The Practical Application of Heat Acclimatization Induction and Intermittent Exercise-Heat Exposures in Endurance Athletes

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The Practical Application of Heat Acclimatization Induction and Intermittent Exercise-Heat Exposures in Endurance Athletes

Yasuki Sekiguchi, PhD

University of Connecticut, 2020

Background: Heat acclimation (HA) and heat acclimatization (HAz) are impactful strategies to mitigate negative impact of exercise performance in the heat. However, there is no practical strategy to prevent decay following HAz and HA. Purpose: The purpose of this study was to investigate the effect of HA following HAz or dual heat acclimatization (DHA) on endurance performance and the effect of heat training (HT) on endurance performance following DHA.

Methods: Twenty-six endurance athletes (mean (M)±SD; age, 35±12yrs; body mass, 72.8±8.9kg; height, 178.7±6.3 cm; VO\textsubscript{2max}, 57.3±6.7ml·kg\textsuperscript{-1}·min\textsuperscript{-1}) completed five 4km time trials (TT) (baseline-unacclimatized, test\textsuperscript{#1}; post-HAz, test\textsuperscript{#2}; post-HA/DHA, test\textsuperscript{#3}; 4 weeks post-DHA, test\textsuperscript{#4}; 8 weeks post-DHA, test\textsuperscript{#5}) in the heat (M±SD; ambient temperature [T\textsubscript{amb}], 35.5±0.7 °C; relative humidity [%RH], 46.3±2.2%; Wet Bulb Globe Temperature (WBGT), 29.2±0.7 °C). After test\textsuperscript{#1}, participants performed self-directed summer training followed by test\textsuperscript{#2}. Then, they completed a five-days of a HT over eight days in the heat (M±SD; T\textsubscript{amb}, 39.2±0.4 °C; [%RH, 51.1±2.6%; WBGT, 33.2±0.7 °C). During the HA sessions, participants exercised to induce hyperthermia for 60 minutes, which is defined as hypermeric zone HA (HZHA, 38.50°C and 39.75°C). Participants were then divided into three groups; maximal heat training group (HT\textsubscript{MAX}), minimum heat training (HT\textsubscript{MIN}), and the control group (HT\textsubscript{CON}). HT\textsubscript{MAX} completed a total of sixteen visits and HT\textsubscript{MIN} completed a total of eight visits over the course of eight weeks. The exercise used for the HT matched the HA sessions. Percent 4km time change (TT\textsubscript{p}) was calculated based on test\textsuperscript{#3} results. Results: TT\textsubscript{p} was significantly faster at test\textsuperscript{#3}
compared to test$^1$ (M±SD; 4.8±10.1 %, p=0.024) and test$^2$ (M±SD; 3.1±7.4 %, p=0.040). TT$_p$ was significantly faster in HT$_{MAX}$ (M±SD; -4.2±5.4 %) compared to HT$_{MIN}$ (M±SD; 1.9±6.5 %, p=0.044) and HT$_{CON}$ (M±SD; 10.7±17.0 %, p=0.024) at test$^5$. There were no differences of TT$_p$ in HT$_{MIN}$ between test$^3$, test$^4$ (M±SD; 0.95±5.55%), and test$^5$ (M±SD; 1.93±6.45%).

**Conclusions:** These results indicated that HT twice per week demonstrated improvement after 8 weeks following DHA, while HA$_{CON}$ lost adaptations in 4 weeks and even greater losses in 8 weeks. HT once per week may maintain adaptations for 4 weeks and potentially for 8 weeks.
The Practical Application of Heat Acclimatization Induction and Intermittent Exercise-Heat Exposures in Endurance Athletes

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University of Connecticut

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The Practical Application of Heat Acclimatization Induction and Intermittent Exercise-Heat Exposures in Endurance Athletes

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Chapter 1 Study Overview

Study Introduction

Strength and conditioning coaches and sport scientists are given the task of preparing athletes, both mentally and physically, for competing in a wide range of environmental conditions. Athletes who compete at the National Collegiate Athletic Association (NCAA), International (ex. Olympics, World Cup), and many other levels often have training and competitions in locations with extreme heat. Training and competing in the heat has negative implications for performance and safety, including a higher internal body temperature, increased heart rate, changes in perceptual measures, and slower time-trials. Additionally, exertional heat stroke is among the top three leading causes of death in sport and other exertional heat illnesses, including heat exhaustion, heat syncope, and heat cramps, are a prevalent and recurring issues across all levels of sport. Heat acclimatization (HAz) and heat acclimation (HA) are impactful strategies that can be used to optimize performance and safety when competing in the heat.

