appear to be somewhat more complicated. An anticipatory mechanism whereby thermal signals are integrated via a feedforward-feedback response has been proposed (Marino, 2004). This theory suggests that alterations in pace during exercise in the heat are consciously or unconsciously made so that the individual may complete a known distance in the shortest time possible before developing severe heat illness (Tucker, 2008). If this is indeed the case, commencing exercise with a lower  $T_c$  and/or blunting the rise in  $T_c$  during exercise, may somehow attenuate this pathway, allowing athletes to complete a set amount of work faster.

Duffield et al. (2010) showed that 20 min of pre-exercise lower body cold water immersion ( $10^{\circ}\text{C}$ ) significantly improved 40-km cycling time trial performance in the heat ( $33 \pm 0.8^{\circ}\text{C}$ ,  $50 \pm 3\%$  RH). While  $T_{re}$ ,  $T_{sk}$ ,  $T_b$  and thermal sensation were all lower during the initial stages of exercise following precooling compared with the control condition of no cooling, differences in pacing were only observed in the final 10 min of cycling, once all physiological and perceptual differences were no longer apparent; a finding which is not uncommon (Ihsan, et al., 2010; Kay, et al., 1999). Duffield et al. (2010) suggested that rather than the precooling improving performance *per se*, it may have attenuated the reduction in performance commonly observed in the latter stages of exercise in the heat. Nevertheless, the precise mechanisms by which this occurs are still to be determined. Others have suggested that exercise performance is determined by the rate of progression towards critically high internal temperatures (Quod, et al., 2008). As such, the lower initial  $T_c$  with precooling allows for a higher rate of heat storage, and



thus athletes are able to complete a set distance faster before reaching a critical  $T_c$ . Likewise, this theory remains to be confirmed. Regardless, it appears that the greater the magnitude that  $T_c$  is reduced, the greater the performance benefit (Marino, 2002; Quod, et al., 2006).

Several other theories have been presented concerning the mechanisms underlying the deleterious effects of heat strain on exercise performance. Reduced cerebral blood flow, and thus cerebral glucose depletion and potentially a build-up of branch chain amino acids in cerebral blood (Nybo & Secher, 2004) have been suggested as potential contributors (Nybo, et al., 2003), as have a reduction in neurotransmitter levels (Cheung & Sleivert, 2004; Nybo, 2008), endotoxemia (Lambert, 2004) and metabolic disturbances (Febbraio, 2001; Febbraio et al., 1996b). While precooling may attenuate one or more of these affects, whether this then contributes to the superior exercise performance observed following precooling remains unidentified, and largely unexplored.

Studies 1 and 2 of this thesis demonstrated that lowering pre-exercise  $T_c$  via ice slurry ingestion allowed for greater heat storage during exercise, and extended running time to exhaustion in the heat. Notwithstanding the limitations of accurately estimating  $T_b$  and heat storage based on changes in  $T_c$  and  $T_{sk}$  (Jay et al., 2007), the data clearly displays that subjects were able to store more heat following ice slurry ingestion. Whilst increasing heat storage capacity and prolonging the attainment of critically high  $T_c$  may be the primary mechanism responsible for the improved exercise performance observed with ice slurry ingestion, evidence from the current work suggests that additional mechanisms may play a meaningful role. In both Studies 1 and 2, end point  $T_{re}$  was significantly higher following ice slurry ingestion.

This is contrary to previous studies which have shown that subjects will reach the point of volitional exhaustion at a similar  $T_c$ . This is true in trained (Gonzalez-Alonso, et al., 1999b; Nielsen, et al., 1993) and untrained (Cheung & McLellan, 1998; Hasegawa, et al., 2006; Lee, et al., 2008b) populations, as well as following the application of a precooling manoeuvre (Gonzalez-Alonso, et al., 1999b; Hasegawa, et al., 2006; Lee, et al., 2008b). This increased  $T_c$  capacity subsequently extended running time to exhaustion, thus enhancing exercise performance. A potential explanation for this phenomenon is that ice slurry ingestion caused a meaningful reduction in brain temperature, extending the time taken to achieve critically high brain temperatures. This, in turn, allowed subjects to run for longer, resulting in the generation and storage of more internal heat, and thus, a higher  $T_{re}$ . As ice slurries were ingested through the mouth, and brain temperature is likely of greater importance than  $T_c$  during exercise in the heat (Caputa, et al., 1986), this is one plausible explanation. Thus, it is apparent that in addition to the benefits observed following external precooling, ice slurry ingestion may have the added benefit of cooling the brain to a greater extent. It is important to note that although an increased  $T_{re}$  at exhaustion observed in Studies 1 and 2 resulted in enhanced exercise performance, it is possible that this effect may be dangerous to the athlete when exercising under conditions of high heat strain.

The means by which ice slurry ingestion may cause a physiologically meaningful reduction in brain temperature is not clear, however, several possibilities exist. Due to the close proximity of the oesophagus to the carotid arteries, ice slurry ingestion may have resulted in the cooling of blood flowing to the brain. Additionally, it has been suggested that cool facial blood returning to the brain is a means by which brain temperature may be lowered with face cooling (Cabanac &

Caputa, 1979), however, recent evidence suggests that this is unlikely (Nybo, et al., 2002b). Berg et al. (1966) showed that the ingestion of 500 g of cracked ice significantly reduced  $T_{ty}$  (measured using a thermistor probe) by  $0.5 \pm 0.02^{\circ}\text{C}$ , which was used as an indication of hypothalamic temperature. Although the reliability of  $T_{ty}$  as a measure of brain temperature has been questioned (Simon, 2007), Vanden Hoek et al. (2004) have shown a strong correlation between changes in brain temperature and  $T_{ty}$  using a thermistor probe during ice slurry infusion in swine.

Another potential mechanism by which ice slurry ingestion may improve exercise performance in the heat is via alterations in thermoreception. While thermosensitive receptors are known to exist in the hypothalamus (Wendt et al., 2007) and skin (Nadel, et al., 1971) in humans, receptors within the core itself have also been discovered. Thermoreceptors have been identified in the mouth, spinal cord (Hensel, 1981), oesophagus (El Ouazzani & Mei, 1982), abdominal viscera (Cottrell, 1984; Gupta, et al., 1979; Riedel, et al., 1973) and abdominal cavity (Rawson & Quick, 1970) in several animal species, as well as in the stomach and small intestine in humans (Villanova, et al., 1997). Additionally, the glossopharyngeal (ninth cranial) nerve is known to carry impulses for temperature sensation from the posterior third of the tongue and upper pharynx to the brain (Pallett & O'Brien, 1985). Therefore, it is possible that stimulating these receptors via ice slurry ingestion alters afferent feedback pertaining to the thermal state of the body, causing participants to perceive exercise at a given thermal load as easier, resulting in the improvements to exercise performance documented.

Evidence of this was apparent in Study 2 of this thesis. During exercise, thermal sensation and RPE were similar between ice slurry ingestion and cold water

immersion protocols, despite  $T_{re}$ ,  $T_{sk}$  and  $T_b$  being significantly lower in the latter condition. Conversely, although thermoregulatory measures were similar between the ice slurry and control conditions for the majority of exercise, thermal sensation and RPE were significantly lower following ice slurry ingestion. These results suggest that a sensory effect resulting from endogenous cooling may exist. Further evidence of this was observed in Study 3 of the present work, whereby torque production during a 2-min sustained MVC was significantly higher with ice slurry compared to warm water ingestion following exercise-induced hyperthermia, despite no differences in  $T_{re}$ ,  $T_{sk}$ ,  $T_b$ , heart rate or thermal sensation. It is hypothesised that this improvement in exercise performance may have been due to the activation/suppression of brain regions associated with reward, pleasure, motivation, arousal and fatigue as a result of stimulating core thermoreceptors with a cold stimulus. Several studies have demonstrated that rinsing the mouth with a carbohydrate solution during exercise is able to enhance endurance performance, despite no changes in carbohydrate metabolism (Carter, et al., 2003; Chambers, et al., 2009; Pottier, et al., 2010; Rollo, et al., 2010; Rollo, et al., 2008). It has been suggested that these improvements are due to the stimulation of energy receptors in the mouth stimulating the aforementioned brain regions; a suggestion which was strengthened by Chambers and colleagues' (2009) observation of increased stimulation in brain regions associated with reward and motor control in response to oral carbohydrate exposure in a rested state. Furthermore, Gant et al. (2010) demonstrated that maximal voluntary force and motor evoked potentials of the biceps brachii significantly increased immediately after carbohydrate ingestion, and suggested that oral receptors may have signalled energy availability, possibly via

brainstem nuclei. A similar response may occur following the application of a cold stimulus, especially in a hyperthermic state.

