The Effect of Progressive Heat acclimation on Change in Body Heat Content

Martin Poirier
B.Sc. University of Ottawa, 2011

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements for the degree of
Masters of Science in Human Kinetics

School of Human Kinetics, Faculty of Health Sciences,
University of Ottawa, Ottawa, Canada

2013

ACKNOWLEDGEMENTS

I wish to thank the following individuals for their support and guidance in the development and completion of this thesis. Without your help and encouragement this would not have been possible.

To Dr. Glen Kenny - Thank you for giving me the opportunity to pursue my Masters of Science degree under your supervision. Your continuous support and guidance coupled to your ability to motivate and encourage me throughout the ups and downs of the past two years make you an excellent mentor.

To my committee members Dr. Pascal Imbeault and Dr. Denis Prud'homme – Thank you for your time and effort in providing me with constructive feedback on my project.

To my fellow Human and Environmental Physiology Research Unit colleagues – Thank you for your continuous encouragement and support throughout this project.

A special thanks to Dr. Ollie Jay and Dr. Daniel Gagnon, whose knowledge, expertise and advice contributed greatly to the elaboration of the experimental protocol.

A special thanks to Brian Friesen for being my sidekick during this project. Your help, support and encouragement has helped me complete this thesis.

Thank you to all of the participants who volunteered to take part in my project. Your time and commitment towards my thesis is greatly appreciated.

Finally, I would like to thank my mother, Lyne and my father, Pierre. You have always been there to support me, and it is because of you that I continue to persevere towards my ambitions and goals.

I would like to also thank my girlfriend, Shalane. Your encouragement and support over the past two years have helped me succeed and become the person I am today.

Abstract

Heat acclimation increases the local heat loss responses of sweating and skin blood flow which is thought to persist for up to 3 weeks post-acclimation. However, the extent to which increases in local heat loss affect whole-body heat loss as a function of increasing levels of heat stress remains unresolved. Using direct calorimetry, we examined changes in whole-body evaporative heat loss (EHL) during progressive increases in metabolic heat production 1) prior to (Day 0), during (Day 7) and following a 14-day heat acclimation protocol (Day 14) – Induction phase, and; 2) at the end of a 1-week (Day 21) and 2-week decay period (Day 28) – Decay phase. Ten males performed intermittent exercise (3 x 30-min (min) bouts of cycling at 300 (Ex1), 350 (Ex2), and 400 watts·meters^2 (W·m^2) (Ex3) separated by 10 and 20 min rest periods, respectively). During the induction period, EHL at Day 7 was increased at each of the three exercise bouts (Ex1: + 6%; Ex2 +8%; Ex3: +13%, all $p \leq 0.05$) relative to Day 0 (EHL at Ex1: 529 W; Ex2: 625 W; Ex3: 666 W). At Day 14, EHL was increased for all three exercise bouts compared to Day 0 (Ex1: 9%; Ex2: 12%; Ex3: 18%, all $p \leq 0.05$). As a result, a lower cumulative change in body heat content (ΔH_b) was measured at Day 7 (-30%, $p \leq 0.001$) and Day 14 (-47%, $p \leq 0.001$). During the decay phase, EHL at Day 21 and 28 was only reduced in Ex 3 ($p \leq 0.05$) compared to Day 14. In parallel, ΔH_b increased by 39% ($p = 0.003$) and 57% ($p \leq 0.001$) on Day 21 and Day 28 relative to Day 14, respectively. When Day 28 was compared to Day 0, EHL remained elevated in each of the exercise bouts ($p \leq 0.05$). As such, ΔH_b remained significantly lower on Day 28 compared to Day 0 (-16%, $p = 0.042$). We show that 14 days of heat acclimation increases whole-body EHL during exercise in the heat which is maintained 14 days post-acclimation.

TABLE OF CONTENTS

Glossary

M – Rate of metabolic work load (W)

W – Rate of external workload (W)

(M-W) – Rate of metabolic heat production (W)

THL – Rate of total heat loss (W)

EHL – Rate of evaporative heat loss (W)

DHL – Rate of dry heat loss (W)

S – Rate of heat storage (W)

ΔH_b – Change in body heat content (kJ)

E_{req} – required evaporative heat loss to attain heat balance

E_{max} – maximum evaporative capacity of a given environment

VO_{2max} – Rate of maximal oxygen consumption (mL/kg/min)

T_{es} – Esophageal temperature (ºC)

T_{re} – Rectal temperature (ºC)

T_{sk} – Mean skin temperature (ºC)

HR – Heart rate (beats/min)

Ex (1, 2 and 3) – Exercise bouts

R (1, 2 and 3) – Recovery periods

USG – Urine specific gravity

PV – Plasma volume

RH – Relative humidity (%)

List of Figures and Tables

Figures

Tables

PART ONE: EMPIRICAL AND THEORETICAL CONSIDERATIONS

CHAPTER 1

INTRODUCTION

1.1. Introduction

The capacity of the human body to maintain a near constant internal temperature of 37°C is essential to ensure optimal physiological function and survival. Effective human thermoregulation in a given environment is dictated by the ability to balance the heat produced within the body with the heat lost to the environment. In a hot environment, the capacity for heat loss is primarily determined by the amount of sweat that can be evaporated. In fact, when ambient temperatures are equal or greater than that of the skin, the evaporation of sweat becomes the only mean by which the body can dissipate heat (Shibasaki & Crandall, 2011).

When metabolic heat production increases due to sustained physical activity or exercise, the sweat rate required to reach thermal balance increases proportionally (Benzinger, 1959). As a result, an individual's capacity to sweat for a given exercise intensity will directly influence the amount of heat stored within the body and the rise in core temperature. As core temperature increases, so does the demand for heat dissipation which results in a redirection of blood flow from the kidneys, spleen, liver and non-exercising muscles to the skin in order to promote a greater rate of heat loss (Crandall & Gonzalez-Alonso, 2010). This blood redistribution to the cutaneous circulation reduces central blood volume which in turn, stimulates an elevation in heart rate to maintain cardiac output (Crandall & Gonzalez-Alonso, 2010). In situations where elevated and sustained sweating occurs, a significant loss of body water and electrolytes can take place which could further disrupts circulatory and thermoregulatory function in heat stressed individuals (Maughan & Shirreffs, 2004; Nielsen, et al., 1993; Sawka, 1992; Wendt, van Loon, & Lichtenbelt, 2007).

Since the early twentieth century, heat acclimation has been used by the mining industry, the military as well as various athletic sport disciplines to minimize the detrimental and potentially fatal effects of heat stress (Armstrong & Maresh, 1991; Wyndham et al., 1954). The term heat acclimatization refers to the physiological adaptations induced by repeated prolonged exposures to hot environmental conditions. Theoretically speaking, "acclimatization" refers to the physiological adaptations that occur in a natural setting while "acclimation" refers to the adaptations that arise in a controlled environment which is often the case in experimental studies. These words are often used interchangeably in the literature. For this thesis dissertation, the term "acclimation" will be used throughout.

Since environmental heat stress and exercise synergistically increase physiological strain, progressive acclimation to the heat is recommended to reduce the negative and potentially dangerous outcomes of heat stress. In general, the acclimation process takes between 7 and 14 days, and approximately 75% of these adaptations are evident after 4 to 6 days (Armstrong & Maresh, 1991; Pandolf, 1998). The typical physiological adaptations associated with heat acclimation are improved sweating and skin blood flow responses, reduced core and skin temperatures as well as improved fluid balance and cardiovascular stability (Hori, 1995; Sawka, B., & Pandolf, 1996). Altogether, these adaptations contribute to substantial reductions in cardiovascular strain and significantly improve an individual's capacity to work in the heat (Pandolf, 1998). The magnitude of these physiological improvements is directly dependent upon the intensity, duration, frequency and number of heat exposures (Sawka et al., 1996). It is generally accepted that repeated 1-hour exercise sessions in the heat produce the best improvements in a person's capacity to dissipate heat.

Research that has been carried out to study heat acclimation has been primarily concentrated on its induction, such that there is a paucity of information available on the rate of decay (or loss) of the aforementioned physiological adaptations (Garrett et al., 2011). Studies suggest that the classic improvements in thermoregulatory and circulatory function gained during heat acclimation are lost approximately 3 weeks after the cessation of heat exposure (Adam, Fox, Grimby, Kidd, & Wolff, 1960; Armstrong & Maresh, 1991; Garrett, et al., 2011; Pandolf, 1998; Williams, Wyndham, & Morrison, 1967; Wyndham & Jacobs, 1957). It follows that the cardiovascular adaptations that arise early during heat acclimation are the first to be lost followed by a slower decay of sudomotor function (Garrett, Goosens, Rehrer, Patterson, & Cotter, 2009; Garrett, et al., 2011; Pandolf, 1998; Pandolf, Burse, & Goldman, 1977; Saat, Sirisinghe, Singh, & Tochihara, 2005). Despite this proposed timeline, earlier studies that have evaluated the decay of heat acclimation are limited by small sample sizes (i.e., 1-3 participants) (Bean & Eichna, 1943; Eichna, Bean, Ashe, & Nelson, 1945; Robinson, Turrell, Belding, & Horvath, 1943; Stein, Eliot, & Bader, 1949), incomplete heat acclimation (i.e., 2 days of acclimation and groups not equally acclimated) (Henschel et al., 1943; Lind & Bass, 1963) or inappropriate measurements (i.e., oral temperature) (Adam, et al., 1960; Foster, Ellis, Dore, Exton-Smith, & Weiner, 1976; Wyndham & Jacobs, 1957).

Despite the extensive research on heat acclimation, a number of experimental limitations make it difficult to determine the extent to which the body's thermoregulatory capacity is altered during the induction and decay of heat acclimation. The challenges in the interpretation of previous research is limited by the fact that 1) some studies may have used participants already demonstrating a certain degree of heat acclimation (i.e. repeated daily exposure due to place of residence and/or work environment); 2) the environmental

conditions differed from study to study (humid *vs*. dry); 3) the duration and method of heat acclimation varied between studies (i.e. exercise *vs.* passive heating); and 4) the use of absolute work rates and heat loads before and after a period of acclimation may have led to a reduction in the requirements for heat loss in the post-acclimation testing sessions thereby affecting the measured heat loss responses. When comparing the body's physiological capacity to acclimate, it is important that environmental (e.g. humidity, temperature, heat production) and physical (e.g. body mass/surface area) characteristics be taken into consideration (Havenith et al., 1998). When the environment remains unchanged, using non-weight bearing exercise (i.e. cycling) and fixed rates of metabolic heat production (adjusted for body area available for heat exchange) can ensure a uniform thermal load between participants (Gagge & Gonzalez, 1996). This is essential to appropriately assess changes in thermoregulatory responses following heat acclimation. In addition, most studies have only used a single thermal load pre- and post-acclimation to evaluate changes in heat loss responses, therefore, our understanding of how the body's physiological capacity to dissipate heat changes as a function of increasing levels of heat stress remains unresolved.

It is well recognized that the most important improvement that occurs with heat acclimation is an increase in the body's capacity to sweat (Bean & Eichna, 1943; Buono et al., 2009; Cotter et al., 1997; Fox et al., 1963a, 1963b; Ladell, 1951; Nielsen et al., 1993; Patterson et al., 2004; Senay et al., 1976). This has been associated to a centrally mediated response which includes a reduction in the core temperature onset threshold at which sweating is initiated (Cotter, Patterson, & Taylor, 1997; Fox, Goldsmith, Kidd, & Lewis, 1963; Nadel, Pandolf, Roberts, & Stolwijk, 1974; Shvartz, Bhattacharya, Sperinde, Brock, Sciaraffa, & Van Beaumont, 1979) as well as the number of heat activated sweat glands,

which in contrast, has been shown to remain unchanged following acclimation (Candas, Libert, & Vogt, 1980; Inoue, Havenith, Kenney, Loomis, & Buskirk, 1999; Lee, Kim, Shin, Min, & Yang, 2010; Peter & Wyndham, 1966). Conversely, other studies have suggested that peripheral adaptations such as greater sweating sensitivity to changes in core temperature (i.e., the slope of the response) (Henane & Bittel, 1975; Roberts, Wenger, Stolwijk, & Nadel, 1977; Wyndham, 1967) and hypertrophy of the sweat glands (Sato et al., 1990) may account for most of the increase in sweat production following acclimation. Despite these findings, other studies have reported no changes (Burton et al., 1940; Fox et al., 1967; Hessemer et al., 1986) or even reductions in the sweating response post-acclimation (Dasler & Hardenbergh, 1971; Havenith & Middendorp, 1986). These mixed results between studies can be attributed to the multiple methodological discrepancies between studies that were enumerated previously. It has also been suggested that heat acclimation can result in different regional improvements such that a greater relative increase in sweating occurs in the limbs compared to the torso (Hofler, 1968; Regan, Macfarlane, & Taylor, 1996; Shapiro, Hubbard, Kimbrough, & Pandolf, 1981), however, this has not been a universal finding (Cotter, et al., 1997; Patterson, Stocks, & Taylor, 2004). Therefore, the measured improvements in sweating may be dependent on the local site that is being measured. Ultimately, the ability to produce more sweat following acclimation results in a greater potential for heat dissipation which promotes a greater evaporative cooling capacity depending on the environment (i.e., dry vs. humid).

Since the body's physiological capacity to dissipate heat is improved with heat acclimation, the amount of heat stored within the body should theoretically decrease in response to a given thermal stress. It has been shown that body heat storage has remained unchanged (Buono, Heaney, & Canine, 1998; Garden, Wilson, & Rasch, 1966; Ladell,

1951; Shvartz, Saar, Meyerstein, & Benor, 1973), or reduced following heat acclimation (Eichna, Park, Nelson, Horvath, & Palmes, 1950; Horstman & Christensen, 1982; Shvartz, et al., 1973). Of note, all of the studies that have evaluated the induction and decay of heat acclimation have exclusively used local heat loss responses (i.e. sweating and skin blood) as well as core and skin temperature measurements to evaluate changes in the body's thermoregulatory capacity. However, it has been shown that the local heat loss measurements of sweating and skin blood flow may not accurately reflect whole-body heat exchange, and that core and skin temperatures may not accurately represent the residual body heat storage since the specific heat capacity of all the different tissues are not accounted for (Jay et al., 2007; Kenny et al., 2008).

1.2. Rationale and statement of the problem

Due to the methodological discrepancies between studies, it remains unknown the extent to which changes in local heat loss affect whole-body heat loss as a function of increasing levels of heat production during the induction and decay of heat acclimation. By assessing whole-body heat exchange in the modified Snellen calorimeter, we have access to a gold standard method to measure the physiological adaptations of the body's capacity to dissipate heat (i.e., whole-body heat loss) with progressive heat acclimation.

In order to accurately assess the extent to which the physiological capacity to dissipate heat changes at increasing heat loads, this study employed a novel intermittent exercise model which consisted of 3 non-weight bearing exercise bouts (i.e., cycling) at three fixed rates of metabolic heat production adjusted for body surface area (300, 350 & 400 watts·meters^2 (W·m^2). This exercise model was recently used to assess physiological sex differences in local sweat rate and whole-body evaporative heat loss (Gagnon &

Kenny, 2012) and ensured that the heat load from participant to participant was the same, not to mention prior to and following the acclimation period in this study.

1.3. Objective

The objective of this study was to evaluate the time course of heat acclimation induction and decay on whole-body heat loss (evaporative and dry heat loss) and the change in body heat content during exercise performed at increasing rates of metabolic heat production equal to 300, 350, and 400 $W \cdot m^2$.

1.4. Hypothesis

It was hypothesized that heat acclimation would result in an increased whole-body evaporative capacity at each of the three levels of metabolic heat production thereby resulting in a progressive decrease in body heat content. Secondly, it was hypothesized that the improvements in whole-body evaporative heat loss would gradually decline with each successive week (2 week decay period) of non-heat exposure consequently resulting in progressively greater body heat storage.

1.5. Relevance of the study

To date, a comprehensive study directed at advancing our understanding of whole-body responses to heat acclimation induction and decay has not been possible. In the current study, we used the world's only whole-body direct calorimeter (a device to precisely measure the amount of heat emitted by the human body) to accurately assess how a 14-day heat acclimation protocol affects the body's physiological capacity to dissipate heat at increasing levels of exercise heat production. By understanding how the body's

physiological capacity to dissipate heat adapts as a function of different levels of exercise heat stress, we can develop a better understanding of the human body's ability to thermoregulate during challenges associated with elevations in environmental heat load (higher ambient temperatures increases the requirements for evaporation and circulatory responses to achieve a given rate of heat dissipation), metabolic rate during exercise in the heat (greater increases in metabolic rate above resting levels augments the rate at which heat must be dissipated to the environment), or the combination of the two. Furthermore, this study will provide the framework for future research that may aim to evaluate how physical characteristics, sex, aging and/or chronic diseases affect the body's ability to adapt to heat stress conditions.

1.6. Delimitations and limitations

This study only evaluated heat acclimation induction and decay in younger males (18-25 years), therefore these data are not representative of other age ranges and may not be representative of female responses to heat acclimation. Furthermore, the study requires that participants be healthy and somewhat physically inactive, therefore the conclusions coming from this study are not directly applicable to individuals who may suffer from chronic diseases which may further alter thermoregulatory and cardiovascular control.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1. Human thermoregulation

Despite the diverse thermal environments found on earth, humans have the capacity to use powerful autonomic and behavioural effector responses to regulate their body core temperature at approximately 37ºC to ensure optimal physiological function and survival (Taylor, 2006). Classical studies from the 1800's and early 1900's have identified the hypothalamus as the thermoregulatory center of the body, which is responsible for the integration of all the afferent input from central and peripheral thermal receptors and appropriately adjusting various mechanisms to maintain core body temperature (Boulant & Bignall, 1973; Carlisle, 1969; Hensel, 1981). Increases and decreases in body temperature are sensed peripherally by cold and warm thermoreceptors located just under the epidermis and centrally by thermoreceptors located in the hypothalamus, along the spinal cord, in the abdominal cavity and in major blood vessels (Carter et al., 1999; Romanovsky, 2007). This system operates in a negative feedback loop which is constantly adjusting effector responses to cold or warm stimuli's to either augment heat production (i.e., shivering) and prevent or promote heat loss (i.e., vasoconstriction and vasodilation/sweating, respectively).

When exposed to an internal and/or external heat stress, afferent input from central and peripheral thermoreceptors is sent to the pre-optic anterior hypothalamus (PO/AH) (Fig. 1). Once integrated, thermoeffector signals modulate skin vasculature (i.e., initiate skin vasodilation) and sweat gland activity (i.e., increase sweat production) thereby increasing the rate of heat loss to the environment (Armstrong et al., 1993). These responses are crucial for the body to increase dry and evaporative heat loss in order to maintain a physiologically acceptable core temperature.