Adaptations known to improve exercise performance in the heat include decreases in heart rate, internal body temperature, perceived exertion, sweat sodium and chloride concentrations, and increases in plasma volume and sweat rate. In addition to the performance effects, research has found that mandating HAz reduced heat illness prevalence by 55%. However, when an individual discontinues consistent heat exposure, all of the physiological and perceptual benefits of HA will return to the pre-HA state. This process is known as HA decay.
Even though there are known improvements in performance with HAz, and research has shown that these benefits cease without heat exposure, only one study has investigated strategies to maintain HA benefits for an extended duration. (11) The reported strategy involved an exercising heat exposure once every five days following HA. (11) This study observed that maintenance every five days still resulted in a small decay in the physiological benefits of HA after 25 days while the control group demonstrated larger decay. Additionally, this study did not report any performance tests in any environmental conditions that might be improved by the maintenance of HA. Thus, the overall aim of this study was to assess the practical application of HAz, HA, and intermittent exercise-heat training in endurance athletes.

**Aims and Research Questions**

**Aim 1**

Assess changes in body heat exchanges following HAz and HA (Dual Heat Acc [DHA]) in endurance trained athletes.

**Research Question 1**

Do metabolic heat production, evaporative heat loss, and dry heat loss change throughout HAz and HA in endurance trained athletes?

**Hypothesis 1**

Evaporative heat loss and dry heat loss will increase following HAz and HA while metabolic heat production will decrease.
**Independent Variables**

Time (Test 1 [Baseline-un-acclimatized], Test 2 [Post-HAz], Test 3 [Post-HA/DHA])

**Dependent Variables**

Metabolic heat production, Evaporative heat loss, Dry heat loss, Running economy, Rate of maximal evaporation, Total evaporation required for heat balance, Sweat rate, Internal body temperature, Skin temperature

**Aim 2**

Investigate the effect of short-term HA following HAz (DHA) on endurance performance and the effect of intermittent heat training on endurance performance following DHA in trained endurance athletes.

**Research Question 2a**

Does short-term HA following HAz (DHA) improve 4km time trial in endurance trained athletes?

**Hypothesis 2a**: HA will elicit the improvement of 4km time trial performance following HAz.

**Independent Variables:**

Time (Test 1 [Baseline-un-acclimatized], Test 2 [Post-HAz], Test 3 [Post-HA/DHA])

**Dependent Variables:**

4km time trial performance
Research Question #2b: Does intermittent heat training twice per week and once per week alter 4km time trial performance following DHA in endurance trained athletes?

Hypothesis 2b: There is a dose-response relationship with the number of weekly-intermittent exercise-heat training on 4km time trial performance.

Independent Variables:

Time (Test 3 [Post-HA/DHA], Test 4 [Post 4 weeks of heat training], Test 5 [Post 8 weeks of heat training]), Heat training (Two times per week of heat training, One time per week of heat training, No heat training)

Dependent Variables:

4km time trial performance

Aim 3: Assess a practical method to determine adaptations following HA and HAz (DHA) using relationships between heart rate, sweat rate, thermal sensation, and the internal body temperature.

Research Question #3: Are there relationships between adaptations in heart rate, sweat rate, thermal sensation, and the internal body temperature following HA and HAz (DHA)?

Hypothesis 3: Combining adaptations of heat rate, sweat rate, and thermal sensation will be associated with a positive adaptation in the internal body temperature.

Independent Variables:

Heat rate, Sweat rate, Thermal sensation
Dependent variables:

Internal body temperature

Method of Techniques

To examine the research aims, 36 endurance trained male participants were recruited (age 18-55 years old and VO$_{2\text{max}}$ ≥45 ml·kg$^{-1}$·min$^{-1}$). Participants completed, natural HAz throughout their normal summer training, 5 days of HA in the lab, intermittent-heat training sessions, five lab testing, and five VO$_{2\text{max}}$ test. Data were collected from May 2019 to November 2019. A description of the study timeline can be seen below (Figure 1).

Figure 1. Study timeline

VO$_{2\text{max}}$ test

Participants performed a graded exercise test on a treadmill using a ramping protocol in a
thermoneutral environment to determine their maximal aerobic capacity (VO\textsubscript{2max}) five times throughout the study. Participants were fitted with a Hans Rudolph mask attached to a breathing tube to collect the expired air delivered to the metabolic cart system during the exercise test (T150; COSMED, Traunstein, Germany). The metabolic cart continuously measured respiratory exchange ratio (RER) and oxygen consumption (VO\textsubscript{2}). The participant completed a self-selected pace warm-up before the test. During the test, the speed was increased either 0.5 or 1.0 mile·h\textsuperscript{-1} after 2 minutes of each stage. Rating of perceived exertion and heart rate, using a heart rate chest strap, were measured at the end of each stage. Participants continued exercise until reaching to their maximal effort. VO\textsubscript{2max}, velocity of VO\textsubscript{2max}, and maximum heart rate were collected at the end of test.

**Lab Testing**

*Timeline of Testing*

1. Test\textsuperscript{#1} (Baseline-unacclimatized state) was performed before the start of HAz.
2. Test\textsuperscript{#2} (Post-HAz) occurred late August to early September to evaluate the effects of HAz
3. Test\textsuperscript{#3} (Post-HA/DHA) was completed following five days of short-term HA in September.
4. Test\textsuperscript{#4} (4 weeks of HT) were conducted to exam the effects of HT in October
5. Test\textsuperscript{#5} (8 weeks of HT) were conducted to exam the effects of HT in November.