In addition to the proposed alterations in thermoreception, the simple act of swallowing might also be a potential mechanism by which ice slurry ingestion improves exercise performance. Arnaoutis et al. (2010) demonstrated that ingestion of, but not mouth rinsing 25 ml of water at the beginning and every 5 min during exercise increased cycling time to exhaustion at 75% maximum power output in dehydrated (2%) subjects. It was suggested that the activation of pharyngeal receptors may have lead to the enhanced performance shown. The act of swallowing has also been shown to cause a rapid decline in plasma arginine vasopressin prior to any alterations in plasma osmolality or electrolyte levels (Seckl, et al., 1986), and significantly increase supraoptic nucleus firing rate well before absorption takes place (Vincent, et al., 1972). Therefore, a swallowing-mediated pharyngeal response to ice slurry ingestion may also induce performance enhancing effects, in addition to temperature related sensory pathways. This is unlikely to have occurred in Studies 1 and 2 of the current work, whereby ice slurry ingestion was used as a precooling agent, but may have played a role in Study 3, and in various research designs which have utilised fluid ingestion during exercise.

As ingestion of an ice slurry will eventually reach the stomach/gastrointestinal region, it is probable that the ice absorbed a considerable amount of internal heat, and thus lowered temperature in this area. Evidence of this was shown by Ihsan et al. (2010), whereby gastrointestinal temperature was lowered  $1.1 \pm 0.59^{\circ}\text{C}$  following crushed ice ingestion. Elevated temperatures in this region can increase epithelia permeability, resulting in endotoxemia (Moseley et al., 1994).

Therefore, cooling this area may enhance endurance performance by attenuating the potential effects of endotoxemia. As the influence of endotoxemia on exercise performance is not well understood, further examination into these effects, and subsequently those of ice slurry ingestion on performance is necessary.

Ice slurry ingestion resulted in no changes to  $T_{sk}$  or heart rate during exercise in both Studies 1 and 2, when compared with the control conditions. This observation was confirmed by Ihsan et al. (2010) who showed that pre-exercise crushed ice ingestion did not cause a reduction in  $T_{sk}$  and heart rate prior to or during exercise. Sweat rate was not different between ice slurry versus cold water (4°C) ingestion in Study 1 ( $1.89 \pm 0.61$  vs.  $2.05 \pm 0.43$  L·h<sup>-1</sup>  $P = 0.242$ ), however, tended to be lower during study 2 ( $2.06 \pm 0.49$  vs.  $2.28 \pm 0.61$  L·h<sup>-1</sup>;  $P = 0.056$ ) compared to when participants ingested warm water (37°C). These results may suggest that ice slurry ingestion is able to lower sweat rate during exercise compared to drinking warm but not cooler fluids. Regardless, the data from these studies shows that ice slurry ingestion is able to enhance endurance capacity without alterations to  $T_{sk}$  or heart rate, confirming findings from previous research which show changes in  $T_c$  are more influential than changes in  $T_{sk}$  (Gonzalez-Alonso, et al., 1999b; Hunter, et al., 2002; Morrison, et al., 2004; Thomas, et al., 2006), and that thermal strain is of greater importance than cardiovascular strain.

Evidence from this thesis suggests that endogenous cooling is able to enhance exercise performance in the heat via different mechanisms to external cooling. Whilst the lowering of pre-exercise  $T_c$  is clearly of importance, results from this series of studies, as well as published literature, have shown that other factors are likely involved. Indeed, further research is required to more accurately explain

the physiological and performance responses observed during exercise in hot environments following a variety of precooling manoeuvres.

### **6.3 Practical outcomes**

Currently, the most popular forms of precooling used in research involve cold water immersion (Booth, et al., 1997), the use of cooling jackets/vests (Arngrimsson, et al., 2004), or a combination of the two (Quod, et al., 2008). Although shown to be effective in a laboratory setting, these methods are difficult to implement in the field. Cold water immersion can be difficult due to lack of access to large amounts of water, or electricity or ice to maintain water temperature. Furthermore, athletes often describe cold water immersion as uncomfortable. While considered more practical, practitioners often report the difficulty of using ice vests and jackets, as they are heavy, bulky, a challenge to transport, uncomfortable for the athlete, and a concern to some coaches that they may influence sport specific mechanics if worn during a warm-up. Moreover, not all studies investigating the use of cooling garments have shown improvements in performance (Castle, et al., 2006; Duffield, et al., 2003; Duffield & Marino, 2007; Quod, et al., 2008).

Results from this thesis have shown ice slurry ingestion to be a safe, effective and easily implemented precooling manoeuvre, comparable to that of cold water immersion. Although this method also has its limitations, such as accessibility of slushy machines and the associated difficulties with transporting a machine and access to power in the field, it is certainly a more practical strategy for use in major sporting competition. When slushy machines are not available in the field, ingesting crushed ice appears to be a successful alternative (Ihsan, et al., 2010). In addition to its use as a cooling manoeuvre, ice slurry ingestion can also be used to hydrate

athletes prior to, during and post competition (Ross, et al., 2011); important given the adverse effects of hypohydration on exercise performance, especially in hot environments (Sawka, 1992).

The combined findings from Studies 1 and 2 provide direction for the practitioner wishing to use ice slurry ingestion as a precooling manoeuvre. While ice slurry ingestion was shown to be effective in enhancing performance, cooling the core without a concurrent reduction in  $T_{sk}$  may result in less than optimal performance. A faster rate of rise in  $T_c$  following ice slurry ingestion was witnessed in Study 2, and has also been shown by Stanley et al. (2010). This effect resulted in a faster time to attain critically high  $T_c$  in Study 2, and in the case of the study conducted by Stanley et al. (2010), no improvements in exercise performance. As ice ingestion results in minimal (Study 1) to no (Study 2, (Ihsan, et al., 2010)) reductions in  $T_{sk}$ , this effect may be due to the reduced core-to-skin temperature gradient following consumption, potentially decreasing the ability to transfer heat to the environment. As such, cooling the skin in addition to the core is likely of great benefit; not unlike that performed by Ross et al. (2011) who used ice towels to cool the periphery in conjunction with ice slurry ingestion.

The reduction in  $T_{re}$  following ice slurry ingestion in Study 2 was considerably less ( $0.43 \pm 0.14^\circ\text{C}$ ) than in Study 1 ( $0.66 \pm 0.14^\circ\text{C}$ ). As ingestion took place in a thermoneutral environment in Study 1 ( $\sim 24.5^\circ\text{C}$ ) and a hot environment in Study 2 ( $34.0 \pm 0.1^\circ\text{C}$ ), it is possible that the ambient conditions where ingestion takes place is important for optimising its' success. Ross et al. (2011) also had subjects consume ice slurries in a hot environment ( $32\text{-}35^\circ\text{C}$ , 50-60% RH) and found that ingestion of 500 g and 1 kg resulted in  $0.25 \pm 0.17^\circ\text{C}$  and  $0.60 \pm 0.28^\circ\text{C}$  reductions in  $T_{re}$ , respectively. Both these reductions are less than that witnessed in



Study 1 of this thesis, where approximately 600 g of ice slurry was ingested. When possible, athletes should attempt to consume ice slurries in a cool environment prior to exercise, such as in a changing room.

In addition to the performance benefits elicited, ice slurry ingestion was shown to be very palatable and well tolerated by most subjects. In Study 1, three of 10 participants experienced sphenopalatine ganglioneuralgia (brain freeze) during ingestion in temperate conditions, while in Study 2, this was expressed by 6 of 8 subjects. This supports anecdotal evidence suggesting the incidence of brain freeze is greater in hot weather (Smith, 1968). However, the effects of brain freeze were short-lived, and did not linger into the run phase. Furthermore, no subjects reported any gastro-intestinal discomfort following ice slurry ingestion.