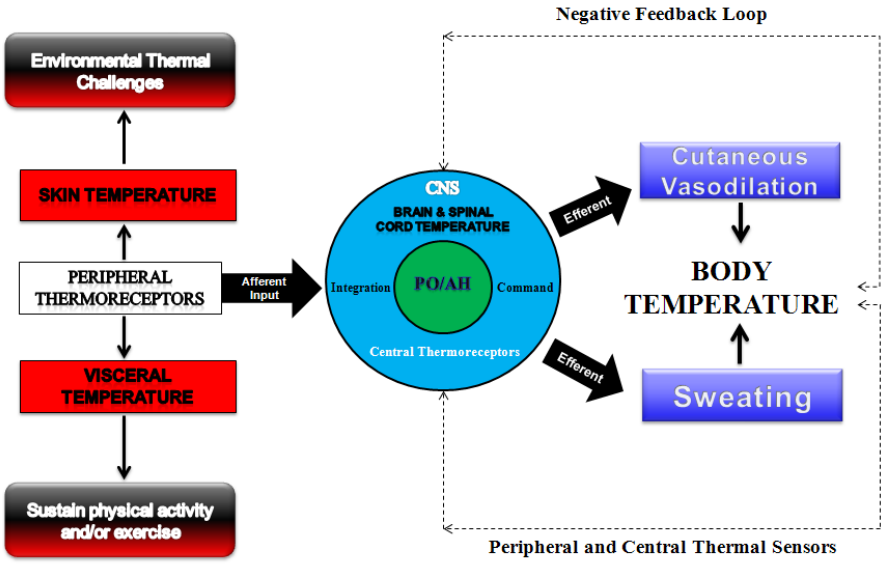

Figure 1. Illustration of the effector heat loss responses of cutaneous vasodilation and sweating in response to increasing skin and core temperature. (Adapted from Nagashima et al., 2000).

2.2. Heat balance

As homeotherms, humans have the capacity to maintain a near constant body temperature, this being independent of the temperature of its surroundings. In other words, the heat released within the body combined to the heat transmitted into the body must be counterbalanced by the heat loss to the environment. This concept is clearly illustrated by the following formula (Parsons, 2003):

$$\mathbf{M - W = (K + C + R + E_{SK}) + (C_{RES} + E_{RES}) + S}$$

Where all terms have units of W m^{-2} and,

M = rate of metabolic heat production
W = rate of mechanical work
K = rate of conductive heat loss
C = rate of convective heat loss from the skin
R = rate of radiative heat loss from the skin
$\mathbf{E_{SK}}$ = rate of evaporative heat loss from the skin
$\mathbf{C_{RES}}$ = rate of convective heat loss from pulmonary ventilation
$\mathbf{E_{RES}}$ = rate of evaporative heat loss from pulmonary ventilation
S = rate of body heat storage

Heat exchange with the environment occurs by internal heat exchanges inside the different tissues and compartments of the body as well as between the skin and the external environment. Internally, heat exchange occurs through convection and conduction while external heat exchange occurs by the means of convection, conduction, radiation and evaporation (Wendt et al., 2007). Conduction refers to the transfer of heat when a surface comes into direct contact with another surface, which largely depends on the temperature difference between the two surfaces (Keim et al., 2002). Secondly, radiation is the mechanism by which heat is lost or gained from the body to the environment by means of electromagnetic waves, which also depends on the thermal gradient between the body and the environment (i.e., solar radiation) (Keim et al., 2002). Heat transfer that occurs between a surface and a gas (i.e., air) or liquid (i.e., water) is called convection, and is dependent not only on the temperature gradient but also the rate of movement and the relative heat storage capacity of the gas or liquid (Keim et al., 2002). During heat stress, the most important heat loss mechanism is evaporative heat loss which consists of the evaporation of sweat from the surface of the skin. It follows that the amount of sweat that is evaporated is directly associated to the air velocity and partial pressure gradient between the skin and the environment (Keim et al., 2002).

From the presented heat balance formula, the heat stored within the body is dependent on the heat gain or heat loss: $\pm$ metabolic activity (M-W) $\pm$ radiation (R) $\pm$ conduction (K) $\pm$ convection ($C + C_{RES}$) – evaporation ($E_{SK} + E_{RES}$). When heat production is equivalent to the rate of heat loss, the body is in thermal balance. If heat production exceeds the body's ability to dissipate heat, the body stores heat and as a result core temperature rises. On the contrary, if heat loss is greater than heat production, negative heat storage occurs and core temperature will progressively decrease.

2.3. Heat loss responses during exercise

At the onset of exercise, the rate of metabolic heat production can increase significantly from resting levels (10- to 20-fold) (Sawka & Wenger, 1998). Since the muscles of the human body are only 20-30% efficient in converting energy from organic substrates to ATP, the remaining 70-80% is released as heat. In the early stages of exercise, the heat loss response will not instantly match the increase in metabolic heat production (Webb, 1995). As a result, heat is initially stored in the active musculature which causes muscle temperature to immediately increase (Nadel, 1984). As exercise continues, the sympathetic activity increases which results in vasoconstriction of the renal, hepatic and splanchnic circulation thus redirecting the blood to the active muscles (Rowell, 1974). Subsequently, the heat stored within the muscle will be transferred by conduction/convection to the blood perfusing the muscle (Lim et al., 2008). In addition, conductive heat transfer will also occur between the exercising muscles and the surrounding tissues and compartments. Once the heat is transmitted from the muscles to the core, internal temperature will rise, prompting an increase in the heat loss response mechanisms of skin blood flow and sweating. The core temperature at which these heat loss responses are initiated are referred to as *"thresholds"* and the slope of the skin blood flow/sweat response to increases in core temperature refers to the *"sensitivity"* of the response (Charkoudian, 2003).

2.3.1 Skin blood flow

The ability of the body to regulate skin blood flow at varying body temperatures is one of the central components of human thermoregulation. The control of skin blood flow is regulated by the sympathetic vasodilator system, which increases skin blood flow when exposed to a thermal stress. This system is accountable for 80-95% of the total increase in

skin blood flow during heat stress (Johnson & Proppe, 1996; Rowell, 1993), which consequently promotes greater convective heat transfer from the core to the periphery. In a thermoneutral environment, the skin receives ~ 500 mL (5-10% of the cardiac output) whereas during heat stress, up to 8 liters (50-70% of cardiac output) can be redirected to the skin in order to dissipate heat to the environment (Crandall et al., 1996; Rowell, 1974, 1993). This significant increase in skin blood flow leads to a decrease in stroke volume, central blood volume, aortic pressure, mean arterial pressure and cardiac output (Crandall & Gonzalez-Alonso, 2010). Consequently, a cardiovascular drift leads to an increase in heart rate and a reduction of vascular conductance in non-cutaneous beds in order to avoid significant reductions in arterial blood pressure and maintain appropriate levels of cardiac output to sustain the metabolic demands of the exercise (Crandall & Gonzalez-Alonso, 2010; Kounalakis et al., 2008; Rowell, 1974). This cardiovascular strain is further exacerbated when exercise is performed in the heat as a competition arises between the thermoregulatory system and the cardiovascular system to support the metabolic demand of the exercise as well as the heat transfer to the skin. If exercise is carried out for a prolonged period of time, maximal heart rate will be attained due to decreases in stroke volume. In such a situation, cardiac output will not be able to increase which will lead to a progressive reduction in mean arterial pressure (Rowell, 1974). If the net heat gain cannot be counterbalanced by the heat loss responses of skin blood flow and sweating, hyperthermia can occur and the risk of suffering from heat illnesses is increased.

2.3.2. Sweating

Thermal activation of sweating is the most important heat loss mechanism in humans. As ambient temperature exceeds skin temperature, the rate of dry heat loss (R, K, C) is reversed and the body gains heat from the environment (Nielsen, 1938; Wendt et al.,

2007). Under such conditions, evaporative heat loss becomes the only heat dissipating mechanism representing >80% of the total body heat loss during exercise as opposed to 25% in resting thermoneutral environments (Cain & McLellan, 1998; Gavin, 2003). This increase in sweating is essential to maintain a given rate of total heat loss.

Sweat glands are usually classified into two types, the apocrine and the eccrine gland, the later one being the main gland responsible of thermoregulatory sweating in humans (Shibasaki et al., 2006). Activated at the onset of puberty, the apocrine glands are innervated by adrenergic nerves and are distributed in the armpits and pubic regions and secrete a viscous fluid which has a distinct odour (Saga, 2002). On the contrary, the eccrine sweat glands are stimulated by cholinergic sympathetic nerves and secrete hypotonic sweat which consists of mainly water and electrolytes (Saga, 2002; Shibasaki & Crandall, 2011). Despite a large variability between individuals, the number of eccrine sweat glands is estimated to range anywhere between 2 to 4 million, the greatest density being on the forehead, followed by the upper limbs, the trunk and then the lower limbs (i.e., excluding the palms of the hands and the soles of the feet) (Kondo et al., 1998; Sato & Dobson, 1970). Interestingly, only ~5 % of sweat glands are active at once, signifying an outstanding potential for sweat production (Kenny & Journeay, 2010).

The rate at which sweat is produced depends on the environmental temperature as well as the metabolic work that is being performed. In fact, the amount of sweat that is produced is related to the frequency of the nerve impulses, which is mainly driven by an increase in core temperature as opposed to mean skin temperature (Nadel et al., 1971b; Nadel et al., 1974; Romanovsky, 2007; Werner, 2009). Despite the inherent differences of various exercise modalities, sports, occupational settings, individual characteristics and environmental conditions, research has shown that individuals can achieve sweat rates of

0.5 to 2.0 L • h^{-1} (Sawka et al., 2007), which can reach 10-15L per day under severe heat stress (Kenny & Journeay, 2010).

During the first few minutes of exercise, the increase in sudomotor activity occurs due to an increase in the number of heat activated sweat glands as well as an increase in the amount of sweat that is produced by each gland (Kondo et al., 2001). The near maximum recruitment of heat activated sweat glands has been shown to take as little as 8 min of passive heat stress and exercise (Kondo et al., 2001). It has been shown that during low exercise intensity (i.e., 35% of VO_{2max}), the increase in sweat rate is mediated by an increase in activated sweat glands and sweat gland output. As exercise intensity increases (i.e., 50 to 65% VO_{2max}), the increase in sweat rate is mainly due to an increase in sweat gland output and not to the number of heat activated sweat glands (Kondo et al., 1998). Furthermore, regional differences in sweating capacity have been reported at rest and during exercise in regard to sweat gland densities, sweat rates, sweating sensitivity and onset thresholds (Cotter et al., 1995, 1997; Hofler, 1968; Park & Tamura, 1992; Takano et al., 1996). Even though there is a high variability between subjects, these differences have been linked to a greater sweating response in the torso (i.e., back, chest & abdomen) as compared to the limbs (Nadel et al., 1971b).

An individual's whole-body sweat rate at steady-state should be mainly determined by the status of their heat balance, when it is normalized for differences in body surface area (Bain et al., 2011). In order to attain equilibrium between the rate of metabolic heat production and the rate of total heat loss, a sufficient amount of sweat is required to generate a rate of evaporation equal to the amount of heat that is generated by the combination of metabolic activity and dry heat exchange. When low-intensity exercise is performed in a temperate environment, whole-body sweat rate can be associated to the

estimation of the rate of evaporation required to reach thermal balance (E_{req}) (Lustinec, 1973). Ultimately, a greater E_{req} is linked to a greater whole-body sweat rate. When E_{req} is stabilized, it has been shown to be inversely proportional to the maximum evaporative capacity of a given environment (E_{max}) (Givoni & Bemer-Nir, 1963; Lustinec, 1973; Shapiro et al., 1982). In hot/dry climates, most of the sweat produced can be evaporated, but as relative humidity (RH) increases and the evaporative capacity exceeds the E_{max}, skin wettedness (i.e., portion of the skin that is covered in sweat) increases and dripping of sweat is most likely to occur which does not contribute to heat loss. In other words, as E_{max} approaches E_{req}, a reduction in sweating efficiency (i.e., amount of sweat that evaporates) is observed (Candas et al., 1979a).

2.4. Heat acclimation induction

More than two centuries ago, in 1768, Dr. James Lind of Haslar Hospital, Portsmouth UK, published a monograph entitled "Essay on Diseases Incidental to Europeans in Hot Climates which stated that repeated exposures to hot climates reduced possible danger to health (Shapiro et al., 1998). Since that time, numerous research projects have been carried out in order to further our understanding of the physiological responses to repeated heat exposures. As previously explained, the term "acclimatization" refers to the physiological adjustments that occur in a natural setting while "acclimation" refers to the adaptations that take place in a controlled environmental setting. Both terms are often used interchangeably in the literature.

The physiological adaptations that occur during prolonged heat exposure are associated to a decreased physiological strain elicited by a given intensity in a given hot environment, thereby significantly improving an individual's capacity to perform in any

thermally challenging environment. Due to the wealth of research that has been conducted over the years, it is well recognized that heat acclimation results in enhanced sweating and skin blood flow responses, reduced core and skin temperatures as well as improved fluid balance and cardiovascular stability (Hori, 1995; Sawka et al., 1996). Altogether, these physiological improvements synergistically reduce the negative and potentially dangerous outcomes of performing exercise or work in the heat.

Studies suggest that most of the physiological adaptations to heat acclimation occur within 7–10 days and that 75% of the physiological adaptations occur within the first 4 to 6 days (Armstrong & Maresh, 1991; Pandolf, 1998; Shapiro et al., 1998). During the early stages of acclimation, the modifications are more or less of cardiovascular nature while an increase in sweating capacity is the main adjustment that occurs in the later stages (up to 14 days) (Armstrong & Maresh, 1991).

2.4.1. Core temperatures

One of the classic signs of successful heat acclimation is a lower core temperature for a given exercise intensity in a given hot environment when compared to pre-acclimation values (Buono et al., 1998; Eichna et al., 1950; Horstman & Christensen, 1982; Ladell, 1951; Mitchell et al., 1976; Pandolf et al., 1988; Wyndham et al., 1973). This reduction in core temperature elevation during exercise has been primarily associated to more efficient heat loss mechanisms, most importantly evaporative heat loss. While this is evident in hot/dry environments, the evaporative cooling capacity in hot humid conditions is considerably reduced. However, studies that have evaluated core temperature responses during heat acclimation in hot-humid environments still report end-exercise core temperatures to be lower than pre-acclimation values (Buono et al., 1998; Garden et al.,

1966; Ladell, 1951; Mitchell et al., 1976; Shvartz et al., 1979; Shvartz et al., 1973; Wyndham et al., 1973). It is of common knowledge that resting core temperatures can decrease anywhere between 0.2 and 0.8°C following heat acclimation (Kampmann et al., 2008), which may account for the lower core temperature elevation during exercise in the heat.

Taking into account that the capacity to dissipate heat is improved with heat acclimation, it would be assumed that the amount of heat stored within the body would decrease as an individual would become more acclimated. Studies have shown that the amount of heat that is stored within the body has remained unchanged during exercise in humid heat (Buono et al., 1998; Garden et al., 1966; Ladell, 1951; Shvartz et al., 1973), and reduced following acclimation to dry heat (Eichna et al., 1950; Horstman & Christensen, 1982; Shvartz et al., 1973). Nonetheless, these studies used thermometric models to estimate changes in body heat content and previous research has shown that core and skin temperatures may not accurately represent the residual body heat storage since the specific heat capacity of all the different tissues are not accounted for (Jay & Kenny, 2007). Therefore, the estimation of whole-body heat storage using skin and core temperatures may lead to incorrect conclusions regarding the effects of heat acclimation and whole-body heat balance.

2.4.2. Sweating adaptations

The most important change that occurs during heat acclimation is the increase in whole-body sweat rate at a given exercise intensity or core temperature (Buono et al., 2009; Fox et al., 1963b; Nielsen et al., 1993; Senay et al., 1976), however, the mechanisms by which this occurs are not entirely understood. Studies evaluating sudomotor function following heat acclimation bring forward two potential explanations for the reported

improvements in sweat secretion. The first mechanism refers to a modification of the sweat glands themselves (i.e., sweat gland output, sweating sensitivity - peripheral mechanisms) and the second suggest an increase in the neural activation of sweat glands (i.e., number of heat activated sweat glands, lower onset threshold - central mechanisms), or a combination of both.

First and foremost, the sweating onset threshold following acclimation is reduced following acclimation (Cotter et al., 1997; Fox et al., 1963b; Nadel et al., 1974; Shvartz et al., 1979), as well as greater sweating sensitivity to changes in core temperature (Henane & Valatx, 1973; Roberts et al., 1977; Wyndham, 1967). It has been hypothesized that the changes in onset threshold are due to a greater firing rate of warm sensitive neurons at lower body temperatures which denotes a centrally mediated response, while sweating sensitivity is associated to a peripheral modulation of the sweat glands (Boulant, 2006; Nadel et al., 1971b; Nadel et al., 1974). Other studies have shown improvements in sweat production following heat exposure by stimulating the eccrine glands with pharmacological and electrical stimuli's therefore supporting the idea of a peripheral modification of the eccrine glands (Buono et al., 2009; Chen & Elizondo, 1974; Inoue et al., 1999; Lee et al., 2010). These findings are consistent with previous findings from Peter and Wyndham (1966) and Candas, Libert, and Vogt (1980) who demonstrated that the increase in sweating was associated a greater sweat output per gland as opposed to an increase in the maximum number of heat activated sweat glands following heat acclimation (Candas et al., 1980; Peter & Wyndham, 1966). In addition, Sato, Owen, Matthes, Sato, and Gisolfi (1990) further support the idea of a peripheral modification as the increase in sweat gland output in heat acclimatized monkeys was associated to an increase in tubular length and size of the eccrine glands (Sato et al., 1990).

Furthermore, some studies suggest that differential increases in local sweating occurs following heat acclimation, such that the post-acclimation limb sweat rates are elevated to a greater extent than central body sites (Hofler, 1968; Regan et al., 1996; Shvartz et al., 1979). However, other reports indicate that preferential sweat redistribution to the periphery does not take place following heat acclimation (Cotter, et al., 1997; Patterson, et al., 2004). Nevertheless, sweat production is significantly increased following repeated heat exposures and the percentage of the skin that will be covered in sweat post-acclimation will be greater, thus greatly amplifying the potential for evaporative heat loss. Due to this increase in skin wettedness, the chance of dripping is much greater, especially as the E_{req} approaches and exceeds the E_{max} (Candas et al., 1979a). Candas, Libert, and Vogt (1979) compared the relationship between sweating efficiency and skin wettedness following a 10-day passive heat acclimation protocol and determined that the portion of the skin that was covered by sweat increased from 83% in a non-acclimated state to as much as 100% following the 10-day heat exposure (Candas et al., 1979b). However, sweating efficiency decreased to as much as 53% following acclimation, thus implying that a significant amount of sweat had dripped and had not contributed to any heat loss but only leads to a quicker rate of dehydration.

Despite all these findings, it remains unclear to which extent the whole body's evaporative capacity changes as a function of increasing rates of metabolic heat productions during and following a 14-day heat acclimation protocol. Moreover, we are trying to understand improvements in evaporative capacity from local measurements which do not necessarily provide the best overview of how the whole-body's capacity to evaporate is improved following heat acclimation.

2.4.3. Skin blood flow adaptations

In addition to an enhanced evaporative cooling, changes in skin blood flow following heat acclimation have been shown to be initiated at a lower core temperature threshold which widens the core-to-skin thermal gradient, thus increasing the potential for heat loss from the body to the environment (Eichna et al., 1950; Roberts et al., 1977; Rowell et al., 1967). It has also been suggested that there is a moderate increase in the sensitivity of the skin blood flow response for a given rise in core temperature (Fox et al., 1963b; Ichinose et al., 2005; Sawka et al., 1989; Takeno et al., 2001). However, there is evidence that heat acclimation leads to a progressive reduction in skin blood flow (Eichna et al., 1950; Wyndham et al., 1968). This observation is thought to be the result of a decrease in skin temperature due to an increase in the evaporation of sweat from the skin surface (Nielsen, 1994). In return, the skin venous compliance will be reduced and enable that blood volume to be redistributed to the core which helps reduce the cardiovascular strain that is apparent during acute heat exposure.