*Testing Procedures*
To assess physiological adaptations, the first part of the testing session included exercise on a motorized treadmill for 60 minutes at 60% VO$_{2\text{max}}$. Following this test, there was a thirty-minute break. After break, participants performed a 4k time trial on a motorized treadmill. This test was used to assess adaptations in performance (Figure 2).

![Testing design](image)

**Figure 2.** Testing design

**Variables**

Internal body temperature (rectal temperature), Heart rate, Rating of perceived exertion, Level of thirst, Thermal sensation, Sweat rate, Sweat electrolyte, Skin temperature, Metabolic heat production, Evaporative heat loss, Dry heat loss, Running economy, Rate of maximal evaporation, Total evaporation required for heat balance, 4km time trial performance

**Environmental Conditions**

These lab testing sessions were performed in 34°C with 50% relative humidity in a controlled environmental chamber for the hot testing session.
**Hydration**

To ensure participants begin testing in a euhydrated state, urine color (12) and urine specific gravity (USG) were assessed using a urine sample provided upon arrival to the lab prior to the start of testing. Urine color was assessed using a validated color chart and USG was assessed by placing a urine sample on a handheld refractometer (Model TS400; Reichert Inc., Depew, NY). Participants did not consume fluid during exercise. During the 30-minute break between the 60 minutes of exercise and 4k time trial, participants prescribed fluid based on body mass loss to start the 4k time trial in a euhydrated state.

**Nutrition**

Participants were asked to consume and log their normal diet 3 days prior to the first day of testing and were asked to replicate this diet before each testing session.

**Heat Acclimatization**

Following test #1, participants were asked to complete their normal training routine. Training loads, including total distance covered, training time, and average HR, were captured throughout the study by training load monitoring devices (Garmin [Forerunner® Fenix® Vivoactive® Garmin™ Ltd., Olathe, Kansas, USA]; Polar H10 and Polar Beat application, [H10®, Polar Electro™, Kempele, Finland]). The location of training was determined by the GPS device and the closest weather station was utilized. Daytime WBGTs (7 a.m. - 7 p.m.) were modeled using Heat Stress Advisor software package (version 2005; Zunis Foundation, Tulsa, OK; Coyle
2000), which is designed to work with weather station data; nighttime WBGTs were calculated using the Liljegren model with solar radiation set to zero.

**Heat Acclimation**

Following the period of HAz, for test#2, participants performed 5 days of HA in the lab. During HA, participants performed exercise in the heat to induce hyperthermia for 60 minutes, which is defined as hyperthermic zone (HZHA) method. Hyperthermia was defined as internal body temperature between 38.50-39.75°C. Participants’ exercise intensity was modified to maintain as high internal body temperature as possible within this hyperthermic zone to achieve greater area under the curve of internal body temperature. These HA sessions were performed in 40°C with 50% relative humidity in a controlled environmental chamber for the hot testing session.

**Intermittent Heat Training**

Following HAz and HA or DHA, for test#3, participants were randomly divided into three groups with matching VO₂max, body mass and age; maximal heat training group (HTMAX), minimum heat training (HTMIN), and the control group (HTCON). HTMAX completed a total of sixteen visits, which was approximately two times a week of HT and HTMIN completed a total of eight visits over the course of eight weeks, which was approximately one time a week of HT. The HZHA was also used for the HT.
**Justification of Sample Size**

Our sample size calculation was performed based on the previous study examining the effectiveness of intermittent heat exposures every five days following heat acclimation. (11) This study demonstrated participants who received intermittent heat exposures achieved 0.47°C lower in internal body temperature with a 95% confidence interval of [-0.24 to 1.19°C] with an effect size of 0.68. Based on this information, the power level of 0.8 the estimated sample size required 24 participants total or 8 participants per group for a two-sided test with 0.05 alpha level. The G Power Calculator was utilized for this calculation.

**Statistical Analysis**

All data were reported as mean ± standard deviation, mean difference ± standard error, effect sizes, and 95% confidence intervals. Effect size (ES) were calculated using Hedges' g with the resulting effects identified as either small (0.2-0.49), medium (0.5-0.79), or large (> 0.8) effects. (13) The level of significance was set at p≤0.05. All statistical analyses were performed using statistical software (SPSS, v.25. IBM Corporation, Armonk, NY) or JMP, version 15 (SAS Institute Inc., Caryn N.C., USA).

*Research question #1*

Repeated measures ANOVAs with LSD pairwise comparisons were performed to assess differences between mean metabolic heat production, evaporative heat loss from skin, dry heat loss, total evaporation required for heat balance (E_{req}), the rate of maximal evaporation (E_{max}),
and running economy in test#1, test#2, and test#3. Stepwise linear regression was used to predict maximum internal body temperature from metabolic heat production, evaporative heat loss, dry heat loss, skin temperature, sweat rate, and minimum internal body temperature.