An interesting finding from Study 1 of the present work was that ice slurry ingestion caused significantly greater reductions in FVC than cold fluid ingestion ( $0.21 \pm 0.14$  vs.  $0.07 \pm 0.18$  L). Although this was unlikely to have influenced subsequent exercise performance given the relatively low exercise intensity, a significantly lowered FVC may have implications during higher intensity exercise, if consumed during, rather than pre-exercise, or for individuals with respiratory conditions (e.g. asthma). Further research is required to determine how changes in FVC following ice slurry ingestion may influence performance over a variety of exercise modes and intensities.

Results from this thesis suggest that both internal and external cooling procedures have their distinct advantages over one another. Cold water immersion has the ability to significantly reduce  $T_c$ ,  $T_{sk}$  and  $T_b$ , leading to a significantly larger heat sink compared with ice slurry ingestion. Conversely, ice slurry ingestion may

have the advantages of increased brain cooling and the associated internal cooling sensory effect. Therefore, a combination of internal and external cooling manoeuvres may be optimal. Indeed, this was shown to be the case by Ross et al. (2011), who compared a combination cooling procedure of ingesting  $14 \text{ g}\cdot\text{kg}^{-1}$  of ice slurry plus ice towel treatment with the conventional precooling strategy adopted by elite Australian cyclists, consisting of a 10-min cold water immersion followed by 20 min of wearing an ice jacket. The ice slurry/ice towel manoeuvre improved 46-km cycling time trial performance in the heat ( $32\text{-}35^{\circ}\text{C}$ , 50-60% RH) by 1.3% ( $\sim 1:06$  min) compared with the control condition of no cooling, whereas the effect of the conventional strategy was “unclear”. It is possible that a combination of internal and external cooling benefits played a meaningful role, as performance was superior despite  $T_{\text{re}}$  being  $\sim 0.6^{\circ}\text{C}$  lower with the plunge/jacket protocol prior to exercise. Alternatively, the cyclists may have mis-paced the early portion of the trial based on feeling cooler at the start of exercise, as suggested by the authors. Hasegawa and colleagues (2006) also demonstrated that a combination of internal and external cooling resulted in the greatest improvements in exercise performance in the heat ( $32^{\circ}\text{C}$ , 80% RH). They showed that combining a 30-min plunge in  $25^{\circ}\text{C}$  to the torso with water ingestion during exercise ( $14\text{-}16^{\circ}\text{C}$ , equal to sweat loss from a previous trial) was most effective for enhancing performance, compared with just external or internal cooling procedures alone.

Few other studies have investigated the influence of ice ingestion on thermoregulatory responses and exercise performance in the heat. Ihsan et al. (2010) used a practical protocol to determine whether ingestion of  $6.8 \text{ g}\cdot\text{kg}^{-1}$  of crushed ice pre-exercise was able to improve 40-km cycling time trial performance. Ice ingestion reduced gastrointestinal temperature by  $1.1 \pm 0.59^{\circ}\text{C}$ , and subsequently improved

cycling performance by 6.5% compared with tap water ( $26.8 \pm 1.3^{\circ}\text{C}$ ) ingestion. Similar to that of Duffield et al. (2010), performance was enhanced following ice ingestion despite gastrointestinal temperature only being lower for the first 100 kJ of work performed. This is likely due to the fact that a 10-min warm up and 5-min transition period was implemented prior to the time trial. These additions give the results greater application to actual competitive sporting performance, a weakness of many precooling studies performed to date which may inflate the performance improvements of the manoeuvres investigated.

Conversely, Stanley et al. (2010) demonstrated that ingesting 1 L of ice slush beverage in the 50-min period separating 75 min of steady state cycling at ~60% peak power output and a 75% peak power output  $\times$  30 min performance trial ( $33.7 \pm 0.8^{\circ}\text{C}$ ,  $60.3 \pm 2.0\%$  RH), did not improve performance. This was despite ice ingestion reducing  $T_{\text{re}}$  by  $0.4^{\circ}\text{C}$  compared with the control condition of an  $18.4 \pm 0.5^{\circ}\text{C}$  drink. The authors suggested that performance was similar between conditions due to the faster rate of rise in  $T_{\text{c}}$  observed during the ice slush trial, potentially due to compromised heat loss capacity as a result of the lowered core-to-skin temperature gradient.

Similarly, Burdon et al. (2010a) also observed no performance benefit from ingesting small amounts of ice during exercise. They determined that ingesting 30 ml of ice puree every 5 min during 90 min of steady state cycling did not improve performance during the subsequent 15-min performance test in a warm environment ( $28^{\circ}\text{C}$ , 70% RH). As ice ingestion did not result in enhanced performance, the authors concluded that a sensory response was not witnessed, but warranted further research. It would have been interesting to have observed the effects had ice puree

been ingested during the actual performance trial, and/or greater volumes of ice were ingested.

#### **6.4 Limitations**

Although this thesis has demonstrated that ice slurry ingestion is an effective precooling agent for improving sub-maximal endurance performance in the heat, several limitations were apparent in the testing procedures. The exercise protocol adopted for Studies 1 and 2 was a time to exhaustion test, as opposed to a time trial. Time to exhaustion tests have been criticised for their lack of application to real world sporting events, where athletes must complete a set distance as fast as possible. Furthermore, as pace is fixed during time to exhaustion trials, alterations in pacing are not able to be examined. Indeed, different mechanisms appear to be involved during self-paced exercise (Duffield, 2008). While it has been shown that time to exhaustion protocols provide a lower level of absolute reliability than time trial tests, they still accurately predict actual time trial performance (Laursen et al., 2007). Furthermore, it has been suggested that time to exhaustion protocols may eliminate the “noise” associated with pacing (Hinckson & Hopkins, 2005), and may therefore be a better choice of test when assessing steady state endurance capacity. The other advantage of time to exhaustion protocols over time trials is that when examining the influence of an intervention, such as precooling, the former are able to elicit larger changes between conditions, as a result of their greater signal-to-noise ratio (Laursen, et al., 2007).

Another limitation related to the ecological validity of the present research and the ability of the results to be extrapolated to the competitive sport setting pertains to the fact that there was no warm-up undertaken prior to the

commencement of running in Studies 1 and 2. Thus, as athletes often perform an extensive warm-up prior to important events, it is likely that the performance benefits observed in the present studies following precooling were inflated relative to what would be observed in field conditions. Additionally, predominantly moderately trained, non-heat-acclimatised participants were used as subjects in each study, and convective cooling in the form of air flow relative to the subject's running speed was not applied (Saunders, et al., 2005). These results may therefore not apply directly to trained athletes performing in out-of-door conditions who are usually acclimatised to the environmental conditions prior competition. Again, these limitations would result in an overestimation of the performance benefits expected in the field.

## **6.5 Directions for future research**

To date, there are few published studies that have investigated the influence of ice slurry ingestion on exercise performance in the heat (Burdon, et al., 2010a; Ihsan, et al., 2010; Ross, et al., 2011; Siegel, et al., 2010; Stanley, et al., 2010). The results of this thesis and the aforementioned studies provide evidence that ice slurry ingestion is an effective precooling manoeuvre, and as such, further research is warranted. As the primary exercise protocol employed in the present work was time to exhaustion running, future research should utilise time trial protocols, with a specific focus on alterations in pacing, for greater application to real world sporting competition. Comparing ice slurry ingestion, cold water immersion and a combination manoeuvre in such a setting would likely result in greater understanding regarding the mechanistic similarities and differences between internal and external precooling. From a practical standpoint, research investigating the timing and volume of consumption is also necessary in order to maximise the performance benefits. Following the results from Study 3 of this thesis, further research into the

sensory effects of ice slurry ingestion on dynamic prolonged exercise performance is warranted; similar to the work completed by Burdon et al. (2010a), but administering ice slurries during a prolonged exercise performance trial.

Recently, several studies have investigated the influence of varying drink temperatures consumed during prolonged exercise performance in the heat, with the majority demonstrating cooler fluids are of a greater advantage (Burdon, et al., 2010a; Burdon, et al., 2010b; Lee, et al., 2008a; Lee & Shirreffs, 2007; Lee, et al., 2006, 2008b). As the current work focused primarily on pre-exercise ice slurry ingestion, future research should focus on the potential that ingesting ice slurries during exercise may have on improving performance in the heat.