2.4.4. Cardiovascular stability

In the first day of heat exposure, heart rate for a given exercise intensity reaches levels much higher than what is observed in a temperate environment. This initial cardiovascular strain is the result of large amounts of blood being redistributed to the periphery to enable greater heat dissipation to the environment. However, a considerable increase in cardiovascular stability becomes apparent with each subsequent heat exposure indicated primarily by a lower exercising heart rate for a given intensity (Armstrong & Maresh, 1991) and increased blood volume (Harrison, 1985; Sawka et al., 2000).

It is generally assumed that the cardiovascular and thermoregulatory improvements witnessed during the early stages of heat acclimation are mediated by an expansion of plasma volume (Harrison, 1985; Sawka et al., 2000; Senay et al., 1976). This increase in plasma volume can vary anywhere from +3% to +27% (Armstrong et al., 1987) and can result in a 15 to 25% decrease in heart rate for a given exercise intensity (Sciaraffa et al., 1981). Plasma volume expansion is thought to be mediated by an influx of proteins as well as increased sodium retention (renal and sweat) and shifting of body water to the circulatory system (Taylor, 2000). Furthermore, aldosterone and arginine vasopressin (AVP) are two key hormones in the control of plasma volume expansion. Aldosterone is produced by the adrenal cortex and helps reabsorb sodium ions in the kidney and sweat glands. On the other hand, AVP is an anti-diuretic hormone that helps the body retain water and solutes in the kidneys as well as maintain blood pressure. When dehydration occurs due to prolonged exercise in the heat, fluid homeostasis is disturbed which stimulates the production of aldosterone and AVP. Since fluid-regulatory adjustments are important in improving cardiovascular responses to repeated heat stress, Garret, Rehrer, and Patterson (2011) propose that permissive dehydration will facilitate the acclimation process by increasing fluid-electrolyte retention and plasma volume expansion, which in turn, will reduce the cardiovascular strain. Interestingly, it has also been reported that the increase in plasma volume is a temporary response that decays 8 to 14 days into the acclimation process, and is substituted by long term modifications such as an increased capacity to sweat, consequently reducing the temperature of the skin and the required skin blood flow for a given thermal stress (Armstrong & Maresh, 1991). This reduction in skin blood flow leads to an increase in central blood volume and, therefore, reduces the need for plasma volume expansion.

2.4.5. Hot/dry vs. Hot/wet acclimation

When acclimation is performed in a hot/dry climate (~ 40°C and ≤ 30% RH), the environment allows a great deal of sweat to evaporate. As a result, the sweat gland activity is on "over-drive" which subsequently elicits an extensive "training" of the sweat glands. Due to the increased capacity to sweat and evaporate following acclimation in a hot/dry environment, the cardiovascular adjustments are not as extreme as those observed in hot/humid climates, and are simply control mechanisms for homeostasis that follow changes in blood volume and hydration status (Shapiro et al., 1998).

In a hot/humid environment (~40°C and >80% RH), the E_{max} becomes the limiting factor for sweat to evaporate. When exercise is performed in a hot/humid climate, skin wettedness increases substantially and when not evaporated, this sweat can reduce sweat production (Candas et al., 1980). Therefore, the only way to match between net heat gain and net heat loss is by reducing the metabolic heat production and/or reducing the rate of dry heat gain from the environment. It has been shown that metabolic heat production can be reduced by more than 5% following humid heat acclimation due to greater metabolic efficiency as a result from lower blood catecholamines, glucose and lactate levels as well as a glycogen sparing effect (Sawka et al., 1983). Additionally, skin blood flow is greater in a hot/humid environment as opposed to a hot/dry environment skin which elevates skin temperature to a greater extent. As such, the core-to skin thermal gradient is reduced which helps maintain core to periphery thermal conductance and reduce dry heat gain thereby maintaining a more constant core temperature (Shapiro et al., 1998). Since increase in skin blood flow leads to a considerable reduction in stroke volume, a major difference between dry and humid heat acclimation is that the former involves greater cardiovascular adjustments in order to sustain an appropriate cardiac output and avoid heat syncope.

Since the mechanisms by which acclimation occurs in dry vs. humid environmental conditions are quite different, it seems to be advisable to acclimate to a climate where work or exercise will be performed. In fact, studies suggest that individuals who were acclimated to a hot/dry environment will not see a great improvement in performance in a hot/wet climate (Aoyagi et al., 1994; Chang & Gonzalez, 1999). Profuse sweating with no evaporation does not contribute to heat loss but simply to a quicker state of dehydration and lower skin temperatures will only increase dry heat gain. In addition, individuals who are acclimated to a hot/dry climate may not develop the necessary cardiovascular adjustments required to tolerate a hot/humid environment. Despite these environmental differences, it is suggested that the mechanisms of acclimation are very similar between environments as long the RH is below 70% and the WBGT (Wet Bulb Globe Temperature) is the same (Griefahn, 1997).

2.4.6. Acclimation procedures

In general, it is acknowledged that acclimatizing to the heat in a natural setting is the most effective way to become more tolerant to the heat; however, it is not always possible to do so as certain occupations (i.e., military) and sports require individuals to frequently move from one environment to another. In such situations, controlled procedures can be undertaken in order to prepare individuals for heat exposure.

Passive heat acclimation (i.e., water baths, saunas, vapour-barrier suits and thermal chambers) can be used to elicit some degree of acclimation. Despite being able to elevate skin temperatures to adequate levels, these methods are not ideal in order to sustain elevated core temperatures capable of eliciting maximal physiological adaptations. Therefore, passive heat acclimation is not as efficient in optimally improving

thermoregulatory and cardiovascular function as exercising in the heat and is considered a technique of last resort (Shapiro et al., 1981; Taylor, 2000; Wyndham et al., 1973).

Exercise in a temperate environment that adequately increases core temperature for an extended duration can provide a certain level of acclimation. However, when exercise is performed in a temperate climate, elevations in cutaneous temperature may not be sufficient to induce complete acclimation (Regan, et al., 1996; Shvartz, et al., 1973). Additionally, it has been demonstrated that exercise without substantial increases in core temperature do not result in any acclimation effects (Hessemer et al., 1986).

Exercise in the heat is acknowledged as the most efficient method of acclimation. This modality ensures that skin and core temperatures are adequately elevated to elicit optimal thermoregulatory and circulatory adjustments. Exercise can be incorporated into an acclimation program using these 3 main methods: 1) constant work-rate methods; 2) self-regulated exercise; and 3) controlled hyperthermia (Garrett et al., 2011). Although the constant-work rate method is the most commonly used in the literature, it should be considered that the relative thermal load may differ from participant-to-participant which may increase the variability in the observed acclimation effects. Although the self-regulated method can allow participants to adjust the exercise intensity based on their cardiorespiratory fitness, the load that is placed on each participant may also be different which may increase the variability in the responses between participants. In contrast, the controlled hyperthermia technique (also referred to as the isothermal model), ensures that an equal strain is placed on each of the participants. This method entails elevating and maintaining a core temperature above the sweating threshold, and it has been suggested that it provides a more complete adaptation then the two other methods (Taylor, 2000).

2.4.7. Experimental protocols

A variety of protocols have been used to assess improvements in thermoregulatory function following heat acclimation such as weight-bearing exercise at a fixed external workload, at a fixed % $VO_{2max;}$ or until maximal exhaustion. These different protocols can elicit different levels of metabolic heat production, and therefore requirements for heat loss can be different from pre-post acclimation and between individuals. As such, this can significantly influence the measured responses and subsequent conclusions.

It has been shown that body mass (i.e. influences the rate of metabolic heat production) and body surface area (i.e. influence on heat exchange) are the main physical characteristics that can affect local and whole-body sweat rate during exercise (Havenith et al., 1998). In order to negate the influence of body mass on metabolic heat production, and, body surface area on heat exchange, it is recommended to use non-weight bearing exercise (i.e., cycling) and fixed rates of metabolic heat production that are adjusted to the body surface area available for heat exchange (Gagnon & Kenny, 2012; Havenith et al., 1998). When environmental conditions are the same (same E_{max}), the use of fixed rates of metabolic heat production expressed per unit of body surface area guarantees that the E_{req} to E_{max} ratio will be similar between experimental sessions and individuals (Gagge & Gonzalez, 1996). In other terms, the required evaporation for heat balance will be uniform which will enable the proper assessment of each individual's physiological capacity to dissipate heat during and following heat acclimation, this independent of physical characteristics of each participant.

2.5. Heat acclimation decay

Few studies have evaluated the timeline response in the rate of decay in the body's ability to dissipate heat subsequent to a heat acclimation protocol (Armstrong & Maresh, 1991; Garrett et al., 2009; Pandolf, 1998; Weller et al., 2007). In general, the important physiological adaptations induced by heat acclimation such as a decrease in heart rate, lower core temperatures, more dilute sweat, earlier onset of sweating and skin blood flow have been shown to return to baseline values 3 weeks following removal of the thermal stress (Adam et al., 1960; Armstrong & Maresh, 1991; Garrett et al., 2011; Pandolf, 1998; Williams et al., 1967; Wyndham & Jacobs, 1957). It has been demonstrated that the cardiovascular adaptations that occur in the early stages of acclimation are the first to be lost, and that the later improvements in sudomotor habituation and sweating efficiency will decay at a slower pace (Garrett et al., 2009; Pandolf, 1998; Pandolf et al., 1977; Saat et al., 2005; Simon, 1974; Williams et al., 1967). However, the rate of decay of acclimation-induced thermoregulatory and cardiovascular improvements has varied greatly in the literature.

The different findings between researchers may be the result of methodological differences such as the heat exposure type, training status, number and duration of acclimation sessions. For example, there is evidence that suggest that acclimation arising from dry-heat exposure takes longer to decay as opposed to humid-heat exposure (Pandolf, 1998) and that high cardiorespiratory fitness is associated with a longer preservation of acclimation effects (Pandolf et al., 1977). In addition, two studies did not allow enough time between heat-stress tests (4 and 3 days, respectively) which could have affected the rate of decay of the acclimation effects (Pandolf, et al., 1977; Saat, et al., 2005). In order to avoid any acclimation effect, the interval between heat stress tests evaluating the decay of

acclimation should be performed at 1-week intervals (Barnett & Maughan, 1993). Furthermore, some of the early studies that have evaluated the rate of decay of heat acclimation are limited by small sample sizes, with only 1 to 3 participants tested during the decay phase (Bean & Eichna, 1943; Eichna et al., 1945; Robinson et al., 1943; Stein et al., 1949). Incomplete heat acclimation was evident in two other studies as only 2 days of acclimation was performed and the groups were not equally acclimated (Henschel et al., 1943; Lind & Bass, 1963; Shapiro et al., 1981). Also, other studies used inappropriate measurements to assess core temperature (i.e., oral temperature) and presented limited amounts of data which did not allow for a proper assessment of heat acclimation decay (Adam et al., 1960; Foster et al., 1976; Wyndham & Jacobs, 1957). In summary, the lack of consistency in experimental methodologies has contributed to confounding results, and the need for standardization is much needed to provide accurate and definitive insight on the progressive decay of heat acclimation.

At this time, it is suggested that for every 2 days of non-heat exposure, 1 day of acclimation is lost (Garrett et al., 2011), and that 1 day of heat exposure should be implemented after 5 days away from the heat (Taylor, 2000). However, a recent study by Weller, Linnane, Jonkman, and Daanen (2007) acclimated 16 participants to dry heat using a 10-day controlled hyperthermia acclimation protocol (38.5°C rectal temperature). Following the acclimation, the participants were separated into two groups and re-exposed to the heat following either 12 days or 26 days of non-heat exposure. The authors report that full heat acclimation was re-acquired after 2 and 4 days respectively, thus suggesting that extensive re-acclimation may not be required for up to one month when not exposed to the heat (Weller et al., 2007)

PART TWO: METHODS AND RESULTS OF THE THESIS

CHAPTER 3

METHODS

3.1. Participants

Ethical approval

The current experimental protocol was approved by the University of Ottawa Health Sciences and Science Research Ethics Board in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants who volunteered to take part in this study.

Participants

Ten male participants were recruited within the University of Ottawa community and volunteered to take part in the study. All participants were assumed to be non-heat acclimatized as the testing took place from late September to early April. Furthermore, all participants were not endurance trained as to avoid the potential for partial acclimation from endurance training (Gisolfi, 1973). Mean ± standard deviation characteristics of the participants were as follows: age, 23 ± 3.0 yrs; height, 180 ± 5.0 cm; body mass, 79.52 ± 3.5 kg; Siri body fat, 15.18 ± 4.46 %; body surface area (BSA), 1.99 ± 0.05 m^2; and maximum oxygen uptake (VO_{2max}), 51.35 ± 4.33 $mLO_2 \cdot kg^{-1} \cdot min^{-1}$. All participants were healthy, non-smoking, and did not report having any cardiovascular, metabolic and respiratory diseases.

3.2. Experimental design

All of the experimental sessions took place at the Human and Environmental Physiology Research Unit located at the University of Ottawa. Each participant that volunteered to take part in the study was required to participate in one preliminary session and experimental sessions which required multiple sessions to be conducted on different days (Figure 2).

During the preliminary session, body height, mass, training history as well as maximum oxygen uptake were determined. Body height was measured using a stadiometer (Detecto, model2391, Webb City, MO, USA), while body mass was determined using a digital high-performance weighing platform (model CBU150X, Mettler Toledo Inc., Missisauga, ON, CAN). Subsequently, body surface area was calculated using these measurements (DuBois & DuBois, 1916). Body density was estimated using the hydrostatic weighing technique, and % body fat was then calculated using the equation of Siri (Siri, 1956):

$$\% \text{ Body Fat} = (4.95/\rho - 4.50) \times 100$$

Where: ρ represents density in g/cm^3.

Maximal oxygen consumption (VO_{2max}) was measured using indirect calorimetry (MOXUS system, Applied Electrochemistry, Pittsburgh, PA, USA) during a progressive incremental exercise protocol performed on an upright seated constant-load cycle ergometer (Corival, Love B.V., Gronignen, Netherlands). The starting external workload was 80 W and participants were asked to maintain a cadence of 80 revolutions per minute (rpm). Thereafter, the workload was increased by 20 W every minute until the participant could no longer maintain a minimum cadence of 60 rpm (CSEP, 1986). Other criteria's that were used for termination of the VO_{2max} test were a plateau in oxygen uptake, an increase less than 150 ml/min with further increase in workload, and/or a respiratory exchange ratio greater than 1.15 (Howley et al., 1995). A second VO_{2max} test was performed after the induction phase to assess improvements in cardiorespiratory fitness following the 2-weeks of heat acclimation. Noteworthy is that the coefficient of variation in VO_{2max} testing has been measured to be approximately 2-6%, with >90% of this variability attributed to

biological factors (i.e., fatigue, motivation etc.) and < 10% attributed to technological error (i.e. volume measurement and/or gas analyzers) (Howley et al., 1995). Training history of the participants was assessed using the quantitative (3 month) and seven day physical activity recall questionnaires proposed by Kohl *et al.* (Kohl et al. 1988)

3.2.1. Heat tolerance tests (HTT)

The study consisted of 5 heat tolerance tests (HTT) performed in the Snellen whole-body direct air calorimeter during the induction (Day 0, 7 and 14) and decay (Day 21 and 28) of heat acclimation (Figure 2). Each participant performed all of the calorimeter trials at the same time of day. On experimental testing days, participants were asked to arrive to the laboratory well hydrated, having avoided alcohol and caffeine 12 hours prior to each experimental session. Although we acknowledge that the nature of the experimental protocol made it difficult to maintain an elevated level of hydration, participants were asked to remain as hydrated as possible throughout the study (500 mL of water prior to bed and 500 mL upon waking up in the morning were the general guidelines to follow throughout the study). Furthermore, it was asked that each participant avoid any major thermal stimuli on their way to the laboratory (i.e., vigorous walking, running, cycling, etc.). It is noteworthy that participants were asked to avoid performing any types of vigorous exercise during the two weeks of decay.

Upon arrival to the laboratory, a urine sample as well as a nude body weight was obtained. Clothing was standardized to running shorts and sandals for all experimental trials. The heat tolerance sessions began with an instrumentation period at an ambient room temperature of ~24°C. Once all the equipment and probes were in place and functioning, the participant entered the calorimeter which was regulated at an ambient temperature of 35.2 ± 0.1°C, absolute humidity of 5.56 ± 2.39 $g \bullet kg^{-1}$ (~16 % RH). After a 30 minute

baseline rest period in an upright seated position, intermittent exercise was performed at fixed rates of metabolic rate heat production equal to 300, 350 and 400 $W \cdot m^{-2}$, each exercise bout being 30 min in duration. The 1st and 2nd bout of exercise was separated by a 10 min recovery while a 20 min recovery period was allocated between the 2nd and 3rd bouts. Following the last exercise bout, a 45 min resting period was completed to finish the trial. Thereafter, participants were asked to provide another urine sample as well as a post-trial nude body weight measurement.

3.2.2. Heat acclimation sessions

On days 1 to 6 and 8 to 13 inclusively, each participant performed 90 min of exercise on an upright cycle ergometer at an ambient temperature of 40ºC and ~20% RH. The exercise intensity was measured to be ~50% of each participant's measured cardiorespiratory fitness (VO_{2max}).