Research question #2

Repeated measures ANOVAs with both independent and dependent t-tests were performed to assess differences of 4km time trial performance, heart rate, rectal temperature, RPE, thermal sensation, and fatigue level in test#1, test#2, test#3, test#4, and test#5.

Research question #3

To examine the adaptations for heart rate, sweat rate, ending T_{rec}, and TS following HAz, HA, and DHA, the differences between test#1 and test#2, test#2 and test#3, test#1 and test#3 were calculated. Minus values for heart rate, rectal temperature, and thermal sensation, and positive values for sweat rate indicated improvements. Furthermore, rectal temperature for each participant and testing was categorized into either improved or not. Then, the decision tree was used to determine the cut-point of ending heart rate, sweat rate, and thermal sensation to determine if rectal temperature was improved or not. Then, the number of variables among heart rate, sweat rate, and thermal sensation to meet the cut-points were counted. Independent t-tests were performed to examine the difference of rectal temperature between the number of variables meeting cut-points. Also, binary logistic regression was used to predict changes in rectal temperature.
**Human Subjects Research**

The institutional review board (IRB) had approved this study and the IRB protocol number was H19-015.

**Chapter 2 Literature Review**

**Responses to Exercise in the Heat**

Sports scientists, coaches, and medical professions are given the task of preparing athletes to compete in a wide range of environmental conditions, including exercise in the heat. Major sport events at the both National (ex. National Collegiate Athletic Association) and International (ex. the FIFA World Cup Soccer, the world championship, and the Olympics) are often held in locations where heat comes into play. Greater physiological strain, such as an increased heart rate and internal body temperature, is placed on the body when an individual performs exercise in a hot environment compared to exercising in temperate environmental conditions.(14)

During cycling world championships, 85% of elite cyclist reached an internal body temperature of at least 39°C and 25% exceeding 40°C, which was associated with higher fatigue.(15, 16) This explains the reason why marathon performance progressively decreases as the WBGT increases from 5°C to 25°C.(17) In addition to performance decrements, exertional heat illnesses, such as heat exhaustion, heat syncope, and heat cramps, are prevalent issues across all levels of sport and this may result in withdrawal from exercise.(3, 18) For example, 232 exertional heal
illness events were reported in NCAA athletes during five years. Thus, training and competing in the heat have negative implications for performance and safety.

**Human Body Heat Exchange**

Body heat storage is explained by the human heat balance equation: \( S = M - W_k - R - C - K - E \) (W), where \( S \)= body heat storage, \( M \)= metabolic rate, \( W_k \)= external work rate, \( R \)= radiation, \( C \)= convection, \( K \)= conduction, and \( E \)= the rate of evaporative heat dissipation. (21)

Thermoregulation is achieved through a balance between heat production \((M - W)\) and heat loss \((R + C + K + E)\). Metabolic heat production \((M - W)\) refers to the amount of heat which is not used for work after releasing as energy. Approximately 75-90% of the energy produced does not contribute to performing work and it is liberated as heat, which leads to an increase the internal body temperature. (22–24) Sweat evaporation \((E)\) plays an important role in thermoregulation and the body dissipates heat 30-100% of its heat through evaporation. (25, 26) This mechanism is especially critical for heat loss from the body during exercise in the heat. (21) In addition to evaporative cooling from sweat, dry heat loss \((C, K, R)\) is achieved through the transfer of heat from high to low temperature. The balance between heat production and heat dissipation determines the heat storage and the internal body temperature.

**Strategies to Mitigate Negative Impact of Heat**

To optimize exercise performance and safety, practical, effective heat mitigation strategies are needed. A recent meta-analysis examined the magnitude of different heat mitigation strategies,
including fluid ingestion, pre-cooling, heat acclimatization (HAz) and heat acclimation (HA), and aerobic fitness. (21) Findings indicated the most effective strategy for lowering the internal body temperature and improving endurance performance was aerobic fitness, followed by HAz and HA, pre-cooling, and fluid ingestion (Figure 3). (27) While aerobic fitness indicated the largest impact, a change in aerobic fitness for an elite athlete is not easy due to their high level training history. Thus, HA is suggested as one of the impactful and practical strategies to induce positive adaptations and ensure the peak physical condition for the athlete exercising in the heat.

**Figure 3.** Forest plot of combined Hedges’ g weighted averages of heat mitigation strategies. (27)

**Adaptations of Heat Acclimatization and Heat Acclimation**

**Physiological and Perceptual Adaptations**

HA is the set of adaptations that develop following systematic and repeated heat exposures. HA refers to training in a hot artificial environment and HAz indicates training in a natural hot environment. HA requires sufficient heat stress to elicit profuse sweating and elevate skin and internal body temperature, which results in positive physiological and performance adaptations. (20) Figure 4 described the percent change in plasma volume, heart rate, internal
temperature, sweat rate, and exercise capacity and the time course of those adaptations during HA.