Research investigating precooling and intermittent sprint performance is somewhat limited (Castle, et al., 2006; Cheung & Robinson, 2004; Duffield, et al., 2003; Duffield & Marino, 2007; Webborn et al., 2008; Webborn et al., 2005). The majority of this literature has shown no improvements in intermittent sprinting performance, however there is evidence that precooling is able to enhance performance via increasing distance run in sub-maximal efforts (Duffield & Marino, 2007). A concern of many coaches and practitioners regarding precooling for intermittent sprint performance is that lowering  $T_{mu}$  may lead to a reduction in sprint performance due to the slowing of metabolic processes and in turn the contraction speed and power (Nybo, 2008). This may not be the case, however, as Castle et al. (2006) demonstrated that precooling the leg muscles improved intermittent sprint cycling in the heat ( $33.7 \pm 0.3^{\circ}\text{C}$ ,  $51.6 \pm 2.2\%$  RH). Another concern is that cooling the leg muscles prior to intermittent sprinting may increase the risk of injury. If this is indeed the case, ice slurry ingestion may be an optimal precooling manoeuvre for team sports, as it results in no changes to  $T_{sk}$ , and presumably  $T_{mu}$ , providing the

benefits of a lowered  $T_c$  for sub-maximal efforts whilst maintaining a higher  $T_{mu}$  for sprinting efforts.

## **6.6 Conclusions**

The main findings from this PhD thesis were that ice slurry ingestion is an effective precooling manoeuvre for lowering pre-exercise  $T_c$  and prolonging submaximal run time to exhaustion in the heat, and is a comparable form of precooling to the current “gold standard” method of cold water immersion. Furthermore, in addition to the performance benefits achieved via lowering pre-exercise  $T_c$ , ice slurry ingestion is able to prolong running time via increasing the  $T_c$  tolerable before terminating exercise, potentially via reductions in brain temperature, or alterations in thermoreception. Finally, ice slurry ingestion may enhance exercise performance in conditions of heat strain via sensory mechanisms, resulting in stimulation of internal thermoreceptors and/or activating/suppressing brain regions associated with reward, pleasure, motivation, arousal and fatigue. As ice slurry ingestion is an effective and easily implemented precooling strategy in the field, it may be a more logistical option for use in major sporting competitions compared to the more common, yet less practical manoeuvres such as cold water immersion and the application of cooling garments. Further research is warranted to determine the precise mechanisms by which internal cooling is able to enhance exercise performance.

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## **APPENDIX A**

### **INFORMATION LETTER TO PARTICIPANTS**

#### **The influence of ice slurry consumption on thermoregulation and sub-maximal exercise performance in the heat**

**Chief investigator: Rodney Siegel (PhD Candidate)**

School of Exercise, Biomedical and Health Sciences

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Phone: 6304 5156 / email: r.siegel@ecu.edu.au

Thank you for expressing interest in this study. The purpose of this information letter is to provide you with an overview of the study and what is involved if you choose to participate. Please read the information carefully and feel free to ask for further explanation if anything is unclear.

#### **Purpose of the Study**

The purpose of this study is to determine whether the consumption of an ice slurry prior to exercise in hot ambient temperatures is able to reduce core body temperature and subsequently improve sub-maximal exercise performance.

#### **Background**

The rise in core body temperature associated with exercise in hot ambient temperatures is known to impair prolonged exercise performance. Precooling has been shown to successfully reduce core temperature and in turn improve running time-to-exhaustion. The consumption of an ice slurry as a precooling strategy may be more practical in real sporting competitions than previous strategies investigated, such as ice jackets and cold water immersion. Therefore, determining the effectiveness of ice slurry consumption prior to exercise in the heat may provide benefits to athletes competing in such conditions.

## **Description of the Study**

If you agree to participate in this study, you will be asked to come to the Exercise Physiology Laboratory (Joondalup campus, building 19.150) on 4 separate occasions. These sessions will consist of 1 progressive exercise test to determine your fitness level, 1 familiarisation session and 2 testing sessions, all separated by at least 1 week. Several measurements will be taken immediately before, during and after the exercise described below. The sessions will vary in duration from approximately 45 minutes to 2 hours.

## **Exercise**

Prior to the testing sessions you will be asked to perform a graded exercise test to determine your fitness level. The progressive exercise test will involve running on a treadmill with increases in speed of 2 km/h every 4 min until you can no longer maintain the set pace. If you reach a speed of 16 km/h, rather than increasing the speed further, the gradient will be increased 2% every 4 min. Your heart rate and expired air will be analysed continuously throughout the test to determine your aerobic capacity.

During the 2 testing sessions, the same exercise will be performed under 2 different conditions:

- 1) Following ice slurry consumption
- 2) Following water consumption

The exercise will involve running at a set speed (determined from your fitness level in the previous session) for as long as you can, in the heat chamber set at 35°C, 40% relative humidity.

The familiarisation session will be identical to condition 2, in order to familiarise yourself with the exercise and the conditions you will perform under.

## **Measurements**

The following measurements will be taken:

- 1) Prior to the graded exercise test in the first session, your skinfolds measurements will be taken from 9 sites to determine your body composition.
- 2) Your heart rate will be measured continuously throughout the test using a heart rate monitor.

- 3) Core temperature will be measured continuously throughout the test to assess your core body temperature, via self-insertion of a rectal thermistor.
- 4) Your skin temperature will be measured continuously throughout the test using 4 skin thermistors, affixed to your chest, arm, thigh and calf.
- 5) You will be asked to perform a simple lung function test before and after ice slurry/water consumption to determine if the cold ice/water has any effect on the constriction of your airways.
- 6) Approximately 5 ml of blood will be collected before and after exercise to determine your hydration status. The blood sample will be taken from the median cubital vein by a qualified a person trained in taking blood samples.
- 7) Urine samples will be collected before and after exercise to determine your hydration status.
- 8) Nude body mass will be measured to determine how much fluid you lost in sweat during exercise.

### **Risk and Ethical Considerations**

As exercise will be completed in a hot environment (35°C), there is a small risk of heat illness. To help avoid this, exercise will be terminated if your core temperature exceeds 40°C.

No direct comparisons between participants will be made at any stage of the testing. Analysis of the data will be done on a group basis; therefore, you are not competing against other participants in this study. All personal information and recorded testing results will remain confidential and will not be used for any purpose other than the current study. Your name will be removed from the associated data files and only the primary investigator will know which data sets corresponds to each participant.

You will be free to withdraw from the study at any stage and for any reason without prejudice.

### **Requirements and Benefits**

You will be asked to report to the laboratory as explained above. You will be requested not to perform any unaccustomed exercises or sporting activities, not to take any anti-inflammatory drugs or nutritional supplements, and not to alter your diet and lifestyle (exercise, sleeping habits, etc.) during the experimental period.

However, if you need to take any medication during this period, please inform us in advance. Please let us know if you cannot follow the requests stated above.

Your participation is very much appreciated and will help us in learning new and practical ways to improve athletic performance in hot environments. You will be given access to your results from both the progressive exercise test and experimental testing sessions, and learn more about your fitness levels and how to improve your own performance during competition in the heat.

If you would like to understand the research topic and methods used in this study better, we would be more than happy to provide you with more information associated with this project.

### **Medical Questionnaire**

As this study involves exercise, it is required that you are healthy at the time of testing. For this reason, you will be asked to complete a medical questionnaire prior to the commencement of testing. Answering “Yes” to a question will not always disqualify you from being a participant, however, you may be asked to consult your doctor for clearance to participate. The investigators will cover the cost of doing this if required.

### **Questions and/or further information**

If you have any concerns about this study, or would like to speak to an independent person, you may contact the Head of our School, Associate Professor Barry Gibson, on 6304 5037, or the Research Ethics Officer, Human Research Ethics Committee on 6304 2170 or [research.ethics@ecu.edu.au](mailto:research.ethics@ecu.edu.au).

Thank you very much for expressing interest in this research and taking the time to read this information letter.