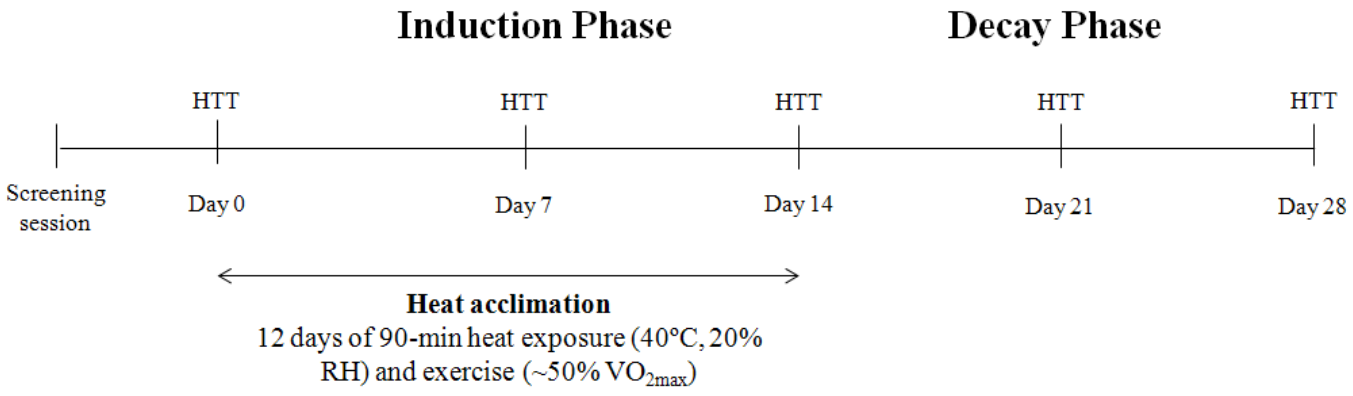

Figure 2. Overview of the experimental design (HTT = heat tolerance test)

3.3. Measurements

3.3.1. Whole-body direct calorimetry

Since whole-body calorimetry is considered the gold standard to accurately measure the rates of whole-body evaporative and dry heat loss as well as the change in body heat content (ΔH_b), the modified Snellen direct air calorimeter was used to directly measure the rate of evaporative (EHL) and dry heat loss (DHL = *R*: radiant heat exchange +*C*: convective heat exchange +*K*: conductive heat exchange) with an accuracy of ±2.3 W for the measurement of total heat loss (THL) (Reardon et al., 2006). The calorimeter inflow to outflow values of humidity and temperature were collected at every 8 seconds (s) interval throughout the experimental trials. The absolute humidity was measured using precision dew point thermometry (RH Systems model 373H, Albuquerque, NM, USA), while the air temperature was measured using RTD high precision thermistors (± 0.002ºC, Black Stack model 1560, Hart Electronics, UT, USA). The air mass flow through the calorimeter was estimated by differential thermometry over a known heat source (2 x 750 W heating elements) placed in the effluent air stream. Differential temperature over the heater was measured using a third high precision thermistor placed down-stream from the heater. Air mass flow rate (kg air/min) was continuously measured during each trial. The real time data for humidity, temperature and air mass flow was displayed and recorded on a personal computer with LabVIEW software (Version 7.0, National Instruments, TX, USA). A complete peer-reviewed technical description of the performance and calibration characteristics of the Snellen whole-body calorimeter is available (Reardon et al., 2006).

Evaporative heat loss (EHL) was calculated from the calorimetry data every min using the following equation:

$$EHL = \frac{(Massflow \times (Humidity_{out} - Humidity_{in}) \times 2{,}426)}{60}$$

Where: Mass flow is the rate of flow of air mass (kg air•s^{-1}); ($Humidity_{out} - Humidity_{in}$) is the calorimeter inflow-outflow difference in absolute humidity (g water • kg air^{-1}); and 2426 is the latent heat of vaporization of sweat (J • g $sweat^{-1}$) at 30°C (Wenger, 1972).

The rate of dry heat loss from radiation, convection and conduction was calculated from the calorimetry data every minute using the following equation:

$$R+C+K = \frac{(Massflow \times (Temperature_{out} - Temperature_{in}) \times 1{,}005}{60}$$

Where: Mass flow is the rate of flow of air mass (kg air•s^{-1}); ($Temperature_{out} - Temperature_{in}$) is the calorimeter inflow-outflow difference in air temperature (ºC), and 1005 is the specific heat of air (J• (kg air • °C)$^{-1}$).

3.3.2. Indirect calorimetry

Indirect calorimetry was used for the simultaneous measurement of metabolic energy expenditure (M). Expired gas samples drawn from the 6 l fluted mixing box located within the calorimeter were analyzed for oxygen (O2) (error of ± 0.01%) and carbon dioxide (CO2) (error of ± 0.02%) concentrations using electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA, USA). Expired air was recycled back into the calorimeter chamber in order to account for respiratory dry and evaporative heat loss. Prior to each HTT, gas mixtures of 4% CO2, 17% O2, and balance nitrogen were used to calibrate the gas analyzers and a 3 l syringe was used to calibrate the turbine ventilometer (error ± 3%, typically <1%). The rate of M was

calculated from min-average values for VO2 and the respiratory exchange ratio (RER) using the following equation (Nishi, 1981):

$$M \equiv \left(\dot{V}O_2 \bullet \left[\frac{RER - 0.7}{0.3} e_c + \frac{1 - RER}{0.3} e_f \right] \right)$$

Where: e_c is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62 kJ).

The calorimetry data was then used to calculate the rate of body heat storage (S) and the change in body heat content (ΔH_b) using the following equations:

$$S = (M - (E + R + C + K) - W)$$

$$\Delta H_b \text{ @ time (t)} = \int_{t=0}^{t} (M - (E + R + C + K) - W)\, dt$$

Where: M is the rate of metabolic energy expenditure; E is the rate of evaporative heat loss; R + C +K is the rate of dry heat loss; and W is the rate of external work (all units in W). The ΔH_b is reported in kilojoules (Mekjavic & Rempel, 1990).

3.3.3. Core and skin temperatures

Esophageal (T_{es}) and rectal (T_{re}) temperatures were measured using paediatric thermocouple probes (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO, USA). The esophageal probe was inserted through a nostril, during which time the participant was asked to swallow sips of water through a straw. The tip of the probe once fully inserted rested 40 centimeters (cm) past the entrance of the nostril, an estimation of heart height as heart position, neck length and head depth can vary between

people. The rectal probe was inserted to a minimum of 12 cm past the anal sphincter. Skin temperature was measured using Type T thermocouples (copper/constantan) (Concept Engineering, Old Saybrook, CT, USA). Mean skin temperature (T_{sk}) was calculated using 4 skin temperatures weighted to the regional proportions proposed by Ramanathan (1964) (Ramanathan, 1964). All temperature data were collected using a data acquisition module (HP Agilent model 3497A; Agilent Technologies Canada Inc., Mississauga, ON, Canada) at sampling rate of 15 s and simultaneously displayed and recorded in spreadsheet format on a personal computer with LabVIEW software (Version 7.0, National Instruments, Austin, TX, USA).

3.3.4. Heart rate

Heart rate was monitored during each of the experimental sessions using a Polar coded transmitter, recorded continuously and stored with a Polar Advantage interface and Polar Precision Performance software (Polar Electro Oy, Finland).

3.3.5. Hydration status

Urine specific gravity was determined in duplicate using a handheld total solids refractometer (model TS400, Reichter Inc., Depew, NY, USA). For each HTT, blood samples were taken during the instrumentation period as well as immediately after the third recovery period by a certified member of the research team. Venous blood was collected with a SST Vacutainer and transferred directly into serum with no additive and plasma K_2EDTA BD Vacutainer® tubes (BD Vacutainer, Franklin Lakes, NJ). Non-additive blood was centrifuged at ~3000 rpm (Hawklsey Microcentrifuge, Sussex, UK) for 8 minutes, whereas the EDTA blood was mixed by inversion, used to determine hematocrit and hemoglobin levels (Coulter® A^{c}·T diff2™ analyzer, Beckam Coulter, Miami, Florida,

USA). Serum aliquots were transferred into polypropylene Eppendorf™ tubes, frozen at -20°C, and stored at -70°C. Each pre- and post serum samples were analyzed with a Micro-Osmometer (Advanced® Model 3320, Norwood, MA, USA) for measurements of osmolality. Changes in plasma volume (PV) from baseline resting were estimated in all heat tolerance tests based on changes in haemoglobin (Hb) and hematocrit (Hct) using the following equation (Dill & Costill, 1974).

$$\%\Delta PV = 100\{(Hb_b/Hb_t)\cdot[1\text{-}Hct_t)/(1\text{-}Hct_b)]\}\text{-}100$$

3.4. Data analysis

Minute averages were calculated for all dependant variables in order to perform the statistical analyses. To determine changes in the onset threshold and thermosensitivity of whole-body evaporative heat loss during the induction and decay of heat acclimation, the visually determined linear segment of the response plotted against mean body temperature was analysed with simple linear regression. The onset threshold corresponded to the intercept of the regression line with the values of evaporative heat loss at rest, while the thermosensitivity was defined as the slope of the regression (Cheuvront et al., 2009). Onset thresholds and thermosensitivities were calculated for all three exercise bouts for each of the experimental testing days. Mean body temperature was calculated as: 0.9 x esophageal temperature + 0.1 x mean skin temperature (Shibasaki et al., 2006), in order to account for the relative influence of core and mean skin temperature on the initiation of sweat production (Hertzman et al., 1952; Nadel et al., 1971a; Nadel et al., 1971b). In order to quantify the percentage of loss of each variable relative to Day 0 during the decay phase (EHL, ΔH_b, T_{re}, HR), the following formula was used (Pandolf et al., 1977):

$$\%\ \text{loss} = \frac{(\text{Avg. Value at Day 21 or Day 28}) - (\text{Avg. Value at Day 14})}{(\text{Avg. Value at Day 0}) - (\text{Avg. Value at Day 14})} \times 100$$

3.5. Statistical analysis

Post-acclimation differences in cardiorespiratory fitness, % body fat, and body mass were compared using paired samples *t* tests. All continuous dependent variables were compared at baseline, at the end of each exercise bout (Ex1, Ex2, and Ex3), and at the end of each recovery period (R1, R2, and R3). The primary results were the measurements obtained from direct calorimetry (i.e., THL, EHL, DHL, and ΔH_b). The secondary measurements included heart rate as well as T_{re} and T_{sk}. All of these variables were analysed using using a one-way repeated measure ANOVA with factor of day (0, 7, 14 21 and 28). Paired samples *t* tests were used to carry out pair-wise post-hoc comparisons. For each analysis, the statistical significance was set to an alpha of $p \leq 0.05$. The statistical analyses were performed using commercially available statistical software (SPSS 20.0 for Windows, SPSS Inc., Chicago, IL, USA). Segmented regression analysis was completed using GraphPad Prism 5.0 (Graph Pad Software, La Jolla, CA, USA) in order to calculate the thermosensitivity of whole-body evaporative heat loss during each of the experimental testing days. All values are reported as mean ± standard error.

CHAPTER 4

RESULTS

RESULTS

4.1. Training history and cardiorespiratory fitness

During the 3 months preceding their participation in the study, participants reported engaging in physical activities on average 6.5 ± 1.0 (range: 3-13) times per week. This resulted in an average physical activity time of 7.0 ± 1.5 (range: 3-18.5) hours per week. On average, this was equivalent to 44.9 ± 6.8 MET-h/wk (Kohl et al., 1988). Moreover, cardiorespiratory fitness of the participants was increased by 5% following the 14-day acclimation protocol (i.e. 51.13 ± 1.46 pre-acclimation *vs*. 53.72 ± 0.99 $mLO_2 \cdot kg^{-1} \cdot min^{-1}$ post-acclimation, p=0.005). However, there were no differences in body mass (i.e. 79.52 ± 1.11 pre-acclimation *vs.* 79.42 ± 1.10 kg post-acclimation, p=0.710), or % body fat (i.e. 15.18 ± 1.41 % pre-acclimation *vs.* 14.03 ± 0.98 % post-acclimation, p=0.15) following the 14-day acclimation protocol.

4.2. Whole-body direct calorimetry

All calorimetry data measured at each 7 day interval from Day 0 to 28 is presented in Table 1 (exercise) and Table 2 (recovery). The required evaporation to achieve heat balance (E_{req}) and EHL for both the induction and decay phases are presented in Figures 3A and 3B, respectively. The percentage loss of EHL during the decay phase is presented in Table 4.

4.2.1. Whole-body heat loss

Induction period

By design, the rate of metabolic heat production did not differ between days during Ex1 (p=0.239), Ex2 (p=0.727), and Ex3 (p=0.341). The external workloads associated to

these rates of metabolic heat production were 121 ± 1.13W (Ex1), 142 ± 1.48 W (Ex2), and 162 ± 1.85 W (Ex3). The E_{req} between days was similar for Ex1 ($p=0.598$). However, a main effect of acclimation day on E_{req} was measured in Ex2 and Ex3 ($p\leq0.01$).

Exercise period. A main effect of acclimation day on THL was measured in all three exercise bouts (all $p\leq0.05$).). After 7 days of acclimation, THL was increased in Ex2 ($p=0.021$) and Ex3 ($p=0.001$) compared to Day 0, however no difference was evident in Ex1 ($p=0.067$). At Day 14, THL was increased in each of the three exercise bouts relative to Day 0 (all $p\leq0.05$).

When THL was separated into EHL and DHL, both variables changed as a function of acclimation day in each of the exercise bouts (all $p\leq0.05$). EHL was significantly increased on Day 7 and Day 14 relative to Day 0 for all three exercise periods ($p\leq0.05$). EHL at Day 14 was significantly greater than Day 7 for each of the three exercise bouts ($p\leq0.05$). After 7 days of acclimation, DHL was increased in Ex2 and Ex3 compared to Day 0 (both $p=0.004$). At Day 14, an increase in DHL was measured in each of the exercise bouts relative to Day 0 (all $p\leq0.05$). DHL in Ex2 and Ex3 were greater on Day 14 than at Day 7 ($p\leq0.05$).

Recovery period. No significant differences in THL and EHL were measured for any of the recovery periods during the induction phase (all $p>0.05$). DHL at Day 7 and Day 14 was greater than at Day 0 in R2 and R3 (all $p\leq0.05$). No differences were evident in R1 at Day 7 and Day 14 compared to Day 0 (both $p>0.05$).

Decay period

Exercise period. During the decay phase, THL on Day 21 was reduced in Ex3 compared to Day 14 ($p=0.028$), however no differences were measured during any of the

exercise bouts on Day 28 ($p>0.05$). When compared to Day 0, THL on Day 21 remained significantly greater at the end of each exercise bout ($p\leq0.05$). When Day 28 was compared to Day 0, THL remained greater at the end of Ex2 ($p=0.014$) and Ex3 ($p\leq0.001$) but not Ex1 ($p=0.079$).

After 1 week of decay, EHL was reduced at the end of Ex2 ($p=0.017$) and Ex3 ($p=0.008$) relative to Day 14, yet no difference was evident in Ex1 ($p=0.054$). On Day 28, EHL was not different than Day 14 at the end of Ex1 ($p=0.182$) and Ex2 ($p=0.105$), however it remained lower at the end of Ex3 ($p=0.014$). EHL measured at the end of each exercise bout on Day 21 and 28 remained significantly greater than Day 0 (all $p\leq0.05$). No differences in DHL were measured on Day 21 compared to Day 14 for each exercise bout ($p>0.05$), however DHL in Ex3 was reduced on Day 28 relative to Day 14 ($p=0.027$). DHL at Day 21 and 28 remained significantly greater than Day 0 in each of the exercise bouts (all $p\leq0.05$).

Recovery period. THL at the end of each recovery period at Day 21 and Day 28 did not differ from Day 14 (all $p>0.05$). In comparison to Day 0, THL at the end of R3 was measured to be significantly lower on Day 21 ($p=0.039$), however no differences were evident at Day 28 ($p=0.106$). Furthermore, EHL during each recovery period did not change as a function of acclimation day during the decay phase ($p>0.05$). DHL for all three recovery periods remained similar at Day 21 and Day 28 compared to Day 14 ($p>0.05$). As such, DHL at the end of all three recovery periods at Day 21 and 28 remained greater than Day 0 ($p\leq0.05$).

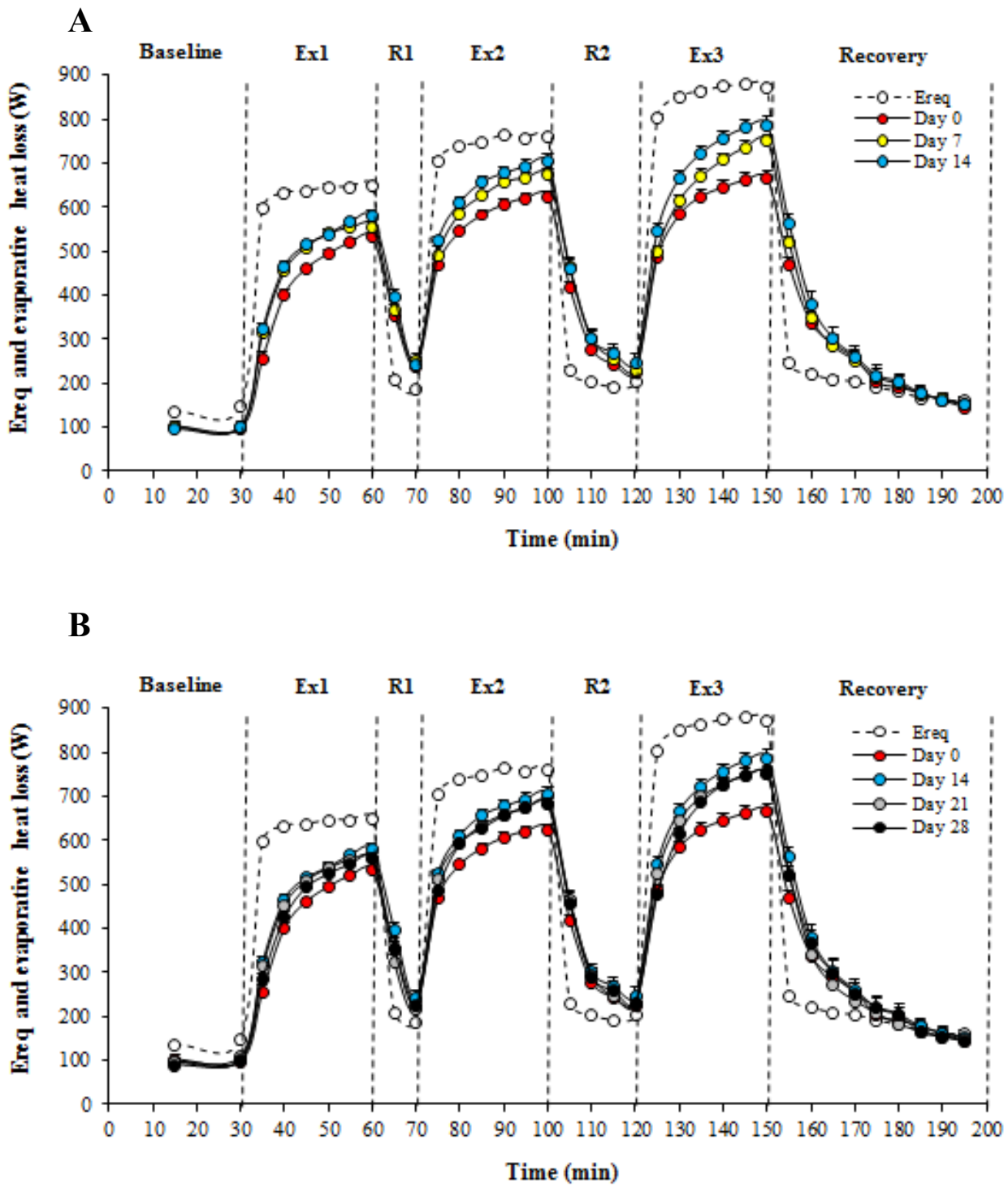

Figure 3. Average requirements for heat loss (-----) for each day during the induction (A) and decay (B) of heat acclimation and the mean (± SE) rate of whole-body evaporative heat loss for Day 0 (●), Day 7 (●), Day 14 (●) Day 21 (●) and Day 28 (●). Day 7 was omitted in the decay graph (B) in order to facilitate the comparison of Day 21 and Day 28 to Day 0 and Day 14. Ex = exercise; R = recovery; E_{req}= required evaporation to attain heat balance.

Table 1

Whole-body calorimetry data during exercise performed at fixed rates of metabolic heat production equal to 300, 350, and 400 W·m^2 during the induction (Day 0, 7, and 14) and decay (Day 21 and 28) of heat acclimation.