Figure 4. The percent change in plasma volume, heat rate, internal temperature, sweat rate and exercise capacity over the course of induction in heat acclimation. Data from Periand, J.D., Racinais, S., Sawka, M.N. Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. Scandinavian Journal of Medicine & Science in Sports, 2015.(28)

One of the most rapid adaptations observed following HA are increased plasma volume leading to increased stroke volume and decreased heart rate, which typically occurs within 3-6 days of exercise heat exposure.(8, 20) The range of plasma volume expansion can be 3-27% which contributes to decreases in heart rate by 15-25%.(28–30) Plasma volume expansion results from the expansion of total body water via increases in aldosterone and arginine vasopressin secretion and total plasma protein.(30, 31) In addition to plasma volume expansion, improved skin cooling, the redistribution of blood, and reduced skin and internal body temperature play roles in reducing cardiovascular strain.(28) Lower heart rate and larger plasma volume also lead to a better maintenance of cardiac output and blood pressure during exercise.(28) An increase in cardiac output is one of the reason explaining the approximate 4-8% improvement in VO_{2max}
following HA.(32, 33) Additionally, perceived exertion and thermal sensation improve within 3-6 days of heat during the HA process.(8, 14, 28)

One of the most important adaptations to HA is a decrease in internal body temperature. Resting and exercising internal body temperature decrease approximately 0.18°C and 0.34°C, respectively, within 5-8 days of exercise heat exposure.(8, 14) Previous research indicated exercise performance (e.g. time to exhaustion) in hot environments was improved when the resting internal body temperature was lower due to higher heat storage capacity.(16) Lower internal body temperature during both resting and exercising allows for increased effort at a relative exercise intensity that can lead to more effective training or enhanced performance due to lower fatigue.(16) Furthermore, it has been observed that 75%-80% of adaptations from HA occur within 4-7 days.(28, 34, 35)

Another important adaptation is increased retention of electrolytes, such as sodium and chloride from the sweat glands and lower electrolyte concentrations in sweat.(28, 36) Approximately 30-60% of sodium and chloride concentrations in sweat decrease following 7-10 days of HA.(26) A better conservation of electrolytes helps to increase water retention.(37) However, there are limited studies looking at sweat electrolyte by whole-body wash down method, which is the gold standard method to analyze sweat electrolyte concentrations, following HA.(26, 38) Furthermore, the onset of sweat and the initiation of increase of skin blood flow start earlier following HA so that heat dissipation through these mechanisms begins at the lower internal
temperature. (14, 28) Additionally, sweat rate increases within 8-14 days of HA. (8) Higher sweat rate results, (upwards of 11% of total loss), in evaporative heat loss. (39)

HA also induces metabolic changes that are beneficial to performance and safety while exercising in the heat. Blood and muscle lactate accumulation are decreased resulting from a reduced in oxygen uptake and glycogen utilization at a given exercise intensity. (14) This reduction has been shown to increase power output and beneficial for sports in which glycogen depletion can cause fatigue, such as marathon or ultra-endurance running. (28, 32, 40)

**Performance Adaptations**

These adaptations independently and collectively enhance exercise performance in a hot environment by improving the body’s thermoregulatory efficiency and decreasing the overall physiological strain. (41) Especially, exercise performance in sports that require strong aerobic or anaerobic capacity such as running, cycling, soccer, and American football are improved by adaptations following HA. (32, 42) HA leads to an improvement of exercise performance, not only exercise in the heat, but also in temperate and cool conditions (Figure 5). (32) Lorenzo et al., demonstrated VO$_{2\text{max}}$ and time trial performance were enhanced following 10 days of HA in in a cool (13°C) and hot (38°C) environment, while the control group did not. (32)
Figure 5. Effect of heat acclimation on VO_{2max} (A) and total work done during a 1-h time trial (B) in a cool (13°C) and hot (38°C) environment. Values are means ± SE for 12 heat acclimation subjects and 8 controls. *P < 0.05 vs. preacclimation within environmental condition.(32)

A recent meta-analysis indicated the magnitude of performance change and factors contributing those changes following HA (Figure 6).(43) The biggest performance enhancement was observed in time to exhaustion followed by time trial, mean power, VO_{2max}, and peak power following HA. The magnitude of performance improvement in time to exhaustion was the largest when a controlled work rate method was used and participants had a higher fitness level. Time trial performance was improved the most when low exercise intensity was utilized for HA, which could be associated with lower fatigue level experiencing from HA. Longer HA length (i.e. 10 days) improved mean power more than short HA length (i.e. 5 days).