Yours Sincerely,

### **Rodney Siegel (PhD candidate)**

School of Exercise, Biomedical and Health Sciences  
Edith Cowan University  
270 Joondalup Drive, Joondalup, WA 6027  
Phone: 6304 5156 / email: [r.siegel@ecu.edu.au](mailto:r.siegel@ecu.edu.au)



## **APPENDIX B**

### **INFORMATION LETTER TO PARTICIPANTS**

The comparison of internal versus external precooling on  
thermoregulatory responses and sub-maximal exercise  
performance in the heat

Chief investigator: Rodney Siegel (PhD Candidate)

School of Exercise, Biomedical and Health Sciences

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Phone: 6304 5156 / email: r.siegel@ecu.edu.au

Thank you for expressing interest in this study. The purpose of this information letter is to provide you with an overview of the study and what is involved if you choose to participate. Please read the information carefully and feel free to ask for further explanation if anything is unclear.

#### **Purpose of the Study**

The purpose of this study is to compare internal versus external cooling methods prior to sub-maximal exercise in hot ambient temperatures, and to determine, which, if any, is the optimal strategy.

#### **Background**

The rise in core body temperature associated with exercise in hot ambient temperatures is known to impair exercise performance. Precooling has been shown to successfully reduce core temperature and in turn improve prolonged exercise performance; however, the effect of internal compared to external cooling strategies is unknown. Determining the most optimal and practical precooling strategy will be of benefit to athletes competing in hot conditions.

## **Description of the Study**

If you agree to participate in this study, you will be asked to come to the Exercise Physiology Laboratory (Joondalup campus, building 19.150) on 5 separate occasions. These sessions will consist of 1 progressive exercise test to determine your fitness level ( $\dot{V}O_2$  max), 1 familiarisation session and 3 testing sessions, all separated by at least 1 week. Several measurements will be taken immediately before, during and after the exercise described below. The sessions will vary in duration from approximately 45 minutes to 2.5 hours.

## **Exercise**

Prior to the testing sessions you will be asked to perform a graded exercise test to determine your fitness level ( $\dot{V}O_2$  max). The graded exercise test will involve running on a treadmill with increases in speed of 2 km/h every 4 min until you can no longer maintain the set pace. If you reach a speed of 16 km/h, rather than increasing the speed further, the gradient will be increased 2% every 4 min. Your heart rate and expired air will be analysed continuously throughout the test to determine your aerobic capacity.

During the 3 testing sessions, the same exercise will be performed under 3 different conditions:

- 1) Following ice slurry ingestion
- 2) Following 30 min of cold water immersion (24°C)
- 3) Following warm water ingestion (control)

The exercise will involve running at a set speed (determined from your fitness level in the graded exercise test) for as long as you can, in a heat chamber set at 34°C, 40% relative humidity.

The familiarisation session will be performed first, and will be identical to condition 2, in order to familiarise yourself with the exercise and the conditions you will perform under.

## **Measurements**

The following measurements will be taken:

- 1) Prior to the graded exercise test in the first session, your skinfolds measurements will be taken from 9 sites to determine your body composition.

- 2) Your heart rate will be measured continuously throughout the test using a heart rate monitor.
- 3) Core body temperature will be measured continuously throughout the testing sessions via self-insertion of a rectal thermistor and a tympanic temperature thermistor.
- 4) Your skin temperature will be measured continuously throughout the test using 4 skin thermistors, affixed to your chest, arm, thigh and calf.
- 5) Urine samples will be collected before and after exercise to determine your hydration status.
- 6) Nude body mass will be measured to determine how much fluid you lost in sweat during exercise.

### **Risk and Ethical Considerations**

As exercise will be completed in a hot environment (34°C), there is a small risk of heat illness. To help avoid this, exercise will be terminated if your core temperature exceeds 40°C.

No direct comparisons between participants will be made at any stage of the testing. Analysis of the data will be done on a group basis; therefore, you are not competing against other participants in this study. All personal information and recorded testing results will remain confidential and will not be used for any purpose other than the current study. Your name will be removed from the associated data files and only the primary investigator will know which data sets corresponds to each participant.

You will be free to withdraw from the study at any stage and for any reason without prejudice.

### **Requirements and Benefits**

You will be asked to report to the laboratory as explained above. You will be requested not to perform any unaccustomed exercises or sporting activities, not to take any anti-inflammatory drugs or nutritional supplements, and not to alter your diet and lifestyle (exercise, sleeping habits, etc.) during the experimental period. However, if you need to take any medication during this period, please inform us in advance. Please let us know if you cannot follow the requests stated above.

Your participation is very much appreciated and will help us in learning new and practical ways to improve athletic performance in hot environments. You will be given access to your results from both the progressive exercise test and experimental testing sessions, and learn more about your fitness levels and how to improve your own performance during competition in the heat.

If you would like to understand the research topic and methods used in this study better, we would be more than happy to provide you with more information associated with this project.

### **Medical Questionnaire**

As this study involves exercise, it is required that you are healthy at the time of testing. For this reason, you will be asked to complete a medical questionnaire prior to the commencement of testing. Answering “Yes” to a question will not always disqualify you from being a participant, however, you may be asked to consult your doctor for clearance to participate. The investigators will cover the cost of doing this if required.

### **Questions and/or further information**

If you have any concerns about this study, or would like to speak to an independent person, you may contact the Head of our School, Associate Professor Barry Gibson, on 6304 5037, or the Research Ethics Officer, Human Research Ethics Committee on 6304 2170 or [research.ethics@ecu.edu.au](mailto:research.ethics@ecu.edu.au).

Thank you very much for expressing interest in this research and taking the time to read this information letter.

Yours Sincerely,

**Rodney Siegel (PhD candidate)**

School of Exercise, Biomedical and Health Sciences

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Phone: 6304 5156 / email: [r.siegel@ecu.edu.au](mailto:r.siegel@ecu.edu.au)

## **APPENDIX C**

### **INFORMATION LETTER TO PARTICIPANTS**

#### **The influence of mouth cooling on neuromuscular function following exercise-induced hyperthermia**

**Chief investigator: Rodney Siegel (PhD Candidate)**

School of Exercise, Biomedical and Health Sciences

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Phone: 6304 5156 / email: r.siegel@ecu.edu.au

Thank you for expressing interest in this study. The purpose of this information letter is to provide you with an overview of the study and what is involved if you choose to participate. Please read the information carefully and feel free to ask for further explanation if anything is unclear.

#### **Purpose of the Study**

The purpose of this study is to determine whether mouth cooling alone is able to improve muscular function following sub-maximal exercise in hot ambient temperatures.

#### **Background**

The rise in core body temperature associated with exercise in hot ambient temperatures is known to impair exercise performance. Cooling has been shown to successfully reduce core temperature and in turn improve exercise performance; however, the effect of cooling the mouth only as a potential strategy is unknown. Determining whether mouth cooling alone is able to improve exercise performance will help us understand the potential mechanisms by which internal cooling strategies are able to improve performance in the heat.

## **Description of the Study**

If you agree to participate in this study, you will be asked to come to the Exercise Physiology Laboratory (Joondalup campus, building 19.150) on 4 separate occasions. These sessions will consist of 1 progressive exercise test to determine your fitness level ( $\dot{V}O_2$  max), 1 familiarisation session and 2 testing sessions, all separated by at least 1 week. Several measurements will be taken immediately before, during and after the exercise described below. The sessions will vary in duration from approximately 1 to 2 hours.

## **Exercise**

Prior to the testing sessions you will be asked to perform a graded exercise test to determine your fitness level ( $\dot{V}O_2$  max). The graded exercise test will involve running on a treadmill with increases in speed of 2 km/h every 4 min until you can no longer maintain the set pace. If you reach a speed of 16 km/h, rather than increasing the speed further, the gradient will be increased 2% every 4 min. Your heart rate and expired air will be analysed continuously throughout the test to determine your aerobic capacity.

During the 2 testing sessions, the same exercise will be performed under 2 different conditions:

- 1) With ice slurry ingestion
- 2) With warm water ingestion (control)

The exercise will involve running at a set speed (determined from your fitness level in the graded exercise test) for as long as you can in a heat chamber set at 34°C, 50% relative humidity. Immediately before and immediately after running, you will be asked to perform a 2 min sustained maximal contraction of the elbow flexors, with electrically evoked stimulation of the biceps muscle at 30, 60, 90 and 120 sec.

The familiarisation session will be performed first, and will be identical to condition 1, in order to familiarise yourself with the exercise and the conditions you will perform under.