	300 W·m^2					**350 W·m^2**					**400 W·m^2**				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
M-W, *W*	608.0 ±6.9	601.0 ±3.0	596.5 ±5.0	603.1 ±8.4	597.1 ±5.5	696.6 ±6.5	700.5 ±6.7	696.9 ±6.6	702.3 ±7.8	700.6 ±7.6	808.3 ±8.9	797.8 ±8.9	806.3 ±8.5	798.7 ±8.3	796.6 ±8.4
Ereq, *W*	641.4 ±7.0	643.0 ±3.4	643.1 ±8.2	650.9 ±10.6	642.5 ±8.0	738.4 ±6.7	756.8 ±9.5*	768.9 ±11.6*	771.9 ±11.0*	767.5 ±9.1*	850.3 ±8.2	869.1 ±12.2	899.8 ±11.0*§	884.0 ±10.5*†§	882.0 ±15.6
THL, *W*	493.7 ±8.6	516.9 ±7.8	529.8 ±8.5*	512.0 ±6.7*	511.5 ±8.5	583.1 ±6.5	611.2 ±7.3*	627.4 ±9.5*	610.4 ±6.4*	615.0 ±7.9*	621.5 ±11.2	676.3 ±11.1*	690.3 ±12.1*	662.4 ±10.2*†	665.6 ±13.2*
EHL, *W*	529.2 ±7.9	558.3 ±9.6*	576.3 ±11.0* §	559.3 ±10.7*	555.5 ±10.5*	624.5 ±9.7	671.3 ±11.8*	700.6 ±15.1*§	679.4 ±12.8*†	681.5 ±14.4*	666.1 ±16.3	747.7 ±14.2*	785.9 ±16.9*§	750.7 ±13.2*†	750.3 ±15.5*†
DHL, *W*	-34.2 ±4.9	-41.4 ±3.4	-46.4 ±5.2*	-46.5 ±5.3*	-43.9 ±5.2*	-41.4 ±6.6	-60.1 ±5.8*	-73.2 ±9.6*§	-68.9 ±9.2*§	-66.5 ±10.2*	-44.6 ±9.3	-71.4 ±7.6*	-95.6 ±12.2*§	-86.2 ±11.3*§	-84.7 ±13.5*†
ΔH_b, *kJ*	353.5 ±9.3	282.5 ±14.3*	266.5 ±17.9*	283.9 ±12.4*	312.9 ±9.8*§†‡	290.0 ±14.2	235.6 ±14.8*	204.3 ±20.4*§	240.7 ±14.5*†	247.2 ±14.1*†	418.5 ±18.8	347.7 ±21.1*	311.2 ±23.3*§	346.0 ±16.0*†	377.1 ±19.5*†‡

Notes. Values are mean ± SE. The values represent the average of the last 5 minutes of each exercise period. M-W= rate of metabolic heat production; Ereq= required evaporative heat loss to attain heat balance; THL= total heat loss; EHL= evaporative heat loss; DHL= dry heat loss; ΔH_b= change in body heat content; *W*= watts; W·m^2 = watts·meters^2*; kJ*= kilojoules. (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05**.** (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

Table 2

Whole-body calorimetry data for each recovery period during the induction (Day 0, 7, and 14) and decay (Day 21 and 28) of heat acclimation

	Recovery 1 (10 min)					**Recovery 2 (20 min)**					**Recovery 3 (45 min)**				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
M-W, *W*	163.2 ±4.8	163.8 ±8.4	157.2 ±4.0	149.2 ±7.0	161.8 ±9.5	152.1 ±4.6	147.7 ±5.9	153.7 ±6.5	142.2 ±4.1	146.3 ±5.3	149.7 ±7.1	150.4 ±6.0	141.5 ±5.7	139.8 ±4.1	142.1 ±4.2
Ereq, *W*	187.4 ±7.5	189.5 ±8.1	190.9 ±6.7	178.8 ±7.3	193.6 ±12.7	179.5 ±7.9	190.0 ±9.7	211.0 ±10.7*	192.5 ±10.3	198.1 ±12.1	171.9 ±11.7	184.4 ±12.1	188.9 ±14.8*	183.7 ±11.7*	188.3 ±13.5*
THL, *W*	216.6 ±15.7	223.1 ±12.0	211.5 ±9.5	188.6 ±13.1	198.0 ±13.3	224.3 ±17.4	214.1 ±18.3	208.4 ±17.3	207.8 ±20.0	212.8 ±20.7	220.8 ±37.9	212.05 ±35.2	206.7 ±41.8	181.4 ±33.0*§	193.3 ±40.3
EHL, *W*	240.3 ±16.8	253.4 ±14.7	244.8 ±11.8	218.2 ±14.2	227.2 ±15.4	250.7 ±16.5	257.1 ±21.3	265.7 ±18.7	257.6 ±19.0	264.5 ±20.6	241.0 ±38.4	245.5 ±38.5	254.2 ±46.8	225.3 ±34.7	239.5 ±43.2
DHL, *W*	-24.2 ±4.4	-30.3 ±3.6	-33.7 ±5.6	-29.6 ±4.3	-29.3 ±4.9	-26.4 ±5.7	-43.0 ±7.2*	-57.3 ±9.6*	-49.8 ±9.1*	-51.7 ±10.4*	-20.2 ±6.6	-33.5 ±8.0*	-47.5 ±11.8*§	-43.9 ±9.7*§	-46.2 ±12.6*
ΔH_b, *kJ*	-71.4 ±7.9	-78.8 ±5.5	-92.9 ±5.9*	-66.2 ±5.7†	-73.9 ±7.9	-124.6 ±14.6	-141.5 ±16.3	-140.1 ±14.2	-143.0 ±8.8	-135.1 ±12.2	-190.5 ±25.2	-175.8 ±18.4	-188.3 ±19.9	-159.0 ±15.9	-161.9 ±21.8

Notes. Values are mean ± SE. The values represent the average of the last 5 minutes of each exercise period. M-W= rate of metabolic heat production; Ereq= required evaporative heat loss to attain heat balance; THL= total heat loss; EHL= evaporative heat loss; DHL= dry heat loss; ΔH_b= change in body heat content; *W*= watts*; kJ*= kilojoules. (*) Significantly different than Day 0, $p \leq 0.05$. (§) Significantly different than Day 7, $p \leq 0.05$**.** (†) Significantly different than Day 14, $p \leq 0.05$. (‡) Significantly different than Day 21, $p \leq 0.05$.

4.2.2. Change in body heat content

The change in body heat content for each exercise bout is presented in Table 1 while the change in body heat content for each recovery period is presented in Table 2. Figure 4A presents the total ΔH_b for all three exercise bouts combined while Figure 4B demonstrates the ΔH_b for all three recovery periods combined. Furthermore, the cumulative ΔH_b for all three exercise/recovery cycles combined is presented in Figure 4.

Induction period

Exercise period. A main effect of acclimation day on the ΔH_b was measured during each of the exercise bouts (all $p \leq 0.001$). The ΔH_b was significantly reduced in each of the exercise bouts after 7 and 14 days of acclimation relative to Day 0 (all $p \leq 0.01$). When the ΔH_b of all three exercise bouts was combined (Figure 4A), a significant reduction was evident on Day 7 and Day 14 compared to Day 0 ($p \leq 0.001$). The ΔH_b measured at Day 14 was significantly lower than Day 7 ($p=0.002$).

Recovery period. A main effect of acclimation day was only measured during R1 ($p=0.019$) as no differences were evident in R2 ($p=0.491$) and R3 ($p=0.251$). At Day 7, the amount of heat stored during R1 was not lower than Day 0 ($p=0.292$), however a significant reduction was measured at Day 14 ($p=0.017$). When the ΔH_b from all three recovery periods was combined, no main effect of acclimation day was measured ($p=0.321$) (Figure 4B).

Cumulative change in body heat content. The cumulative ΔH_b was significantly reduced after 7 and 14 days of heat acclimation relative to Day 0 (both $p \leq 0.001$). The cumulative amount of heat stored on Day 14 was lower than Day7 ($p=0.005$).

Decay period

Exercise period. The ΔH_b during Ex2 ($p=0.009$) and Ex3 ($p=0.023$) was significantly increased on Day 21 compared to Day 14, but no difference was measured for Ex1 ($p=0.127$). The ΔH_b at Day 21 remained significantly lower than Day 0 in each of the exercise bouts (all $p \leq 0.001$). At Day 28, the amount of heat stored during each of the three exercise bouts was significantly greater than Day 14 (all $p \leq 0.05$), however ΔH_b remained significantly lower than Day 0 in each of the exercise bouts (all $p \leq 0.05$). The total ΔH_b from all three exercise bouts combined was increased at Day 21 and Day 28 compared to 14 ($p \leq 0.05$). Nonetheless, the total ΔH_b during exercise at Day 21 and 28 remained significantly lower than Day 0 (both $p \leq 0.05$). The percentage loss in body heat storage at Day 21 and Day 28 is presented in Table 4.

Recovery period. The ΔH_b during R1 was significantly lower on Day 21 compared to Day 14 ($p=0.015$), however it was not different from Day 0 ($p=0.428$). Moreover, the ΔH_b during each of the recovery periods at Day 28 was not different from Day 0 or Day 14 (all $p>0.05$).

Cumulative change in body heat content. The cumulative ΔH_b was significantly increased on Day 21 and Day 28 compared to Day 14 ($p \leq 0.001$), however it remained significantly lower than Day 0 on Day 21 ($p=0.003$) and Day 28 ($p=0.042$).

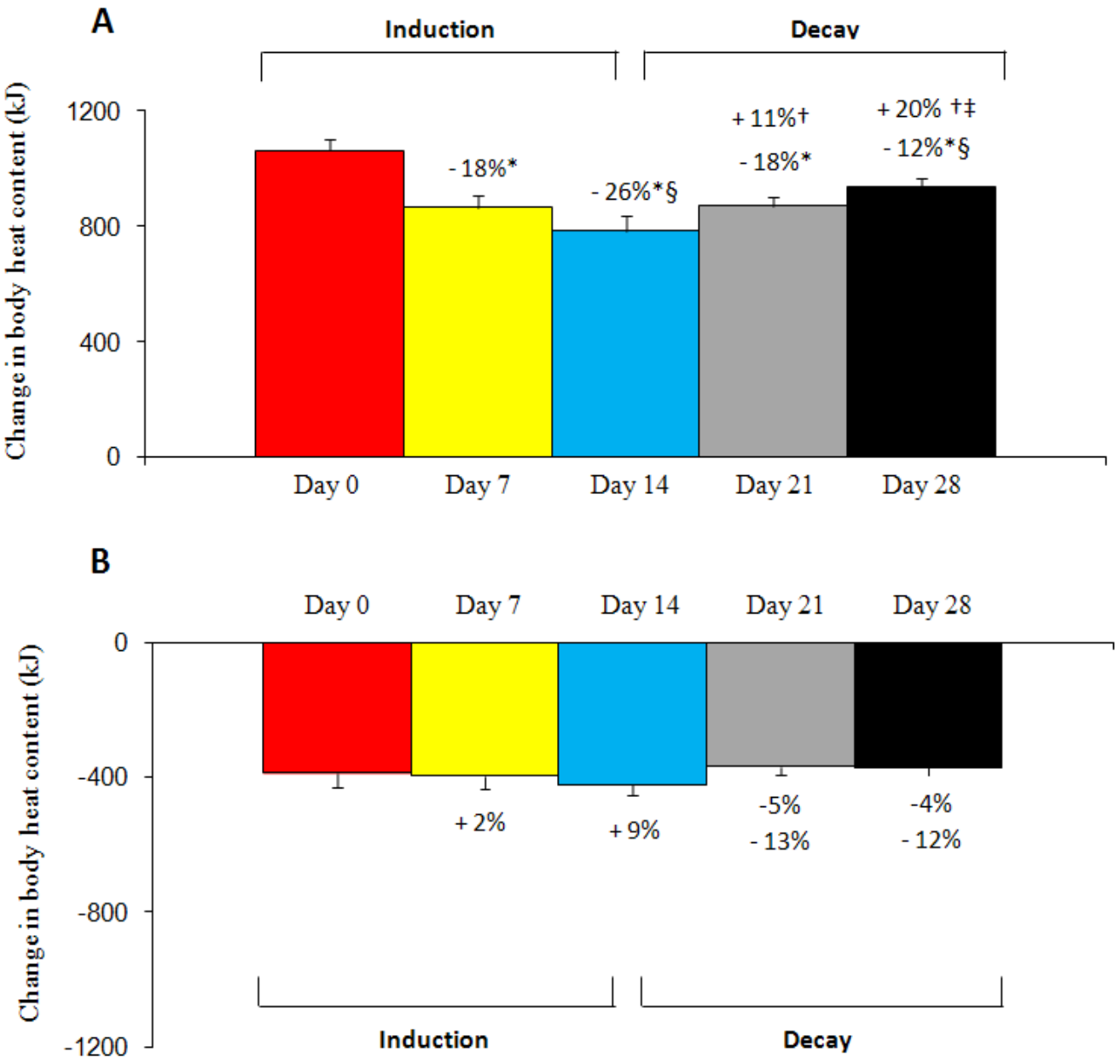

Figure 4. Mean ± SE changes in body heat content during all three exercise bouts combined (A) and during all three recovery periods combined (B). (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05. (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

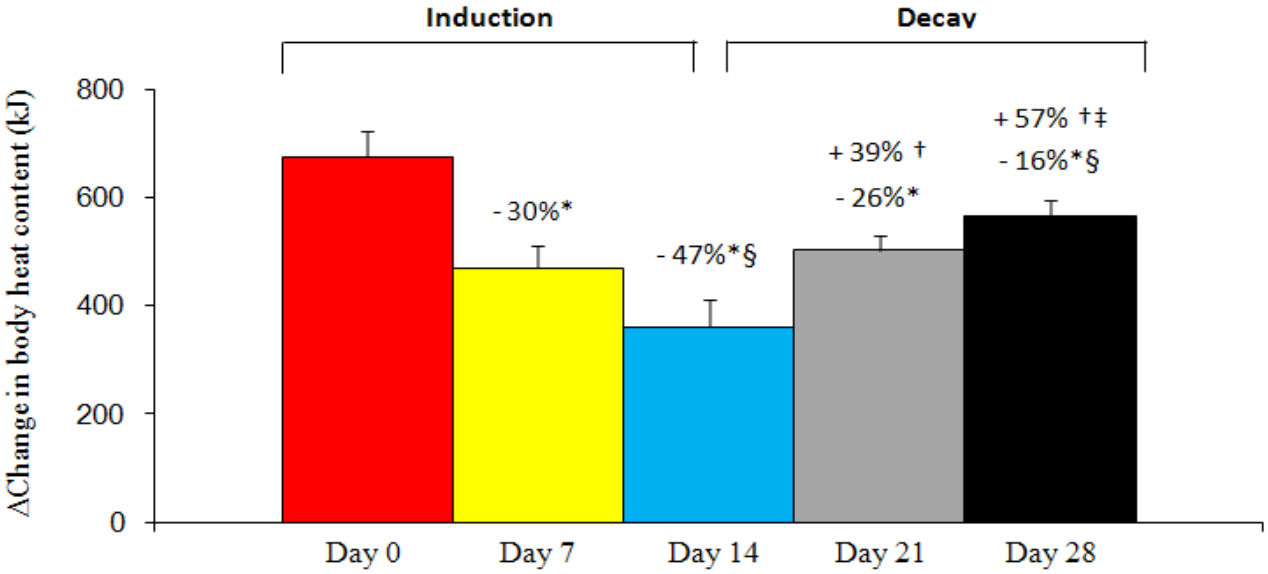

Figure 5. Mean ± SE cumulative change in body heat content. (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05**.** (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

4.2.3. Onset thresholds and thermosensitivities

Induction versus decay. The onset thresholds and thermosensitivies of whole-body evaporative heat loss for each of the three exercise periods are presented in Table 3. Onset thresholds for EHL did not change as of function of acclimation day during Ex1 (p=0.075), Ex2 (p=0.356), and Ex3 (p=0.289). A main effect of acclimation day was measured for the thermosensitivity of EHL. While no differences were measured in Ex1 (p=0.173) and Ex3 (p=0.177), responses differed during Ex 2 (p≤0.001). A greater thermosensitivity was measured on Day 7 (p=0.021), Day 14 (p=0.009), Day 21 (p=0.001), and Day 28 (p=0.045) relative to Day 0. Value at Day 21 was significantly different than at Day 7 (p=0.004).

Table 3

Onset thresholds and thermosensitivities of evaporative heat loss during exercise performed at fixed rates of metabolic heat production equal to 300, 350, and 400 W·m^2 during the induction (Day 0, 7, and 14) and decay (Day 21 and 28) of heat acclimation.

	300 W·m^2					**350 W·m^2**					**400 W·m^2**				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
Onset thresholds (°C)	36.63 ±0.06	36.44 ±0.10	36.42 ±0.04	36.39 ±0.05	36.45 ±0.04	36.84 ±0.08	36.73 ±0.08	36.72 ±0.06	36.71 ±0.05	36.80 ±0.06	37.03 ±0.08	36.87 ±0.08	36.83 ±0.07	36.91 ±0.11	36.96 ±0.07
Whole-body thermosensitivity (W·m^{-2} ·°C)	500.9 ±42.9	554.4 ±58.0	562.3 ±39.1	536.8 ±37.2	504 ±38.1	489.9 ±80.6	616.6 ±69.1*	685.5 ±41.0*	710.3 ±69.3*§	634.4 ±44.3*	517.9 ±53.0	602.7 ±78.3	689.7 ±119.5	635.2 ±77.1	563.8 ±46.2

Values are presented as mean ± standard error. W·m^2 = watts·meters^2; °C = degrees Celsius. (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05**.** (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

4.3. Rectal temperature

The absolute (T_{rec}) and relative changes in rectal temperature (ΔT_{rec}) for each exercise bout and recovery period are presented in Table 5 and 6, respectively. The percentage loss in T_{rec} during the decay phase is presented in Table 4.

Induction period

Baseline rest. A main effect of acclimation day was measured on resting T_{rec} ($p \leq 0.001$). Following 7 and 14 days of heat acclimation, T_{rec} at rest was significantly lowered by 0.28°C (36.70 ± 0.09°C, $p \leq 0.001$) and 0.31°C (36.67 ± 0.06°C, $p \leq 0.001$) relative to Day 0 (36.98 ± 0.08°C), respectively.

Exercise period. After 7 days of acclimation, rectal temperature was only significantly lower than Day 0 during Ex3 ($p=0.003$) as no differences were measured during Ex1 ($p=0.068$) and Ex2 ($p=0.064$). At Day 14, T_{rec} was lower at the end of all three exercise bouts relative to Day 0 (all $p \leq 0.05$). The relative change in T_{rec} from baseline to the end of each exercise bout was similar between Day 0 and Day 14 ($p=0.147$). On Day 7, the change in T_{rec} during Ex1 was greater than Day 0 ($p=0.021$).

Recovery period. T_{rec} at Day 7 was significantly lower at the end of R2 and R3 (both $p=0.018$) compared to Day 0. No difference was measured during R1 ($p=0.074$). After 14 days of acclimation, T_{rec} was significantly reduced at the end of the three recovery periods when compared to Day 0 (all $p \leq 0.05$). The relative change in T_{rec} was not different between days for each of the recovery periods (all $p > 0.05$).