**Figure 6.** Magnitude of performance changes observed in each performance test following heat acclimation. Data are presented as Hedge’s g and 95% confidence intervals. (43)

**Method of Heat Acclimatization and Heat Acclimation Induction**

**Types of Methods**

There are several methods of HA that have been achieved and those include the self-paced exercise method, constant work rate method, the controlled intensity method, the clamped heart rate method, the isothermal method, and passive heating method. Self-paced exercise has been used especially for HAz in team sports athletes. While this method might the easiest for some situations, it might not induce the most effective HA adaptations due to less controls. The constant work rate and the controlled intensity methods refer to setting a pre-determined work rate (ex, running at 12km·h⁻¹) or exercise intensity (ex, VO₂max at 65%) and maintaining this work rate or intensity throughout HA induction. The limitation of these methods are that the intensity are not changed, therefore, the time spent at hyperthermia level during each HA session typically decreases each day throughout HA due to the positive adaptations. The isothermal method indicates using exercise intensity to maintain a predetermined internal body temperature (typically 38.5°C). However, there is no consensus of opinion for this critical temperature to
induce the maximal adaptations and some researchers have suggested that higher internal body temperatures may result in larger adaptations while future research is needed. (45) While passive heating is a cost effective and less stressful method, it can induce partial adaptations. (28) Each method has advantages and disadvantages and future studies are needed to examine the optimal method(s) to induce maximal adaptations following HA.

Factors to Consider for Method

There are several important factors to consider to induce HA, including frequency, duration, exercise intensity, length, environmental conditions, and the balance between HA and training outside of HA. The frequency of HA refers to the number of days between sessions (e.g. consecutive sessions or days of rest between sessions). (47) HA in consecutive days may lead to faster adaptations, having recovery following HA is important to maximize adaptations. (48) Optimal duration of HA sessions suggests 60 to 120 minutes range for each session while longer exercise duration might be better as experiencing longer time at the desired internal body temperature, and the sweating responses needed to induce adaptations. (49) Length of HA refers to the total number of days, short-term HA (<7 days), medium-term HA (8-14 days), and long-term HA (>14 days). (45) Exercise intensity and environmental conditions should be determined to induce appropriate hyperthermia and enough sweat which result in greater adaptations following HA. Lastly, considering balance between HA and training outside of HA, monitoring training loads are critical factors. (50)

Decay of Heat Acclimation
However, when an individual discontinues heat exposure, physiological and performance adaptations are typically lost. This process is known as HA decay. Decay is calculated by this equation in the Figure 7; % Decay=(B-C)/(B-A).(51) Following HA, heart rate and internal body temperature will typically diminish at a rate of 2.5% per day without heat exposure.(51) Only a few studies have examined decay in sweat rate and other physiological variables, therefore, % decay is still unknown. While the data is limited, performance enhancements following HA seem to persist for 1-2 weeks without heat exposures.(51) The rate of decay is likely to be changed by the magnitude of adaptations induced by HA.

![Figure 7](image.png)

**Figure 7.** Example of the heat acclimation decay calculation. A is the heat unacclimatized state, B is the acclimated state, and the C is the status on return following a decay period without heat exposure.(51)

**Strategies to Avoid Decay**

Decay is one of biggest obstacles when HA is implemented in sport settings. Examining the method(s) to maintain adaptations following HA is critical for athletes, sport scientists, and medical professions aiming to maximize performance for specific competitions without interfering with sport specific training and imposing stress to the body. One study has
investigated the strategy of maintaining the benefits from HA for an extended duration following HA. (52) This strategy involved an exercising heat exposure once every five days for 25 days (intermittent heat-exposure) and demonstrated positive benefits compared to a control group (Figure 8). (52)

![Graph](image)

**Figure 8.** Group comparison of adaptation decay 25 days after initial heat acclimation. Negative value denotes a loss of adaptation. CON= no heat exposure group; IHE= intermittent exercise-heat exposure group. Decay (%) calculated using an equation from Pandolf et al. (52, 53)

Even though the intermittent heat exposure group demonstrated benefits compared to the control group, the decay was still observed. HA induction method in this study consisted of 10 days of heat exposures (40°C, 40% relative humidity), including 4 days of interval exercise (resting, walking, jogging, and running) on day 1 and day 6 for 24min and 120min on day 2 and day 7, 6 days of isothermal method (at least 60min at 38.5°C of internal body temperature). The intermittent heat-exposure protocol involved 120min of exercise at 45%VO_{2peak}. (52, 54) There are some considerations for the future study. The optimal frequency, intensity, duration of intermittent heat-exposure to induce sufficient hyperthermia and sweat to maintain full
adapatations following HA. (28) Additionally, other important factors including participant’s fitness level, the magnitude of adapatations induced by HA, and the effect on performance, need to be considered.