## **Measurements**

The following measurements will be taken:

- 1) Prior to the graded exercise test in the first session, your skinfolds measurements will be taken from 9 sites to determine your body composition.
- 2) Your heart rate will be measured continuously throughout the test using a heart rate monitor.
- 3) Core body temperature will be measured continuously throughout the testing sessions via self-insertion of a rectal thermistor and a tympanic temperature thermistor.
- 4) Your skin temperature will be measured continuously throughout the test using 4 skin thermistors, affixed to your chest, arm, thigh and calf.
- 5) Urine samples will be collected before and after exercise to determine your hydration status.
- 6) Nude body mass will be measured to determine how much fluid you lost in sweat during exercise.
- 7) Neuromuscular function will be measured via the series of 2 min sustained contraction tasks detailed above.

### **Risk and Ethical Considerations**

As exercise will be completed in a hot environment (34°C), there is a small risk of heat illness. To help avoid this, exercise will be terminated once your core temperature exceeds 40°C. Additionally, you may experience some slight discomfort from the electrically evoked stimulation of the biceps.

No direct comparisons between participants will be made at any stage of the testing. Analysis of the data will be done on a group basis; therefore, you are not competing against other participants in this study. All personal information and recorded testing results will remain confidential and will not be used for any purpose other than the current study. Your name will be removed from the associated data files and only the primary investigator will know which data sets corresponds to each participant.

You will be free to withdraw from the study at any stage and for any reason without prejudice.

### **Requirements and Benefits**

You will be asked to report to the laboratory as explained above. You will be requested not to perform any unaccustomed exercises or sporting activities, not to take any anti-inflammatory drugs or nutritional supplements, and not to alter your diet and lifestyle (exercise, sleeping habits, etc.) during the experimental period. However, if you need to take any medication during this period, please inform us in advance. Please let us know if you cannot follow the requests stated above.

Your participation is very much appreciated and will help us in learning new and practical ways to improve athletic performance in hot environments. You will be given access to your results from both the progressive exercise test and experimental testing sessions, and learn more about your fitness levels and how to improve your own performance during exercise in the heat.

If you would like to understand the research topic and methods used in this study better, we would be more than happy to provide you with more information associated with this project.

### **Medical Questionnaire**

As this study involves exercise, it is required that you are healthy at the time of testing. For this reason, you will be asked to complete a medical questionnaire prior to the commencement of testing. Answering “Yes” to a question will not always disqualify you from being a participant, however, you may be asked to consult your doctor for clearance to participate. The investigators will cover the cost of doing this if required.

### **Questions and/or further information**

If you have any concerns about this study, or would like to speak to an independent person, you may contact the Head of our School, Associate Professor Barry Gibson, on 6304 5037, or the Research Ethics Officer, Human Research Ethics Committee on 6304 2170 or [research.ethics@ecu.edu.au](mailto:research.ethics@ecu.edu.au).

Thank you very much for expressing interest in this research and taking the time to read this information letter.

Yours Sincerely,



**Rodney Siegel (PhD candidate)**

School of Exercise, Biomedical and Health Sciences

Edith Cowan University

270 Joondalup Drive, Joondalup, WA 6027

Phone: 6304 5156 / email: [r.siegel@ecu.edu.au](mailto:r.siegel@ecu.edu.au)

## **APPENDIX D**

### **INFORMED CONSENT FORM**

**“The influence of ice slurry consumption on thermoregulation  
and sub-maximal exercise performance in the heat”**

I have read the information sheet and the consent form. I agree to participate in the study entitled “The influence of ice slurry consumption on thermoregulation and sub-maximal exercise performance in the heat” and give my consent freely. I understand that the study will be carried out as described in the information sheet, a copy of which I have retained. I realise that whether or not I decide to participate is my decision. I also realise that I can withdraw from the study at any time and that I do not have to give any reasons for withdrawing. I have had all questions answered to my satisfaction.

---

Participant name

---

Date

---

Participant signature

## APPENDIX E

### MEDICAL QUESTIONNAIRE

#### The influence of ice slurry consumption on thermoregulation and sub-maximal exercise performance in the heat

The following questionnaire is designed to establish a background of your medical history, and identify any injury or illness that may influence your testing or performance.

Please answer all questions as accurately as possible and if you are unsure about anything please ask. Answering “Yes” to a question will not automatically disqualify you from participation in this study.

#### Participant Details

Name: \_\_\_\_\_ DOB: \_\_\_\_\_

#### Medical History

Have you ever had, or do you currently have any of the following?

If you answer “YES” please give details

High or abnormal blood pressure	Y	N	_____
Heart disease	Y	N	_____
High cholesterol	Y	N	_____
Rheumatic fever	Y	N	_____
Heart abnormalities	Y	N	_____
Asthma	Y	N	_____
Diabetes	Y	N	_____
Epilepsy	Y	N	_____
Heat intolerance	Y	N	_____

Back pain	Y	N	_____
Leg pain	Y	N	_____
Neck pain	Y	N	_____
Severe allergies	Y	N	_____
Any infectious diseases	Y	N	_____
Any neurological disorders	Y	N	_____
Any neuromuscular disorders	Y	N	_____
Are you currently on any medications?	Y	N	_____
Have you had the flu in the last two weeks?	Y	N	_____
Have you recently had any injuries?	Y	N	_____
Do you have any recurring muscle or joint injuries?	Y	N	_____
Is there any other condition not previously mentioned which may affect your exercise performance?	Y	N	_____

### **Lifestyle habits**

Do you exercise regularly?	Y	N
If YES, how many hours per week?	_____	
Do you smoke tobacco or any other nicotine products?	Y	N
If YES, how much per week?	_____	
Do you consume alcohol?	Y	N
If YES, how many standard drinks per week?	_____	
Do you consume tea and/or coffee?	Y	N
If YES, how much per week?	_____	

---

Participant name

---

Date

---

Participant signature

## **APPENDIX F**

### **DIETARY STANDARDISATION INSTRUCTIONS**

**PREPARED BY PROFESSOR LOUISE BURKE,  
DEPARTMENT OF SPORTS NUTRITION, AIS**

## **The influence of ice slurry consumption on thermoregulation and sub-maximal exercise performance in the heat**

**Chief investigator: Rodney Siegel (PhD Candidate)**

**School of Exercise, Biomedical and Health Sciences**

**Edith Cowan University**

**100 Joondalup Drive, Joondalup, WA 6027**

**Phone: 6304 5156 / email: r.siegel@ecu.edu.au**

In this study, we will be investigating effect of both ice slurry ingestion and cold water immersion on fatigue during prolonged running. To do this effectively, we need to reduce the “day to day variability” in running performance that might otherwise mask small, alterations in exercise performance. One tactic is to standardise all the conditions under which trials are performed – including dietary preparation. Important factors include:

- Amount of carbohydrate and energy eaten during the 24 hours before the trial
- Fluid intake on the day before and morning of the trial
- Pre-trial meal

These instructions will help you to achieve a similar preparation for each trial

### **Carbohydrate and fluid goals**

Aim: we want you to eat at least 6 g of carbohydrate per kg of your body weight on the day before each trial, and the same pre-trial meal on the morning of your trial (providing at least 1 g carbohydrate/kg). We also want you to consume at least 2 litres of fluid on this day (including all drinks consumed at meals or during training), and 400 ml of fluid at the meal consumed just before the trial.

Steps:

1. Fill in your name..... and  
current body weight?.....kg
2. Calculate your carbohydrate intake (minimum) for the day before the trial:  
 $6 \times \text{BM} = \dots\dots\dots\text{g}..$

Calculate your carbohydrate intake (minimum) for the last meal, eaten 2  
hours before you start the trial:  $1 \times \text{BM} = \dots\dots\dots\text{g}..$

3. Keep a food record for the day before your first trial, concentrating on the carbohydrate-rich foods found in the table over the page, and the amount of fluid consumed. Use the table on the following page to add up how much carbohydrate is eaten at each meal or snack. Aim for the targets of at least 6 g/kg and at least 1 g/kg. Each of these “blocks” of food provides approximately 50 g of carbohydrate. It is not necessary to eat a whole block, or round numbers of blocks. Try to keep count in terms of quarter or half blocks
4. Once you have completed the first day’s record, this sets the amount that you need to eat for the next trials. It is simplest to try to repeat a very similar meal pattern for each of these days – i.e. stick to the same type and amount carbohydrate foods. If this is impractical, use the carbohydrate counter to replace one carbohydrate food with the amount of another carbohydrate choice that provides a similar amount of carbohydrate.