Decay period

Baseline rest. During the decay phase, baseline T_{rec} remained significantly lower on Day 21 (36.65 ± 0.04°C, p≤0.001) and Day 28 (36.74 ± 0.03, p=0.016) compared to Day 0 (36.98 ± 0.08°C).

Exercise period. T_{rec} at Day 21 was lower in Ex1 (p=0.004) and Ex2 (p=0.044) compared to Day 14, however no difference was measured in Ex3 (p=0.264). The measured T_{rec} response at Day 21 remained lower in each exercise bout when compared to Day 0 (p≤0.05). At Day 28, T_{rec} did not significantly differ than Day 14 in each of the three exercise bouts (all p>0.05). When Day 28 was compared to Day 0, T_{rec} at the end of Ex1 (p=0.049) remained lower, however no differences were measured at the end of Ex2 (p=0.08) and Ex3 (p=0.065).

Recovery period. On Day 21, T_{rec} measured at the end of R1 (p=0.039) was lower than Day 14, yet no differences were measured in R2 (p=0.533) and R3 (p=0.705). T_{rec} at the end of each recovery period remained significantly lower on Day 21 relative to Day 0 (p≤0.01). When Day 28 was compared to Day 14, no significant differences were measured during any of the recovery periods (all p>0.05). In comparison to Day 0, T_{rec} at the end of R1 (p=0.134) and R2 (p=0.06) at Day 28 did not differ, however T_{rec} remained lower at the end of Ex3 (p=0.036). Moreover, the change in T_{rec} from baseline to the end of the three recovery periods was similar between testing days (p>0.05).

4.4. Mean skin temperature

Induction vs. Decay. T_{sk} response during exercise is presented in Table 5 and during recovery in Table 6. T_{sk} did not change as a function of acclimation day at baseline (p=0.435) or during Ex1 (p=0.218) and Ex2 (p=0.082), however a main effect was evident during Ex3

($p=0.021$). T_{sk} during Ex3 was only significantly lower on Day 7 ($p\leq0.001$) and Day 21 ($p=0.05$) compared to Day 0. No differences were measured on Day 14 ($p=0.062$) and Day 28 ($p=0.515$) compared to Day 0. T_{sk} did not change as a function of acclimation day during any of the recovery periods (all $p>0.05$).

4.5. Heart rate response

Heart rate response during exercise is presented in Table 5 while heart rate during recovery is presented in Table 6. The percentage loss of the heart rate response is presented in Table 4.

Induction period

Baseline period. Heart rate at rest did not change as a function of acclimation day (Day 0: 73 ± 4 bpm; Day 7: 71 ± 4 bpm; Day 14: 66 ± 3 bpm; Day 21: 72 ± 4 bpm; Day 28: 70 ± 4 bpm, $p=0.124$).

Exercise period. A main effect of acclimation day on heart rate was observed in each of the exercise bouts (all $p\leq0.05$). Heart rate was significantly reduced at the end of each exercise bout after 7 and 14 days of acclimation relative to Day 0 (all $p\leq0.05$). Heart rate at Day 14 was lower than Day 7 during Ex2 ($p=0.028$), yet no difference was measured in Ex1 ($p=0.110$) and Ex3 ($p=0.057$).

Recovery period. After 7 days of acclimation, heart rate was significantly lower at the end of R3 ($p=0.012$), however no differences were evident in R1 ($p=0.248$) and R2 ($p=0.243$). At Day 14, the heart rate response was reduced at the end of all three recovery periods (all $p\leq0.01$). Heart rates measured at the end of each recovery period at Day 14 were significantly lower than then at Day 7 (all $p\leq0.05$).

Decay period

Exercise period. Heart rate at Day 21 was significantly increased in Ex2 (p=0.018) relative to Day 14, however no differences were measured at the end of Ex1 (p=0.0.086) and Ex2 (p=0.077). The measured heart rate at the end of each exercise bout at Day 21 remained lower in comparison to Day 0 (all $p \leq 0.05$). On Day 28, heart rate was increased in Ex1 (p=0.043) and Ex2 (p=0.018) relative to Day 14, yet no difference was measured in Ex3 (p=0.125). Heart rate at the end of all three exercise bouts on Day 28 did not significantly differ from Day 0 ($p > 0.05$).

Recovery period. On Day 21, heart rate was significantly increased in Ex2 (p=0.047) and Ex3 (p=0.025) relative to Day 14, however no difference was measured in Ex1 (p=0.074). When Day 28 was compared to Day 14, an increase in heart rate was evident in each recovery period (all $p \leq 0.05$). Heart rates at the end of each recovery period were significantly lower on Day 21 compared to Day 0 ($p \leq 0.05$), however they returned to pre-acclimation values for each recovery period on Day 28 (all $p > 0.05$).

Table 4

Percentage loss of evaporative heat loss, body heat content, rectal temperature and heart rate for each exercise bout after 1 (Day21) and 2 weeks (Day 28) of heat acclimation decay

	Decay Phase					
	300 W·m^2		**350 W·m^2**		**400 W·m^2**	
	14 to 21	14 to 28	14 to 21	14 to 28	14 to 21	14 to 28
EHL, *%*	36	44	28	25	30	30
ΔH_b, *%*	20	53	42	50	32	61
T_{rec}, *%*	-72	22	-40	34	-13	43
HR, *%*	42	63	45	64	38	53

Notes. W·m^2 = watts·meters^2; EHL= evaporative heat loss; ΔH_b = change in body heat content; T_{rec}= rectal temperature; HR= heart rate. (-) indicates a percent reduction in comparison to Day 14.

Table 5

Rectal/skin temperatures and heart rate at the end of exercise performed at fixed rates of metabolic heat production equal to 300, 350, and 400 W·m^2 during the induction (Day 0, 7, and 14) and decay (Day21 and 28) of heat acclimation

	300 W·m^2					**350 W·m^2**					**400 W·m^2**				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
T_{rec}, *°C*	37.70 ±0.11	37.52 ±0.09	37.47 ±0.08*	37.31 ±0.08*§†	37.52 ±0.05*‡	38.21 ±0.14	37.98 ±0.10	37.91 ±0.10*	37.79 ±0.10*†	38.0 ±0.09‡	38.70 ±0.13	38.39 ±0.09*	38.28 ±0.13*	38.23 ±0.12*§	38.46 ±0.11‡
ΔT_{rec}, *°C*	0.72 ±0.07	0.82 ±0.05*	0.80 ±0.06	0.65 ±0.05†§	0.78 ±0.07	1.24 ±0.10	1.28 ±0.08	1.24 ±0.09	1.14 ±0.09	1.27 ±0.10	1.72 ±0.11	1.69 ±0.09	1.61 ±0.11	1.58 ±0.11	1.72 ±0.11
T_{sk}, *°C*	34.98 ±0.11	34.77 ±0.13	34.93 ±0.11	34.80 ±0.10	35.03 ±0.11	35.24 ±0.08	34.95 ±0.12	35.07 ±0.12	35.0 ±0.10	35.22 ±0.11	35.55 ±0.10	35.18 ±0.12*	35.22 ±0.16	35.23 ±0.11	35.45 ±0.13
HR, *bpm*	137 ±4	130 ±4*	125 ±4*	130 ±4*	132 ±4†	159 ±3	146 ±3*	141 ±5*§	149 ±4*†	152 ±5†	176 ±4	165 ±3*	161 ±5*	167 ±4*†	169 ±4†

Notes. Values are mean ± SE. The values represent the average of the last minute of each exercise period.W·m^2 = watts·meters^2; T_{rec} = rectal temperature; ΔT_{rec} = relative change in rectal temperature; T_{sk} =mean skin temperature; HR= heart rate; *°C*= degrees Celsius; *bpm* = beats per minute. (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05**.** (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

Table 6

Rectal/skin temperatures and heart rate responses at the end of each recovery period during the induction (Day 0, 7, and 14) and decay (Day21 and 28) of heat acclimation

	Recovery 1 (10 min)					**Recovery 2 (20 min)**					**Recovery 3 (45 min)**				
	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28	Day 0	Day 7	Day 14	Day 21	Day 28
T_{rec}, *°C*	37.57 ±0.13	37.37 ±0.11	37.38 ±0.08*	37.25 ±0.07*†	37.40 ±0.06‡	37.89 ±0.15	37.57 ±0.10*	37.55 ±0.09*	37.51 ±0.09*	37.59 ±0.11	38.10 ±0.19	37.71 ±0.13*	37.71 ±0.16*	37.68 ±0.15*	37.75 ±0.10
ΔT_{rec}, *°C*	0.60 ±0.08	0.67 ±0.06	0.71 ±0.07	0.60 ±0.05	0.66 ±0.07	0.91 ±0.12	0.87 ±0.08	0.88 ±0.08	0.86 ±0.08	0.85 ±0.10	1.12 ±0.17	1.01 ±0.12	1.04 ±0.14	1.03 ±0.14	1.01 ±0.10
T_{sk}, *°C*	34.69 ±0.11	34.37 ±0.15	34.50 ±0.16	34.45 ±0.13	34.66 ±0.15	34.50 ±0.08	34.41 ±0.18	34.47 ±0.15	34.39 ±0.15	34.55 ±0.17	34.73 ±0.12	34.70 ±0.19	34.67 ±0.17	34.52 ±0.20	34.76 ±0.21
HR, *bpm*	93 ±3	88 ±3	79 ±3*§	85 ±3*	88 ±4†	98 ±4	92 ±3	86 ±3*§	91 ±4*†	96 ±5†	105 ±4	95 ±4*	90 ±4*§	98 ±4*†	101 ±5†

Notes. Values are mean ± SE. The values represent the average of the last minute of each exercise period. T_{rec} =rectal temperature; ΔT_{rec}= relative change in rectal temperature; T_{sk} =mean skin temperature; HR= heart rate; *°C*= degrees Celsius; *bpm*=beats per minute. (*) Significantly different than Day 0, p≤ 0.05. (§) Significantly different than Day 7, p≤0.05**.** (†) Significantly different than Day 14, p≤ 0.05. (‡) Significantly different than Day 21, p≤ 0.05.

4.6. Hydration status

All data pertaining to the hydration status of the participants is presented in Table 7. Urine specific gravity did not differ between experimental testing days ($p=0.136$). Similarly, serum osmolality was not different prior to each experimental session ($p=0.207$). Serum osmolality levels were significantly increased from baseline to the end of the third recovery ($p\leq0.0001$). However, no significant differences were evident in the post-trial serum osmolality levels between testing days ($p=0.204$). Furthermore, changes in plasma volume from baseline did not significantly differ between experimental sessions ($p=0.762$).

Table 7

Urine specific gravity, serum osmolality and changes in plasma volume during the induction (Day 0, 7, and 14) and decay (Day 21 and 28) of heat acclimation

	Day 0	**Day 7**	**Day 14**	**Day 21**	**Day 28**
Pre USG	1.012 ±0.003	1.018 ±0.004	1.016 ±0.003	1.014 ±0.003	1.013 ±0.003
Post USG	1.017 ±0.002	1.019 ±0.002	1.018 ±0.003	1.018 ±0.003	1.015 ±0.003
Pre Osmolality (mosmol·kgH_2O^{-1})	288 ± 3	292 ± 2	288 ± 2	288 ± 1	285 ± 2
Post Osmolality (mosmol·kgH_2O^{-1})	297 ± 2	299 ± 2	296 ± 2	295 ± 2	295 ± 2
% change PV	-4.89 ± 0.84	-5.86 ± 0.60	-6.12 ± 0.60	-5.59 ± 0.68	-5.56 ± 0.71

Notes. Values are mean ± SE. USG = urine specific gravity; PV=plasma volume; mosmol·kgH_2O^{-1} = milliosmols·kilogram of water

PART THREE:
DISCUSSION AND CONCLUSIONS OF THE THESIS

CHAPTER 5

DISCUSSION

DISCUSSION

The current study examined the induction (14 days) and decay (14 days) of heat acclimation on whole-body heat balance at increasing requirements for heat loss. The main findings demonstrate that 14 days of heat acclimation greatly enhances the body's physiological capacity to dissipate heat as evidenced by 9, 12, and 18% increases in the rate of whole-body evaporative heat loss measured during exercise performed at successively higher rates of heat production of 300, 350 and 400 $W \cdot m^2$, respectively. This resulted in a correspondingly lower change in body heat content measured during each of the three exercise bouts of 25, 30, and 26% relative to the pre-acclimation period. In general, we show that the improvements in whole-body evaporative heat loss are maintained following a 2-week decay period. This was paralleled by a lower amount of heat stored.

5.1. Heat acclimation induction

We show that acclimation induced changes in whole-body sudomotor capacity varies as a function of the heat load, with the greatest improvements observed at the highest heat load. This raises an important point with respect to the disparity in findings reported in previous studies (Taylor, 2013). To date, acclimation studies have used a diversity of single absolute work rates and thermal loads pre- and post-acclimation to evaluate changes in local heat loss responses (i.e. sweating and skin blood flow) (Bean & Eichna, 1943; Boulant, 2006; Buono et al., 1998; Burton et al., 1940; Cotter et al., 1997; Fox et al., 1967; Gisolfi, 1973; Havenith & Middendorp, 1986; Hessemer et al., 1986; Horstman & Christensen, 1982; Horvath & Shelley, 1946; Ladell, 1951; Mitchell et al., 1976; Nadel et al., 1974; Patterson et al., 2004; Roberts et al., 1977; Robinson et al., 1943; Rowell et al., 1967; Shvartz et al., 1979; Shvartz et al., 1973; Strydom et al., 1966). However, our results

showed that the improvements in heat loss responses is dependent on the heat load that is used to evaluate thermoregulatory changes following heat acclimation. Noteworthy, participants in our study were unable to attain heat balance during each of the 30 min exercise bouts prior to acclimation. This allowed us to quantify the improvements in heat dissipation induced by the acclimation protocol at each level of heat production. However, if the pre-acclimation heat load used is too low, the likelihood of demonstrating measurable improvements in heat loss post-acclimation is reduced simply owing to the fact that the individual already possesses the physiological capacity to attain heat balance. For that reason, the mixed results in the literature can in part be secondary to the low heat loads that have been employed to evaluate improvements in heat dissipation following heat acclimation (Buono et al., 1998; Burton et al., 1940; Fox et al., 1967; Fox et al., 1963a; Frye & Kamon, 1981; Havenith & Middendorp, 1986; Hessemer et al., 1986; Horstman & Christensen, 1982; Mitchell et al., 1976; Nielsen et al., 1993; Robinson et al., 1943; Shvartz et al., 1979).

To the best of our knowledge, only one study has examined changes in sudomotor function and skin blood flow at increasing levels of heat stress following a period of heat acclimation. Havenith and Middendorp (1986) reported whole-body sweat rate and forearm blood flow to be reduced at 30, 60, and 90 W following 7 days of heat acclimation. However, this study was limited by a small sample size (only 4 participants), incomplete heat acclimation (only 7 days of acclimation) as well as the use of absolute work rates. This last limitation is important as the requirements for heat loss can differ from participant to participant because of different cardiorespiratory fitness as well as before and after the acclimation period secondary to the acclimation-induced adaptations. There is some evidence that suggests that heat acclimation improves mechanical efficiency (Aoyagi et al.,

1994; Fujii et al., 2012) as well as induces a change in substrate metabolism such that the body will shift to a greater lipid oxidation as opposed to glycogen (Febbraio et al., 1994; Kirwan et al., 1987; Young et al., 1985). If not accounted for, these physiological alterations will impact the rate of heat production and therefore the thermal load post-acclimation. A key aspect of the current study was the use of fixed rates of metabolic heat production expressed per unit of body surface area (combined to fixed environmental conditions) which ensured a uniform thermal load between participants and between testing days. This experimental paradigm allowed us to clearly show that the physiological capacity to dissipate heat is greatly enhanced at 300, 350 and 400 $W \cdot m^2$ following 7 days of heat acclimation. The associated workloads to these rates of heat production were 121 ± 1 W (300 $W \cdot m^2$), 142 ± 1 W (350 $W \cdot m^2$), and 162 ± 1 W (400 $W \cdot m^2$). Since all three exercise workloads used in their study were lower than the first workload employed in the present study, it could be hypothesized that they did not measure any improvements due to the fact that 1) the participants already had the physiological capacity to attain heat balance at each of the work rates that were employed, and/or 2) that the requirements for heat loss were reduced in the post-acclimation testing sessions.

Our results also show that the majority of the improvements in the body's physiological capacity to dissipate heat take place during the first 7 days of acclimation. In fact, ~62% of the maximal increase in evaporative heat loss measured after 14 days of acclimation during exercise at 300 and 350 $W \cdot m^2$ was evident after the first 7 days of acclimation. At 400 $W \cdot m^2$, the increase in evaporative heat loss measured after 7 days represented ~68% of the total improvements induced by the 14-day acclimation protocol. This considerable increase in heat dissipation after 7 days led to a 30% reduction in body heat content relative to Day 0, which corresponds to ~65% of the total reduction in body

heat content induced by the 14 days of acclimation. These findings are consistent with previous studies that have reported that most of the physiological adaptations to heat acclimation take place within the first 7 to 10 days of heat exposure and that ~75% of these adaptations occur within the first 4 to 6 days (Armstrong & Maresh, 1991; Pandolf, 1998; Shapiro, et al., 1998). In addition, our results confirm previous reports that have reported body heat storage to be reduced following a period of acclimation in dry heat (Eichna et al., 1950; Horstman & Christensen, 1982; Shvartz et al., 1973).

In this study, T_{re} at rest was reduced after 7 (0.28°C) and 14 days (0.31°C) of acclimation, both of which are consistent with previous studies (Buono et al., 1998; Cotter et al., 1997; Kampmann et al., 2008; Patterson et al., 2004; Shvartz et al., 1974). One interesting observation is that T_{re} was only significantly lower at the end of the third exercise (400 $W \cdot m^2$) after 7 days; however it was reduced in all three exercise bouts after 14 days of acclimation. In contrast to these results, Havenith and Middencorp (1986) observed significantly lower core temperatures at each workload (30, 60, and 90 W) after 7 days of acclimation (Havenith & Middendorp, 1986). However, this may have been due to a lower heat load at each of the exercise work rates in their post-acclimation tests. A number of other studies have reported lower core temperatures during exercise after varying periods of acclimation (Buono et al., 1998; Garden et al., 1966; Harrison, 1985; Havenith & Middendorp, 1986; Kampmann et al., 2008; Pandolf et al., 1988; Shvartz et al., 1979; Shvartz et al., 1973), and they have been primarily associated to the reductions in resting core temperature (Buono et al., 1998; Kampmann et al., 2008). Our results support this premise as the relative changes in T_{re} did not differ between acclimation days. This observation seem contradictory as one would expect the large increases in heat dissipation and concomitant reductions in heat storage to elicit a lower level of change in core

temperature. However, it is important to remember that heat is not uniformly distributed throughout the tissues of body, and that T_{re} only represents the amount of heat stored surrounding the rectum (Jay et al., 2007). Heat acclimation has also been shown to profoundly influence blood flow (Fox et al., 1963b), which strongly influences where the heat is distributed in the body. Based on our results, it seems that the amount of heat that is stored surrounding the rectum remains relatively the same regardless of the acclimation state of the individual; therefore heat storage has to be decreased in other areas in the body. Nonetheless, future research is required to precisely determine the extent to which heat distribution changes as a function of acclimation. Ultimately, the use of whole-body calorimetry eliminates the possible confounding effects of heat distribution and regional variations of local heat loss and accurately measures changes in whole-body heat loss and heat storage. If we would have calculated heat storage from the measurements of skin and core temperature, the change in body heat content would have been underestimated (Jay et al., 2007), which would have led to misguided conclusions in regards to heat acclimation and whole-body heat balance.