**Research Gaps**

**Aim 1**

While it is well known that higher sweat rate and lower skin temperature could lead to greater heat dissipation, the actual changes in evaporative heat loss and dry heat loss induced by HA are limited. Additionally, the change in metabolic heat production, which is another factor that impacts heat storage, has not been often considered when discussing adaptations following HA. One previous study investigating metabolic heat production and evaporative heat loss following HA concluded metabolic heat production decreased, but evaporative heat loss did not change following HA in untrained individuals. It has been demonstrated that the adaptations following HA between trained and inactive individuals are different. (20) Thus, the purpose of aim 1 was to examine the changes in metabolic heat production, evaporative heat loss, and dry heat loss following HAz and HA and investigate the factors impacting adaptations of heat storage.

**Aim 2**

Most of the studies examining exercise performance utilized HA. While the controlled nature of HA may result in greater adaptations, HAz may be more widely accessible and feasible. No study to date has examined the combined impact of HA following a period of HAz (referred to
herein as Dual Heat Acc (DHA) for the purposes of achieving optimal physiological adaptations and enhanced exercise performance. Additionally, even though the intermittent-heat exposure group showed benefits in HR, internal body temperature, and sweat rate compared to the control group, the decay was still observed. Additionally, the effect of HT on exercise performance was not investigated. Thus, the purposes of aim 2 were 1): to investigate the effect of short-term HA following HAz (DHA) on time-trial performance, 2): the effect of HT on endurance performance following DHA, 3) the factors associated with improvement of performance following HAz and HA.

Aim 3

Monitoring adaptations resulted from HA and HAz can be challenging and often require expensive and/or technically advanced methods. For example, adaptations in each variable (e.g., heart rate, sweat rate, perceptual measurements, and internal body temperature) are often assessed following HA and HAz. (14) heart rate, sweat rate, and perceptual measurements are relatively easier measures to collect compared to internal body temperature, which requires either rectal probes, esophageal probes, and ingestible pills. Esophageal temperature is invasive method and not practical to use during exercise. (55) Even though rectal temperature is widely used in laboratory settings, this method might not be practical or externally valid to use for continuous monitoring during exercise in field settings. (55) Ingestible pills are relatively easy to use in the field settings, however, these pills may be cost-prohibitive / are expensive. Thus, there are some limitations to monitor internal body temperature continuously in field settings. Assessing an adaptation of internal body temperature is critical following HAz and HA since it is
associated with athlete performance and safety. Considering the importance of adaptations resulting from HA and HAz, sport scientists, coaches, and medical professionals need a method to monitor adaptations, especially in field settings, without using internal body temperature measurements. Thus, the purpose of this study was to investigate the relationships between heart rate, sweat rate, thermal sensation, and rectal temperature adaptations to predict adaptations in rectal temperature independent of the induction methods.

**References**


Abstract

While higher sweat rate and lower skin temperature leads to greater heat dissipation, the body heat exchange following heat acclimatization (HAz) and heat acclimation (HA) are unknown. Thus, the purpose of this study was to examine the changes in metabolic heat production ($H_{\text{prod}}$), evaporative heat loss ($H_{\text{evap,skin}}$), and dry heat loss ($H_{\text{dry,skin}}$) following HAz and HA. Twenty-two endurance athletes (mean [M]±standard deviation [SD]; age, 37±12y; body mass, 73.4±8.7 kg; height, 178.7±6.8 cm; $VO_{2\text{max}}$, 57.1±7.2 ml·kg$^{-1}$·min$^{-1}$) completed three tests (baseline, test #1;
post-HAz, test\(^{#2}\); post-HA, test\(^{#3}\), which consisted of 60 minutes steady state exercise at 59\(\pm\)2 % vVO\(_{2}\)\(_{\text{max}}\) in the heat (M\(\pm\)SD; ambient temperature [T\(_{\text{amb}}\)], 35.2\(\pm\)0.6 \(^{\circ}\)C; relative humidity [%RH], 47.5 \(\pm\) 0.4%; Wet Bulb Globe Temperature [WBGT], 29.5\(\pm\)0.6 \(^{\circ}\)C). During the test, VO\(_{2}\) and RER were collected, and H\(_{\text{prod}}\), H\(_{\text{evap, skin}}\), and H\(_{\text{dry, skin}}\) were calculated. Following test\(^{#1}\), participants completed self-directed summer training followed by test\(^{#2}\). Then, they completed five-days of HA over eight days in the heat (M\(\pm\)SD; T\(_{\text{amb}}\), 38.7\(\pm\)1.1 \(^{\circ}\)C; %RH, 51.2\(\pm\)2.3%; WBGT, 33.8\(\pm\)1.1\(^{\circ}\)C). During the HA sessions, participants exercised to induce hyperthermia for 60 minutes, which is defined as hyperthermic zone HA (HZHA, 38.50 \(^{\circ}\)C and 39.75 \(^{\circ}\)C). Then, test\(^{#3}\) was performed. There were no differences in H\(_{\text{prod}}\) between test\(^{#1}\) (M\(\pm\)SD; 459\(\pm\)59 W\(\cdot\)m\(^{-2}\), test\(^{#2}\) (M\(\pm\)SD; 460\(\pm\)61 W\(\cdot\)m\(^{-2}\)), and test\(^{#3}\) (M\(\pm\)SD; 464\(\pm\)55 W\(\cdot\)m\(^{-2}\), p=0.866). However, H\(_{\text{evap, skin}}\) was significantly increased at test\(^{#3}\) (M\(\pm\)SD; 739\(\pm\)176 W) compared to test\(^{#2}\) (M\(\pm\)SD; 655\(\pm\)174 W, p=0.038) and test\(^{#1}\) (M\(\pm\)SD; 635\(\pm\)160 W, p=0.032). Additionally, H\(_{\text{dry, skin}}\) was significantly lower at test\(^{#2}\) (M\(\pm\)SD; 125\(\pm\)8 W\(\cdot\)m\(^{-2}\), p=0.013) and test\(^{#3}\) (M\(\pm\)SD; 121\(\pm\)10 W\(\cdot\)m\(^{-2}\), p<0.001) compared to test\(^{#1}\) (M\(\pm\)SD; 128\(\pm\)7 W\(\cdot\)m\(^{-2}\)). H\(_{\text{dry, skin}}\) at test\(^{#3}\) was also lower than test\(^{#2}\) (p=0.049). While H\(_{\text{dry, skin}}\) was decreased following HA, the decrease in H\(_{\text{dry, skin}}\) was smaller than increase in H\(_{\text{evap, skin}}\). Thus, the primary factor to induced lower heat storage following HA was increased H\(_{\text{evap, skin}}\) in endurance trained athletes.