**Example**, on day one you might have eaten 2 rounds of cheese and salad sandwiches (4 thin slices of bread) for lunch, with a Juice Popper (unsweetened orange juice). The carbohydrate counter tells you that this is equal to 1 block (50 g carbohydrate) for the bread and just under a half block (or about 20 g of carbohydrate) for the Popper. If you want to swap the lunch menu, this same amount of carbohydrate could be found in 2 english muffins (with a similar kind of filling) and one carton of low fat flavoured yoghurt.

5. Keep a record of each day’s food intake so that we can check how well you were able to duplicate your carbohydrate intake and fluid intake for the next trials.
6. Repeat the same process for the meal eaten ~ 2 hours before the trial

## Ready reckoner of 50 g carbohydrate serves from common foods

Professor Louise Burke, Australian Institute of Sport

### CEREALS

Wheat biscuit cereal (e.g. Weetbix)	60g (5 biscuits)
‘Light’ breakfast cereal (e.g. Cornflakes, Weeties)	60 g (2 cups)
‘Muesli’ flake breakfast cereal (e.g. Sustain)	65 g (1.5 cups)
Toasted muesli	90 g (1 cup)
Porridge - made with milk	350 g (1.3 cups)
Porridge - made with water	550 g (2.5 cups)
Rolled oats	90 g (1 cup)
Cereal bar	2.5 x 30 g bar, 3 x 25 g bar
Rice cakes	6 thick or 10 thin
Rice, boiled	180g (1 cup)
Pasta or noodles, boiled	200 g (1.3 cups)
Canned spaghetti	440 g (large can)
Crispbreads and dry biscuits	6 large or 15 small
Fruit filled biscuits	5
Plain sweet biscuits	8-10
Cream filled/chocolate biscuits	6
Bread	110 g (4 slices white or 3 thick wholegrain)
Bread rolls	110 g (1 large or 2 medium)
Pita and lebanese bread	100 g (2 pita)
Chapati	150 g (2.5)
English muffin	120 g (2 full muffins)
Crumpet	2.5
Cake-style muffin	115 g (1 medium)
Pancakes	150 g (2 medium)
Scones	125 g (3 medium)



Iced fruit bun	105 g (1.5)
Croissant	140 g (1.5 large or 2 medium)
Rice-cream or creamed rice	330 g (1.5 cups)
<b>FRUIT</b>	
Fruit crumble	1 cup
Fruit packed in heavy syrup	280 g (1.3 cups)
Fruit stewed/canned in light syrup	520 g (2 cups)
Fresh fruit salad	500 g (2.5 cups)
Bananas	2 medium-large
Mangoes, pears, grapefruit and other large fruit	2-3
Oranges, apples and other medium size fruit	3-4
Nectarines, apricots and other small fruit	12
Grapes	350 g (2 cups)
Melon	1,000 g (6 cups)
Strawberries	1,800 g (12 cups)
Sultanas and raisins	70 g (4 Tbsp)
Dried apricots	115 g (22 halves)
<b>VEGETABLES AND LEGUMES</b>	
Potatoes	350g potato (one very large or 3 med)
Sweet potato	350 g (2.5 cups)
Corn	300 g (1.2 cups creamed corn or 2 cobs)
Green Beans	1,800 g (14 cups)
Baked beans	440 g (1 large can)
Lentils	400 g (2 cups)
Soy beans and kidney beans	400 g (2 cups)
Tomato puree	1 liter (4 cups)
Pumpkin and peas	700 g (5 cups)
<b>DAIRY PRODUCTS</b>	

Milk	1 liter
Flavoured milk	560 ml
Custard	300 g (1.3 cup)
‘Diet’ yogurt and natural yogurt	800 g (4 individual tubs)
Flavoured non-fat yogurt	350 g (2 x 200 g individual tubs)
Ice-cream	250 g (5 scoops)
<b>SUGARS AND CONFECTIONERY</b>	
Sugar	50 g
Jam	3 Tbsp
Syrups	4 Tbsp
Honey	3 Tbsp
Chocolate	80 g
Mars Bar (~ 60 g bar)	1.5 bars
Jelly confectionery	60g
<b>MIXED DISHES</b>	
Pizza	200 g (medium -1/4 thick or 1/3 thin)
Hamburgers	1.3 Big Macs
Lasagna	400 g serve
Fried rice	200 g (1.3 cups)
<b>DRINKS</b>	
Fruit juice - unsweetened	600 ml
Fruit juice - sweetened	500 ml
Cordial	800 ml
Soft drinks and flavoured mineral water	500 ml
Fruit smoothie	250-300 ml
<b>SPORTS FOOD</b>	

Sports drink	700 ml
Carbohydrate loader supplement	250 ml
Liquid meal supplement	250-300 ml
Sports bar	1-1.5 bars
Sports gels	2 sachets
Glucose polymer powder	60 g

**TRIAL 1: DAY BEFORE****date:****name.....**

Meal	FOOD AND DRINKS	CALCULATION OF CARBOHYDRATE CONTENT	CALCULATION OF ML OF FLUID CONSUMED
Breakfast			
Lunch			
Dinner			
Snacks			

Total carbohydrate (AIM = g).....

Total fluid (aim = &gt; 2000 ml) .....

**TRIAL 1: MORNING OF TRIAL – LAST MEAL (2 HOURS PRE TRIAL)**

**date:**                      **name.....**

Meal	FOOD AND DRINKS	CALCULATION OF CARBOHYDRATE CONTENT	CALCULATION OF ML OF FLUID CONSUMED
		AIM =      g	AIM = 400 ML

Note: if you have a late morning/early afternoon trial, you may choose to eat an early breakfast, followed by this last meal. If so, please record the breakfast and repeat for all subsequent trials

Meal	FOOD AND DRINKS	CALCULATION OF CARBOHYDRATE CONTENT	CALCULATION OF ML OF FLUID CONSUMED
		AIM =      g	AIM = 400 ML

## APPENDIX G

### RESEARCH PROPOSAL AND ETHICS APPROVAL



JOONDALUP CAMPUS

100 Joondalup Drive,  
Joondalup  
Western Australia 6027  
Telephone 134 328  
Facsimile (08) 9300 1257

ABN 54 361 405 361

CRRCS IPC 00279B

26<sup>th</sup> August, 2008

Mr Rodney Siegel  
28 Bathurst St  
DIANELLA WA 6059

Dear Mr Siegel,

It is with pleasure that I write on behalf of the Research Students and Scholarships Committee who have approved your PhD research proposal – **The influence of precooling and warm-up interventions on exercise performance.**

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 clearance has been approved. Your ethics approval number is **2911** and period of approval: **25 August 2008 to 21 January 2011.**

You may now commence data collection.

Approval is given for your supervisory team to consist of:

<i>Principal Supervisor:</i>	Dr Paul Laursen
<i>Co-Principal Supervisor:</i>	A/Prof Ken Nosaka

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://www.ecu.edu.au/GPPS/legal\\_legis/uni\\_rules.html](http://www.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 web site: <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]

Finally, could I take this opportunity to offer you our best wishes for your research and the development of your thesis.