We also observed a significant reduction in heart rate following 7 and 14 days of heat acclimation. This has been previously demonstrated in many studies that have used absolute work rates following heat acclimation (Aoyagi et al., 1994; Gisolfi & Robinson, 1969; Horvath & Shelley, 1946; Rowell et al., 1967; Strydom et al., 1966; Wyndham et al., 1968), however, these lower heart rates may have been the result of a lower thermal strain and/or changes in blood volume post-acclimation (Shapiro et al. 1998). Conversely, the use of fixed rates of heat production in this study eliminates the possibility that a reduced thermal strain was responsible for the marked reductions in heart rate. Although cardiovascular measurements were limited in this study, research suggests that the

improvements in cardiovascular stability following a period of heat acclimation are mediated by a combination of peripheral and central mechanisms (Horowitz & Meiri, 1993). The peripheral modulations include an increase in blood volume (Harrison, 1985; Sawka et al., 2000), while the central modulations refer to an increased ventricular contractility which has received much attention in recent years (Horowitz, 2002; Horowitz & Meiri, 1993; Levi et al., 1993; Mirit et al., 2000).

5.2. Heat acclimation decay

In the present study, we observed that 2 weeks of decay does not completely eliminate the improvements in sudomotor capacity induced by 14 days of heat acclimation. Currently, studies suggests that the positive benefits of heat acclimation are maintained for up to 3 weeks following the cessation of heat exposure (Garrett et al., 2011; Pandolf, 1998), and that for every 2 days spent away from the heat, 1 day of acclimation is lost (Givoni & Goldman, 1972). In the current study, we did not observe any differences in cumulative body heat storage between Day 7 and Day 21 which signifies that after 1-week of decay, we retained 7 days of acclimation. Ultimately, this suggests that for 1 day spent away from the heat, we lose 1 day of heat acclimation. However, the rate of decay of evaporative heat loss was not as pronounced during the second week of non-heat exposure, therefore it is not an exact 1 for 1 ratio as some improvements were retained on Day 28 compared to baseline (16 % lower than Day 0).

Empirical evidence suggests that the first adaptations to decay are of cardiovascular origin, which is followed by a slower decay of the core temperature and sweating responses (Pandolf et al., 1977; Williams et al., 1967). Our results show that the improvements in heart rate and T_{re} were maintained for one week but not two weeks of non-heat exposure;

albeit T_{re} remained lower than baseline during the first exercise bout after 2 weeks of decay. These findings are consistent with a recent study by Garret et al. (2009) which reported the same timeline response for both heart rate and T_{re} despite a shorter acclimation protocol (5 days). Our findings are also similar to a study by Williams, Wyndham, and Morrison (1967) that reported the percentage loss of heart rate to be greater than the percentage loss of T_{re} during the first (HR: 65% *vs.* T_{rec}: 26%) and second (HR: 87% *vs.* T_{rec}: 35%) week of decay (see Table 4). However, the measured percentage losses of sweat rate in their study were much greater (1 week: 54%; 2 weeks: 78%) than the reduction in evaporative heat loss that we observed in the first (300 $W \cdot m^2$: 36%; 350 $W \cdot m^2$: 28%; 400 $W \cdot m^2$: 29%) and second week of decay (300 $W \cdot m^2$: 44%; 350 $W \cdot m^2$: 25%; 400 $W \cdot m^2$: 30%). First, these inconsistent findings may be due to differences in the acclimation state of the participants. Participants in William et al.'s (1967) study underwent a 12-day acclimation protocol in underground mines; however, they did not specify the level of thermal strain that was used during the acclimation period. They also used absolute work rates which could have affected the level of thermal strain during the induction and decay phases. Furthermore, they failed to report the cardiorespiratory fitness of their participants which could have contributed to the difference in the rate of decay between both studies (Pandolf et al., 1977).

In comparison to Williams et al. (1967) and the current study, Pandolf, Burse and Goldman (1977) reported much lower T_{re} (Day 6: 13%; Day 12: 18%) and heart rate losses (Day 6:23%; Day 12: 29%) following 6 and 12 days of decay, albeit we did not observe, in our participants, any decrements in the T_{re} response following 7 days. This slower rate of decay could not be associated to the high cardiorespiratory fitness of their participants as our participants had similar levels of cardiorespiratory fitness. As such, the difference may

lie in the habitual exercise behaviors of individuals as opposed to cardiorespiratory fitness *per se.* Participants in the present study were not overly active, however in Pandolf et al.'s (1977) study, participants were soldiers who most likely trained on a daily basis which may have slowed down the process of decay. Also, soldiers are often exposed to heat stress conditions due to the nature of their work, which is exacerbated by their insulative clothing that they have to wear. Combined, all these factors could have contributed to a higher degree of pre-experimental acclimation in Pandolf et al's (1977) study participants.

From an applied perspective, an individual may be at increased risk of heat stress two weeks post-acclimation as opposed to one week following the cessation of heat exposure due to a more pronounced loss of both the heart rate and core temperature responses. As such, the re-induction of acclimation is recommended after 2-weeks of decay in order to protect workers as much as possible from excessive thermoregulatory and circulatory strain. A recent study by Weller et al. (2007) reported that the physiological benefits of a 10-day acclimation protocol were restored after 2 and 4 days of re-acclimation after 12 and 26 days away from the heat, respectively. These findings imply that extensive re-acclimation may not be necessary until an individual has been away from the heat for up to 1 month. However, these findings were solely based on core temperature and local heat loss responses, therefore additional studies are required to determine the time it would take to regain the full acclimation effect of a 14-day acclimation protocol on whole-body heat loss. Currently, it is recommended that 1 day of heat exposure should be imposed for every 5 days that is spent away from the heat environment (Taylor, 2000).

5.3. Considerations

Since the present study was conducted in an environment that favoured the evaporation of sweat from the skin surface (high air mass flow combined to low absolute humidity), our results are not applicable in situations where the evaporation of sweat may be restricted due to high levels of ambient humidity and/or from clothing. As such, future research should aim to determine the extent to which whole-body heat balance and body heat storage is altered by acclimation in environments that do restrict evaporative heat loss. A second important consideration of the current study is that a 5% increase in cardiorespiratory fitness was measured following the 14-day acclimation protocol. Although this is within the coefficient of variation of VO_{2max} testing, it cannot be ruled out that part of the increase in whole-body heat loss, as well as the reductions in core temperature and heart rate may be partly associated to the increase in fitness of the participants. Nevertheless, it is well recognized that the combination of exercise and heat exposure is the best method by which to induce heat acclimation (Armstrong & Maresh, 1991). It has also been suggested that improvements in VO_{2max} greater than 15% are required to have a significant impact on heat tolerance (Gisolfi, 1973; Henane et al., 1977).

CHAPTER 6

CONCLUSION

6.1. Conclusion

In conclusion, we showed that the physiological capacity of the body to dissipate heat is greatly improved after 7 and 14 days of heat acclimation. However, the measured improvements in sudomotor capacity are dependent on the stimulus that is provided such that the greater the heat stimulus, the greater the improvement. Our findings also confirmed that heat acclimation to dry heat does undeniably reduce the amount of heat stored in the body and that most of the improvements in the capacity to dissipate heat arise during the first 7 days of heat exposure. Moreover, we showed that the improvements in sudomotor capacity induced by 14 days of acclimation are retained for 2 weeks following the cessation of heat exposure. However, rectal temperature and heart rate returned to baseline levels following 2 weeks of decay thereby indicating that the improvements in sudomotor capacity are retained for a longer period.

6.2. Acknowledgments

This research was supported by the Deep Mining Research Consortium and the Natural Sciences and Engineering Research Council (RGPIN-298159-2009, held by Dr. Glen P. Kenny) and Leaders Opportunity Fund from the Canada Foundation for Innovation (22529, held by Dr. Glen P. Kenny). Dr. Glen P. Kenny was supported by a University of Ottawa Research Chair Award. Mr. Martin Poirier was supported by a Queen Elizabeth II graduate scholarship in science and technology which was funded by the Ontario's Ministry of Training, Colleges and Universities as well as the Canadian Mining Industry Research Organization.

PART FOUR: REFERENCES

Adam, J. M., Fox, R. H., Grimby, G., Kidd, D., & Wolff, H. (1960). Acclimatization to heat and its rate of decay in man. *J Physiol*(152), 26P-27P.

Aoyagi, Y., McLellan, T. M., & Shephard, R. J. (1994). Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. *Eur J Appl Physiol Occup Physiol, 68*(3), 234-245.

Armstrong, L. E., Costill, D. L., & Fink, W. J. (1987). Changes in body water and electrolytes during heat acclimation: Effects of dietary sodium. *Aviat Space Environ Med, 58*(2), 143-148.

Armstrong, L. E., Curtis, W. C., Hubbard, R. W., Francesconi, R. P., Moore, R., & Askew, E. W. (1993). Symptomatic hyponatremia during prolonged exercise in heat. *Med Sci Sports Exerc, 25*(5), 543-549.

Armstrong, L. E., & Maresh, C. M. (1991). The induction and decay of heat acclimatisation in trained athletes. *Sports Med, 12*(5), 302-312.

Bain, A. R., Deren, T. M., & Jay, O. (2011). Describing individual variation in local sweating during exercise in a temperate environment. *Eur J Appl Physiol, 111*(8), 1599-1607.

Barnett, A., & Maughan, R. J. (1993). Response of unacclimatized males to repeated weekly bouts of exercise in the heat. *Br J Sports Med, 27*(1), 39-44.

Bean, W. B., & Eichna, L. W. (1943). Performance in relation to environmental temperature: Reactions of normal young men to simulated desert environments. *Fed Proc, 2*, 144-158.

Benzinger, T. H. (1959). On physical heat regulation and the sense of temperature in man. *Proc Natl Acad Sci U S A, 45*(4), 645-659.

Boulant, J. A. (2006). Neuronal basis of hammel's model for set-point thermoregulation. *J Appl Physiol, 100*(4), 1347-1354.

Boulant, J. A., & Bignall, K. E. (1973). Hypothalamic neuronal responses to peripheral and deep-body temperatures. *Am J Physiol, 225*(6), 1371-1374.

Buono, M. J., Heaney, J. H., & Canine, K. M. (1998). Acclimation to humid heat lowers resting core temperature. *Am J Physiol, 274*(5 Pt 2), R1295-1299.

Buono, M. J., Martha, S. L., & Heaney, J. H. (2009). Peripheral sweat gland function is improved with humid heat acclimation. *Journal of Thermal Biology, 34*, 127-130.

Burton, A. C., Scott, J. C., McGlone, B., & Bazett, H. C. (1940). Slow adaptations in the heat exchanges of man to changed climatic conditions. *Am J Physiol, 129*, 84-101.

Cain, B., & McLellan, T. M. (1998). A model of evaporation from the skin while wearing protective clothing. *Int J Biometeorol, 41*(4), 183-193.

Candas, V., Libert, J. P., & Vogt, J. J. (1979a). Human skin wettedness and evaporative efficiency of sweating. *J Appl Physiol, 46*(3), 522-528.

Candas, V., Libert, J. P., & Vogt, J. J. (1979b). Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. *J Appl Physiol, 47*(6), 1194-1200.

Candas, V., Libert, J. P., & Vogt, J. J. (1980). Effect of hidromeiosis on sweat drippage during acclimation to humid heat. *Eur J Appl Physiol Occup Physiol, 44*(2), 123-133.

Carlisle, H. J. (1969). Effect of preoptic and anterior hypothalamic lesions on behavioral thermoregulation in the cold. *J Comp Physiol Psychol, 69*(2), 391-402.

Carter, R., 3rd, Watenpaugh, D. E., Wasmund, W. L., Wasmund, S. L., & Smith, M. L. (1999). Muscle pump and central command during recovery from exercise in humans. *J Appl Physiol, 87*(4), 1463-1469.

Chang, S. K., & Gonzalez, R. R. (1999). Benefit of heat acclimation is limited by the evaporative potential when wearing chemical protective clothing. *Ergonomics, 42*(8), 1038-1050.

Charkoudian, N. (2003). Skin blood flow in adult human thermoregulation: How it works, when it does not, and why. *Mayo Clin Proc, 78*(5), 603-612.

Chen, W. Y., & Elizondo, R. S. (1974). Peripheral modification of thermoregulatory function during heat acclimation. *J Appl Physiol, 37*(3), 367-373.

Cheuvront, S. N., Bearden, S. E., Kenefick, R. W., Ely, B. R., Degroot, D. W., Sawka, M. N., et al. (2009). A simple and valid method to determine thermoregulatory sweating threshold and sensitivity. *J Appl Physiol, 107*(1), 69-75.

Cotter, J. D., Patterson, M. J., & Taylor, N. A. (1995). The topography of eccrine sweating in humans during exercise. *Eur J Appl Physiol Occup Physiol, 71*(6), 549-554.

Cotter, J. D., Patterson, M. J., & Taylor, N. A. (1997). Sweat distribution before and after repeated heat exposure. *Eur J Appl Physiol Occup Physiol, 76*(2), 181-186.

Crandall, C. G., & Gonzalez-Alonso, J. (2010). Cardiovascular function in the heat-stressed human. *Acta Physiol (Oxf), 199*(4), 407-423.

Crandall, C. G., Johnson, J. M., Kosiba, W. A., & Kellogg, D. L., Jr. (1996). Baroreceptor control of the cutaneous active vasodilator system. *J Appl Physiol, 81*(5), 2192-2198.

Dasler, A. R., & Hardenbergh, E. (1971). Decreased sweat rate in heat acclimatization. *Fed Proc., 30*, 209.

Dill, D. B., & Costill, D. L. (1974). Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J Appl Physiol, 37*(2), 247-248.

DuBois, D., & DuBois, E. F. (1916). A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Med, 17*, 863-871.

Eichna, L. W., Bean, W. B., Ashe, W. F., & Nelson, N. (1945). Performance in relation to environmental temperature: Reactions of normal young men to hot, humid (simulated jungle) environment. *Bull Johns Hopkins Hosp, 76*, 25-58.

Eichna, L. W., Park, C. R., Nelson, N., Horvath, S. M., & Palmes, E. D. (1950). Thermal regulation during acclimatization in a hot, dry (desert type) environment. *Am J Physiol, 163*(3), 585-597.

Febbraio, M. A., Snow, R. J., Hargreaves, M., Stathis, C. G., Martin, I. K., & Carey, M. F. (1994). Muscle metabolism during exercise and heat stress in trained men: Effect of acclimation. *J Appl Physiol, 76*(2), 589-597.

Foster, K. G., Ellis, F. P., Dore, C., Exton-Smith, A. N., & Weiner, J. S. (1976). Sweat responses in the aged. *Age Ageing, 5*(2), 91-101.

Fox, R. H., Goldsmith, R., Hampton, I. F., & Hunt, T. J. (1967). Heat acclimatization by controlled hyperthermia in hot-dry and hot-wet climates. *J Appl Physiol, 22*(1), 39-46.

Fox, R. H., Goldsmith, R., Kidd, D. J., & Lewis, H. E. (1963a). Acclimatization to heat in man by controlled elevation of body temperature. *J Physiol, 166*, 530-547.

Fox, R. H., Goldsmith, R., Kidd, D. J., & Lewis, H. E. (1963b). Blood flow and other thermoregulatory changes with acclimatization to heat. *J Physiol, 166*, 548-562.

Frye, A. J., & Kamon, E. (1981). Responses to dry heat of men and women with similar aerobic capacities. *J Appl Physiol, 50*(1), 65-70.

Fujii, N., Honda, Y., Ogawa, T., Tsuji, B., Kondo, N., Koga, S., et al. (2012). Short-term exercise-heat acclimation enhances skin vasodilation but not hyperthermic hyperpnea in humans exercising in a hot environment. *Eur J Appl Physiol, 112*(1), 295-307.

Gagge, A. P., & Gonzalez, R. R. (1996). Mechanisms of heat exhange in: Handbook of physiology section 4: Environmental physiology, edited by fregley mj, and blatteis cm. *105*, 45-84.

Gagnon, D., & Kenny, G. P. (2012). Sex differences in thermoeffector responses during exercise at fixed requirements for heat loss. *J Appl Physiol, 113*(5), 746-757.

Garden, J. W., Wilson, I. D., & Rasch, P. J. (1966). Acclimatization of healthy young adult males to a hot-wet environment. *J Appl Physiol, 21*(2), 665-669.

Garrett, A. T., Goosens, N. G., Rehrer, N. J., Patterson, M. J., & Cotter, J. D. (2009). Induction and decay of short-term heat acclimation. *Eur J Appl Physiol, 107*(6), 659-670.

Garrett, A. T., Rehrer, N. J., & Patterson, M. J. (2011). Induction and decay of short-term heat acclimation in moderately and highly trained athletes. *Sports Med, 41*(9), 757-771.

Gavin, T. P. (2003). Clothing and thermoregulation during exercise. *Sports Med, 33*(13), 941-947.

Gisolfi, C., & Robinson, S. (1969). Relations between physical training, acclimatization, and heat tolerance. *J Appl Physiol, 26*(5), 530-534.

Gisolfi, C. V. (1973). Work-heat tolerance derived from interval training. *J Appl Physiol, 35*(3), 349-354.

Givoni, B., & Bemer-Nir, E. (1963). Expected sweat rate as a function of metabolism, environmental factors and clothing. *Research Report UNESCO Haifa: Israel Institute of Technology*.

Givoni, B., & Goldman, R. F. (1972). Predicting rectal temperature response to work, environment, and clothing. *J Appl Physiol, 32*(6), 812-822.

Griefahn, B. (1997). Acclimation to three different hot climates with equivalent wet bulb globe temperatures. *Ergonomics, 40*(2), 223-234.

Harrison, M. H. (1985). Effects on thermal stress and exercise on blood volume in humans. *Physiol Rev, 65*(1), 149-209.

Havenith, G., Coenen, J. M., Kistemaker, L., & Kenney, W. L. (1998). Relevance of individual characteristics for human heat stress response is dependent on exercise intensity and climate type. *Eur J Appl Physiol Occup Physiol, 77*(3), 231-241.

Havenith, G., & Middendorp, H. (1986). Determination of the individual state of acclimatization. *Report IZF 1986-27*.

Henane, R., Flandrois, R., & Charbonnier, J. P. (1977). Increase in sweating sensitivity by endurance conditioning in man. *J Appl Physiol, 43*(5), 822-828.

Henane, R., & Valatx, J. L. (1973). Thermoregulatory changes induced during heat acclimatization by controlled hypothermia in man. *J Physiol, 230*(2), 255-271.

Henschel, A., Taylor, H. L., & Keys, A. (1943). The persistence of heat acclimatization in man. *Am J Physiol, 140*, 321-325.