Sincerely

Karen Leckie  
Manager  
Graduate Research School

# Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat

RODNEY SIEGEL<sup>1</sup>, JOSEPH MATÉ<sup>1</sup>, MATT B. BREARLEY<sup>2</sup>, GREIG WATSON<sup>1</sup>, KAZUNORI NOSAKA<sup>1</sup>, and PAUL B. LAURSEN<sup>1</sup>

<sup>1</sup>School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, WA, AUSTRALIA; and <sup>2</sup>National Heat Training and Acclimatisation Centre, Northern Territory Institute of Sport, AUSTRALIA

## ABSTRACT

SIEGEL, R., J. MATÉ, M. B. BREARLEY, G. WATSON, K. NOSAKA, and P. B. LAURSEN. Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat. *Med. Sci. Sports Exerc.*, Vol. 42, No. 4, pp. 717–725, 2010. **Purpose:** To investigate the effect of ice slurry ingestion on thermoregulatory responses and submaximal running time in the heat. **Methods:** On two separate occasions, in a counterbalanced order, 10 males ingested 7.5 g·kg<sup>-1</sup> of either ice slurry (–1°C) or cold water (4°C) before running to exhaustion at their first ventilatory threshold in a hot environment (34.0°C ± 0.2°C, 54.9% ± 5.9% relative humidity). Rectal and skin temperatures, HR, sweating rate, and ratings of thermal sensation and perceived exertion were measured. **Results:** Running time was longer ( $P = 0.001$ ) after ice slurry (50.2 ± 8.5 min) versus cold water (40.7 ± 7.2 min) ingestion. Before running, rectal temperature dropped 0.66°C ± 0.14°C after ice slurry ingestion compared with 0.25°C ± 0.09°C ( $P = 0.001$ ) with cold water and remained lower for the first 30 min of exercise. At exhaustion, however, rectal temperature was higher ( $P = 0.001$ ) with ice slurry (39.36°C ± 0.41°C) versus cold water ingestion (39.05°C ± 0.37°C). During exercise, mean skin temperature was similar between conditions ( $P = 0.992$ ), as was HR ( $P = 0.122$ ) and sweat rate ( $P = 0.242$ ). After ice slurry ingestion, subjects stored more heat during exercise (100.10 ± 25.00 vs 78.93 ± 20.52 Wm<sup>-2</sup>,  $P = 0.005$ ), and mean ratings of thermal sensation ( $P = 0.001$ ) and perceived exertion ( $P = 0.022$ ) were lower. **Conclusions:** Compared with cold water, ice slurry ingestion lowered preexercise rectal temperature, increased submaximal endurance running time in the heat (+19% ± 6%), and allowed rectal temperature to become higher at exhaustion. As such, ice slurry ingestion may be an effective and practical precooling maneuver for athletes competing in hot environments. **Key Words:** PRECOOLING, RECTAL TEMPERATURE, THERMOREGULATION, TIME TO EXHAUSTION

The rise in core body temperature ( $T_{re}$ ) associated with exercise in hot environments is generally thought to be the principle contributing factor causing fatigue and the reduction in motor output observed during prolonged exercise in the heat (13,32). A fundamental concept in the thermoregulatory literature is that the termination of prolonged exercise in the heat seems to coincide with the attainment of a critically high  $T_{re}$  (15,29). For example, Gonzalez-Alonso et al. (15) showed that despite differences in starting  $T_{re}$ , subjects consistently fatigued at the same  $T_{re}$ . Such an occurrence may serve as a protective mechanism aimed at reducing motor output and heat production before the development of severe heat illness.

As thoroughly reviewed by Marino (24) and Quod et al. (33), precooling is a useful strategy for combating the detri-

mental effects that heat stress has on exercise performance. The main benefit of precooling is the lowering of  $T_{re}$  before exercise in the heat, thereby increasing heat storage capacity and in turn prolonging or even preventing attainment of critical core temperatures. This consequently improves endurance performance in hot conditions. Precooling maneuvers investigated to date have been achieved almost exclusively via external cooling procedures, such as cold water immersion or wearing ice jackets (34), with limited exploration into the potential benefits of internal cooling modalities. Lee et al. (22) investigated the effect of cold (4°C) and warm (37°C) water ingestion before, and during, exercise on cycling performance in hot, humid conditions. Compared with warm water, cold water ingestion reduced rectal temperature ( $T_{re}$ ) by 0.5°C ± 0.1°C before exercise and significantly increased cycling time to exhaustion by 23% ± 6%. It is difficult to ascertain whether the lower mean  $T_{re}$  throughout the trial and subsequent improved exercise performance was due to the cooling effect of the cold water before or during exercise; however, it is probable that both factors contributed.

A more aggressive and practical internal precooling technique might arise from the ingestion of an ice slurry mixture. Ice slurries, commonly called slushies, are icy mixtures that are consumed as a drink. Changing the physical state of

Address for correspondence: Rodney Siegel, B.App.Sc. (Hons), School of Exercise, Biomedical and Health Sciences, Edith Cowan University, 270 Joondalup Dr, Joondalup, WA, Australia 6027; E-mail: r.siegel@ecu.edu.au. Submitted for publication May 2009. Accepted for publication August 2009.

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## The influence of ice slurry ingestion on maximal voluntary contraction following exercise-induced hyperthermia

Rodney Siegel · Joseph Maté · Greig Watson ·  
Kazunori Nosaka · Paul B. Laursen

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**Abstract** The purpose of this study was to determine whether ingestion of a small bolus of ice slurry ( $1.25 \text{ g kg}^{-1}$ ) could attenuate the reduction in maximal voluntary isometric contraction (MVC) torque output during a 2-min sustained task following exercise-induced hyperthermia. On two separate occasions, 10 males (age:  $24 \pm 3$  years,  $\dot{V}O_{2\text{peak}}$ :  $49.8 \pm 4.7 \text{ ml kg}^{-1} \text{ min}^{-1}$ ) ran to exhaustion at their first ventilatory threshold in a hot environment ( $34.1 \pm 0.1^\circ\text{C}$ ,  $49.5 \pm 3.6\%$  RH). Prior to and after exercise, subjects performed a 2-min sustained MVC of the right elbow flexors in a thermoneutral environment ( $24.6 \pm 0.8^\circ\text{C}$ ,  $37.2 \pm 4.5\%$  RH). The post exercise MVC was performed immediately following the ingestion of either  $1.25 \text{ g kg}^{-1}$  of ice slurry ( $-1^\circ\text{C}$ ; ICE) or warm fluid ( $40^\circ\text{C}$ ; CON), in a counterbalanced and randomised order. Run time to exhaustion ( $42.4 \pm 9.5$  vs.  $41.7 \pm 8.7$  min;  $p = 0.530$ ), and rectal ( $39.08 \pm 0.30$  vs.  $39.08 \pm 0.30^\circ\text{C}$ ;  $p = 0.934$ ) and skin temperatures ( $35.26 \pm 0.65$  vs.  $35.28 \pm 0.67^\circ\text{C}$ ;  $p = 0.922$ ) and heart rate ( $189 \pm 5$  vs.  $189 \pm 6$  beats  $\text{min}^{-1}$ ;  $p = 0.830$ ) at the end of the run were similar between trials. Torque output

during the post-exercise 2-min sustained MVC was significantly higher ( $p = 0.001$ ) following ICE ( $30.75 \pm 16.40 \text{ Nm}$ ) compared with CON ( $28.69 \pm 14.88 \text{ Nm}$ ). These results suggest that ice slurry ingestion attenuated the effects of exercise-induced hyperthermia on MVC, possibly via internal thermoreceptive and/or temperature-related sensory mechanisms.

**Keywords** Thermoreception · Thermoregulation · Internal cooling · Isometric strength · Elbow flexors · Rectal temperature

### Introduction

Fatigue during exercise in the heat is in large part caused by central mechanisms pertaining to the increase in body core temperature ( $T_c$ ) (Nybo 2008). This theory is based on evidence that trained subjects exercising in hot environments terminate exercise at a  $T_c$  of  $\sim 40^\circ\text{C}$  regardless of starting temperature, or rate of rise in  $T_c$  (Gonzalez-Alonso et al. 1999; Nielsen et al. 1993). Additionally, several studies have shown the independent effects of  $T_c$  on maximal voluntary force production and voluntary activation using passive heating methods (Morrison et al. 2004; Thomas et al. 2006; Todd et al. 2005). For example, under passive resting conditions, Thomas et al. (2006) observed reductions in maximal voluntary contraction (MVC) and central activation with  $0.5^\circ\text{C}$  incremental increases in  $T_c$  from  $37.2$  to  $39.5^\circ\text{C}$  using a liquid conditioning garment. Once  $T_c$  was lowered back to resting levels, force production and central activation were restored (Thomas et al. 2006). Moreover, in a study using exercise in the heat to induce hyperthermia, Nybo and Nielsen (2001) showed that neuromuscular function of both the exercised (legs) as


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R. Siegel (✉) · J. Maté · G. Watson · K. Nosaka ·  
P. B. Laursen  
School of Exercise, Biomedical and Health Sciences,  
Edith Cowan University, 270 Joondalup Drive,  
Joondalup, WA 6027, Australia  
e-mail: r.siegel@ecu.edu.au

P. B. Laursen  
New Zealand Academy of Sport, Auckland, New Zealand

P. B. Laursen  
Sport Performance Research Institute New Zealand (SPRINZ),  
Auckland University of Technology, Auckland, New Zealand

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