Hensel, H. (1981). Thermoreception and temperature regulation. *Monogr Physiol Soc, 38*, 1-321.

Hertzman, A. B., Randall, W. C., Peiss, C. N., & Seckendorf, R. (1952). Regional rates of evaporation from the skin at various environmental temperatures. *J Appl Physiol, 5*(4), 153-161.

Hessemer, V., Zeh, A., & Bruck, K. (1986). Effects of passive heat adaptation and moderate sweatless conditioning on responses to cold and heat. *Eur J Appl Physiol Occup Physiol, 55*(3), 281-289.

Hofler, W. (1968). Changes in regional distribution of sweating during acclimatization to heat. *J Appl Physiol, 25*(5), 503-506.

Hori, S. (1995). Adaptation to heat. *Jpn J Physiol, 45*(6), 921-946.

Horowitz, M. (2002). From molecular and cellular to integrative heat defense during exposure to chronic heat. *Comp Biochem Physiol A Mol Integr Physiol, 131*(3), 475-483.

Horowitz, M., & Meiri, U. (1993). Central and peripheral contributions to control of heart rate during heat acclimation. *Pflugers Arch, 422*(4), 386-392.

Horstman, D. H., & Christensen, E. (1982). Acclimatization to dry heat: Active men vs. Active women. *J Appl Physiol, 52*(4), 825-831.

Horvath, S. M., & Shelley, W. B. (1946). Acclimatization to extreme heat and its effect on the ability to work in less severe environments. *Am J Physiol, 146*, 336-343.

Howley, E. T., Bassett, D. R., Jr., & Welch, H. G. (1995). Criteria for maximal oxygen uptake: Review and commentary. *Med Sci Sports Exerc, 27*(9), 1292-1301.

Ichinose, T., Okazaki, K., Masuki, S., Mitono, H., Chen, M., Endoh, H., et al. (2005). Ten-day endurance training attenuates the hyperosmotic suppression of cutaneous vasodilation during exercise but not sweating. *J Appl Physiol, 99*(1), 237-243.

Inoue, Y., Havenith, G., Kenney, W. L., Loomis, J. L., & Buskirk, E. R. (1999). Exercise- and methylcholine-induced sweating responses in older and younger men: Effect of heat acclimation and aerobic fitness. *Int J Biometeorol, 42*(4), 210-216.

Jay, O., Gariepy, L. M., Reardon, F. D., Webb, P., Ducharme, M. B., Ramsay, T., et al. (2007). A three-compartment thermometry model for the improved estimation of changes in body heat content. *Am J Physiol Regul Integr Comp Physiol, 292*(1), R167-175.

Jay, O., & Kenny, G. P. (2007). The determination of changes in body heat content during exercise using calorimetry and thermometry. *Journal of Human-Environmental System, 10*, 19-29.

Johnson, J. M., & Proppe, D. W. (1996). Cardiovascular adjustments to heat stress. In. *Handbook of Physiology. Environmental Physiology*, American Physiological Society, Bethesta, MD.

Kampmann, B., Brode, P., Schutte, M., & Griefahn, B. (2008). Lowering of resting core temperature during acclimation is influenced by exercise stimulus. *Eur J Appl Physiol, 104*(2), 321-327.

Keim, S. M., Guisto, J. A., & Sullivan, J. B., Jr. (2002). Environmental thermal stress. *Ann Agric Environ Med, 9*(1), 1-15.

Kenny, G. P., & Journeay, W. S. (2010). Human thermoregulation: Separating thermal and nonthermal effects on heat loss. *Front Biosci, 15*, 259-290.

Kenny, G. P., Webb, P., Ducharme, M. B., Reardon, F. D., & Jay, O. (2008). Calorimetric measurement of postexercise net heat loss and residual body heat storage. *Med Sci Sports Exerc, 40*(9), 1629-1636.

Kirwan, J. P., Costill, D. L., Kuipers, H., Burrell, M. J., Fink, W. J., Kovaleski, J. E., et al. (1987). Substrate utilization in leg muscle of men after heat acclimation. *J Appl Physiol, 63*(1), 31-35.

Kohl, H. W., Blair, S. N., Paffenbarger, R. S., Jr., Macera, C. A., & Kronenfeld, J. J. (1988). A mail survey of physical activity habits as related to measured physical fitness. *Am J Epidemiol, 127*(6), 1228-1239.

Kondo, N., Shibasaki, M., Aoki, K., Koga, S., Inoue, Y., & Crandall, C. G. (2001). Function of human eccrine sweat glands during dynamic exercise and passive heat stress. *J Appl Physiol, 90*(5), 1877-1881.

Kondo, N., Takano, S., Aoki, K., Shibasaki, M., Tominaga, H., & Inoue, Y. (1998). Regional differences in the effect of exercise intensity on thermoregulatory sweating and cutaneous vasodilation. *Acta Physiol Scand, 164*(1), 71-78.

Kounalakis, S. N., Keramidas, M. E., Nassis, G. P., & Geladas, N. D. (2008). The role of muscle pump in the development of cardiovascular drift. *Eur J Appl Physiol, 103*(1), 99-107.

Ladell, W. S. (1951). Assessment of group acclimatization to heat and humidity. *J Physiol, 115*(3), 296-312.

Lee, J. B., Kim, T. W., Shin, Y. O., Min, Y. K., & Yang, H. M. (2010). Effect of the heat-exposure on peripheral sudomotor activity including the density of active sweat glands and single sweat gland output. *Korean J Physiol Pharmacol, 14*(5), 273-278.

Levi, E., Vivi, A., Hasin, Y., Tassini, M., Navon, G., & Horowitz, M. (1993). Heat acclimation improves cardiac mechanics and metabolic performance during ischemia and reperfusion. *J Appl Physiol, 75*(2), 833-839.

Lim, C. L., Byrne, C., & Lee, J. K. (2008). Human thermoregulation and measurement of body temperature in exercise and clinical settings. *Ann Acad Med Singapore, 37*(4), 347-353.

Lind, A. R., & Bass, D. E. (1963). Optimal exposure time for development of acclimatization to heat. *Fed Proc, 22*, 704-708.

Lustinec, K. (1973). Sweat rate, its prediction and interpretation. *Arch Sci Physiol (Paris), 27*(2), 127-136.

Mekjavic, I. B., & Rempel, M. E. (1990). Determination of esophageal probe insertion length based on standing and sitting height. *J Appl Physiol, 69*(1), 376-379.

Mirit, E., Gross, C., Hasin, Y., Palmon, A., & Horowitz, M. (2000). Changes in cardiac mechanics with heat acclimation: Adrenergic signaling and sr-ca regulatory proteins. *Am J Physiol Regul Integr Comp Physiol, 279*(1), R77-85.

Mitchell, D., Senay, L. C., Wyndham, C. H., van Rensburg, A. J., Rogers, G. G., & Strydom, N. B. (1976). Acclimatization in a hot, humid environment: Energy exchange, body temperature, and sweating. *J Appl Physiol, 40*(5), 768-778.

Nadel, E. R. (1984). Temperature regulation and hyperthermia during exercise. *Clin Chest Med, 5*(1), 13-20.

Nadel, E. R., Bullard, R. W., & Stolwijk, J. A. (1971a). Importance of skin temperature in the regulation of sweating. *J Appl Physiol, 31*(1), 80-87.

Nadel, E. R., Mitchell, J. W., Saltin, B., & Stolwijk, J. A. (1971b). Peripheral modifications to the central drive for sweating. *J Appl Physiol, 31*(6), 828-833.

Nadel, E. R., Pandolf, K. B., Roberts, M. F., & Stolwijk, J. A. (1974). Mechanisms of thermal acclimation to exercise and heat. *J Appl Physiol, 37*(4), 515-520.

Nagashima, K., Nakai, S., Tanaka, M., & Kanosue, K. (2000). Neuronal circuitries involved in thermoregulation. *Auton Neurosci, 85*(1-3), 18-25.

Nielsen, B. (1994). Heat stress and acclimation. *Ergonomics, 37*(1), 49-58.

Nielsen, B., Hales, J. R., Strange, S., Christensen, N. J., Warberg, J., & Saltin, B. (1993). Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J Physiol, 460*, 467-485.

Nielsen, M. (1938). Die regulation der kopertemperatur bei muskelerbeit. *Skandinavian Archives of Physiology.*, 193-230.

Nishi, Y. (1981). Measurement of thermal balance in man.

Pandolf, K. B. (1998). Time course of heat acclimation and its decay. *Int J Sports Med, 19 Suppl 2*, S157-160.

Pandolf, K. B., Burse, R. L., & Goldman, R. F. (1977). Role of physical fitness in heat acclimatisation, decay and reinduction. *Ergonomics, 20*(4), 399-408.

Pandolf, K. B., Cadarette, B. S., Sawka, M. N., Young, A. J., Francesconi, R. P., & Gonzalez, R. R. (1988). Thermoregulatory responses of middle-aged and young men during dry-heat acclimation. *J Appl Physiol, 65*(1), 65-71.

Park, S. J., & Tamura, T. (1992). Distribution of evaporation rate on human body surface. *Ann Physiol Anthropol, 11*(6), 593-609.

Parsons. (2003). Human thermal environments, the effect of hot, moderate and cold environments on human health, comfort and performance.

Patterson, M. J., Stocks, J. M., & Taylor, N. A. (2004). Humid heat acclimation does not elicit a preferential sweat redistribution toward the limbs. *Am J Physiol Regul Integr Comp Physiol, 286*(3), R512-518.

Peter, J., & Wyndham, C. H. (1966). Activity of the human eccrine sweat gland during exercise in a hot humid environment before and after acclimatization. *J Physiol, 187*(3), 583-594.

Ramanathan, N. L. (1964). A new weighting system for mean surface temperature of the human body. *J Appl Physiol, 19*, 531-533.

Reardon, F. D., Leppik, K. E., Wegmann, R., Webb, P., Ducharme, M. B., & Kenny, G. P. (2006). The snellen human calorimeter revisited, re-engineered and upgraded: Design and performance characteristics. *Med Biol Eng Comput, 44*(8), 721-728.

Regan, J. M., Macfarlane, D. J., & Taylor, N. A. (1996). An evaluation of the role of skin temperature during heat adaptation. *Acta Physiol Scand, 158*(4), 365-375.

Roberts, M. F., Wenger, C. B., Stolwijk, J. A., & Nadel, E. R. (1977). Skin blood flow and sweating changes following exercise training and heat acclimation. *J Appl Physiol, 43*(1), 133-137.

Robinson, S., Turrell, E. S., Belding, H. S., & Horvath, S. M. (1943). Rapid acclimatization to work in hot climates. *Am J Physiol, 140*, 168-176.

Romanovsky, A. A. (2007). Thermoregulation: Some concepts have changed. Functional architecture of the thermoregulatory system. *Am J Physiol Regul Integr Comp Physiol, 292*(1), R37-46.

Rowell, L. B. (1974). Human cardiovascular adjustments to exercise and thermal stress. *Physiol Rev, 54*(1), 75-159.

Rowell, L. B. (1993). Human cardiovascular control. Oxford University Press, New York.

Rowell, L. B., Kraning, K. K., 2nd, Kennedy, J. W., & Evans, T. O. (1967). Central circulatory responses to work in dry heat before and after acclimatization. *J Appl Physiol, 22*(3), 509-518.

Saat, M., Sirisinghe, R. G., Singh, R., & Tochihara, Y. (2005). Decay of heat acclimation during exercise in cold and exposure to cold environment. *Eur J Appl Physiol, 95*(4), 313-320.

Saga, K. (2002). Structure and function of human sweat glands studied with histochemistry and cytochemistry. *Prog Histochem Cytochem, 37*(4), 323-386.

Sato, F., Owen, M., Matthes, R., Sato, K., & Gisolfi, C. V. (1990). Functional and morphological changes in the eccrine sweat gland with heat acclimation. *J Appl Physiol, 69*(1), 232-236.

Sato, K., & Dobson, R. L. (1970). Regional and individual variations in the function of the human eccrine sweat gland. *J Invest Dermatol, 54*(6), 443-449.

Sawka, M. N., B., W. C., & Pandolf, K. B. (1996). Thermoregulatory responses to acute exercise-heat stress and heat acclimation. *Handbook of Physiology: Environmental Physiology*, 157-186.

Sawka, M. N., Burke, L. M., E., E. R., J., M. R., Montain, S. J., & Stachenfeld, N. S. (2007). Exercise and fluid replacement. *Med Sci Sports Exerc*.

Sawka, M. N., Convertino, V. A., Eichner, E. R., Schnieder, S. M., & Young, A. J. (2000). Blood volume: Importance and adaptations to exercise training, environmental stresses, and trauma/sickness. *Med Sci Sports Exerc, 32*(2), 332-348.

Sawka, M. N., Gonzalez, R. R., Young, A. J., Dennis, R. C., Valeri, C. R., & Pandolf, K. B. (1989). Control of thermoregulatory sweating during exercise in the heat. *Am J Physiol, 257*(2 Pt 2), R311-316.

Sawka, M. N., Pandolf, K. B., Avellini, B. A., & Shapiro, Y. (1983). Does heat acclimation lower the rate of metabolism elicited by muscular exercise? *Aviat Space Environ Med, 54*(1), 27-31.

Sawka, M. N., & Wenger, C. B. (1998). Physiologic response to acute exercise heat stress. *In: Gonzalez RR, editor. Human Performance Physiology and Environmental Medicine at Terrestrial Extremes. In: Benchmark Press*, 97-151.

Sciaraffa, D., Fox, S. C., Stockman, R., & Greenleaf, J. E. (1981). Human acclimation and acclimatization to heat; a compendium of research - 1968-1978. Techincal memorandum no. 81181.

Senay, L. C., Mitchell, D., & Wyndham, C. H. (1976). Acclimatization in a hot, humid environment: Body fluid adjustments. *J Appl Physiol, 40*(5), 786-796.

Shapiro, Y., Hubbard, R. W., Kimbrough, C. M., & Pandolf, K. B. (1981). Physiological and hematologic responses to summer and winter dry-heat acclimation. *J Appl Physiol, 50*(4), 792-798.

Shapiro, Y., Moran, D., & Epstein, Y. (1998). Acclimatization strategies--preparing for exercise in the heat. *Int J Sports Med, 19 Suppl 2*, S161-163.

Shapiro, Y., Pandolf, K. B., & Goldman, R. F. (1982). Predicting sweat loss response to exercise, environment and clothing. *Eur J Appl Physiol Occup Physiol, 48*, 83-96.

Shibasaki, M., & Crandall, C. G. (2011). Mechanisms and controllers of eccrine sweating in humans. *Front Biosci (Schol Ed), 2*, 685-696.

Shibasaki, M., Wilson, T. E., & Crandall, C. G. (2006). Neural control and mechanisms of eccrine sweating during heat stress and exercise. *J Appl Physiol, 100*(5), 1692-1701.

Shvartz, E., Bhattacharya, A., Sperinde, S. J., Brock, P. J., Sciaraffa, D., & Van Beaumont, W. (1979). Sweating responses during heat acclimation and moderate conditioning. *J Appl Physiol, 46*(4), 675-680.

Shvartz, E., Magazanik, A., & Glick, Z. (1974). Thermal responses during training in a temperate climate. *J Appl Physiol, 36*(5), 572-576.

Shvartz, E., Saar, E., Meyerstein, N., & Benor, D. (1973). A comparison of three methods of acclimatization to dry heat. *J Appl Physiol, 34*(2), 214-219.

Simon, E. (1974). Temperature regulation: The spinal cord as a site of extrahypothalamic thermoregulatory functions. *Rev Physiol Biochem Pharmacol*(71), 1-76.

Siri, W. E. (1956). The gross composition of the body. *Adv Biol Med Phys, 4*, 239-280.

Stein, H. J., Eliot, J. W., & Bader, R. A. (1949). Physiological reactions to cold and their effects on the retention of acclimatization to heat. *J Appl Physiol, 1*(8), 575-585.

Strydom, N. B., Wyndham, C. H., Williams, C. G., Morrison, J. F., Bredell, G. A., Benade, A. J., et al. (1966). Acclimatization to humid heat and the role of physical conditioning. *J Appl Physiol, 21*(2), 636-642.

Takano, S., Kondo, N., Shibasaki, M., Aoki, K., Inoue, Y., & Iwata, A. (1996). The influence of work loads on regional differences in sweating rates. *Jpn J Physiol, 46*(2), 183-186.

Takeno, Y., Kamijo, Y. I., & Nose, H. (2001). Thermoregulatory and aerobic changes after endurance training in a hypobaric hypoxic and warm environment. *J Appl Physiol, 91*(4), 1520-1528.

Taylor, N. A. (2000). Principles and practices of heat adaptation. *Journal of the Human-Environmental System, 4*(1), 11-22.

Taylor, N. A. (2006). Challenges to temperature regulation when working in hot environments. *Ind Health, 44*(3), 331-344.

Taylor, N. A. (2013). Human heat adaptation. *Comprehensive Physiology,* In press.

Webb, P. (1995). The physiology of heat regulation. *Am J Physiol, 268*(4 Pt 2), R838-850.

Weller, A. S., Linnane, D. M., Jonkman, A. G., & Daanen, H. A. (2007). Quantification of the decay and re-induction of heat acclimation in dry-heat following 12 and 26 days without exposure to heat stress. *Eur J Appl Physiol, 102*(1), 57-66.

Wendt, D., van Loon, L. J., & Lichtenbelt, W. D. (2007). Thermoregulation during exercise in the heat: Strategies for maintaining health and performance. *Sports Med, 37*(8), 669-682.

Wenger, C. B. (1972). Heat of evaporation of sweat: Thermodynamic considerations. *J Appl Physiol, 32*(4), 456-459.

Werner, J. (2009). System properties, feedback control and effector coordination of human temperature regulation. *Eur J Appl Physiol, 109*(1), 13-25.

Williams, C. G., Wyndham, C. H., & Morrison, J. F. (1967). Rate of loss of acclimatization in summer and winter. *J Appl Physiol, 22*(1), 21-26.

Wyndham, C. H. (1967). Effect of acclimatization on the sweat rate-rectal temperature relationship. *J Appl Physiol, 22*(1), 27-30.

Wyndham, C. H., Benade, A. J., Williams, C. G., Strydom, N. B., Goldin, A., & Heyns, A. J. (1968). Changes in central circulation and body fluid spaces during acclimatization to heat. *J Appl Physiol, 25*(5), 586-593.

Wyndham, C. H., & Jacobs, G. E. (1957). Loss of acclimatization after six days of work in cool conditions on the surface of a mine. *J Appl Physiol, 11*(2), 197-198.

Wyndham, C. H., Strydom, N. B., Benade, A. J., & van Rensburg, A. J. (1973). Limiting rates of work for acclimatization at high wet bulb temperatures. *J Appl Physiol, 35*(4), 454-458.

Wyndham, C. H., Strydom, N. B., Morrison, J. F., Du Toit, F. D., & Kraan, J. G. (1954). Responses of unacclimatized men under stress of heat and work. *J Appl Physiol, 6*(11), 681-690.

Young, A. J., Sawka, M. N., Levine, L., Cadarette, B. S., & Pandolf, K. B. (1985). Skeletal muscle metabolism during exercise is influenced by heat acclimation. *J Appl Physiol, 59*(6), 1929-1935.