**Introduction**

Greater physiological strain, such as an increased heart rate (HR) and internal body temperature, is placed on the body when an individual performs exercise in hot environments compared to exercising in temperate environmental conditions. (1) Additionally, exercise in the heat has
negatively impacts exercise performance and athlete safety. (2) For example, marathon performance progressively decreases as the WBGT increases from 5°C to 25°C. (3) Furthermore, exertional heat stroke is among the top three leading causes of death in sport and other exertional heat illnesses, including heat exhaustion, heat syncope, and heat cramps, are a prevalent and recurring issues across all levels of sport. (4) Thermal and cardiovascular strains are induced by the changes in body heat storage.

Body heat storage is explained by the human heat balance equation: \( S = M - Wk \pm R \pm C \pm K - E \) (W), where \( S \)=body heat storage, \( M \)=metabolic rate, \( Wk \)=external work rate, \( R \)=radiation, \( C \)=convection, \( K \)=conduction, and \( E \)=the rate of evaporative heat dissipation. (5) Thermoregulation is achieved through a balance between heat production (\( M - W \)) and heat loss (\( R + C + K + E \)). Metabolic heat production (\( M - W \)) refers to the amount of heat which is not used for work after releasing as energy. Approximately 75-90% of the energy produced does not contribute to performing work and it is liberated as heat, which leads to an increase the internal body temperature. (6–8) Sweat evaporation (\( E \)) plays an important role in thermoregulation and the body dissipates 30-100% of heat through evaporation. (9, 10) This mechanism is critical for heat loss during exercise in the heat. (5) In addition to evaporative cooling from sweat, dry heat loss (\( C, K, R \)) is achieved through the transfer of heat from high to low temperature. The balance between heat production and heat dissipation determines the heat storage and the internal body temperature.
Heat acclimatization (HAz) and heat acclimation (HA) are impactful strategies to mitigate physiological strain during exercising in the heat. (1) HA refers to training in a hot artificial environment and HAz indicates training in a natural hot environment. Adaptations following HA and HAz include decreases in HR, internal body temperature, skin temperature, rating of perceived exertion, thermal sensation, sweat sodium and chloride concentrations, and increases in plasma volume, sweat rate, and skin blood flow. (11, 12) While all adaptations are important, an adaptation in the internal body temperature is critical to both safety from heat illnesses and performance. An increase in the internal body temperature during exercise in the heat is associated with higher HR and lower stroke volume, mean arterial pressure, and potentially cardiac output. (13, 14) Additionally, higher internal body temperature induced greater fatigue and lower exercise performance in trained individuals. (15)

While it is well known that higher sweat rate and lower skin temperature could lead to greater heat dissipation, the actual changes in evaporative heat loss and dry heat loss induced by HA and HAz are limited. Additionally, the change in metabolic heat production, which is another factor that impacts heat storage, has not been often considered when discussing adaptations following HA and HAz. One previous study investigating metabolic heat production and evaporative heat loss following HA concluded metabolic heat production decreased, but evaporative heat loss did not change in untrained individuals. It has been demonstrated that the adaptations following HA between trained and inactive individuals are different. (2) Thus, the purpose of this study was to examine the changes in metabolic heat production, evaporative heat loss, and dry heat loss.
following HAz and HA and investigate the factors impacting adaptations of heat storage in trained endurance athletes.

**Materials and Methods**

Twenty-two endurance athletes (mean [M]±standard deviation [SD]; age, 37±12y; body mass [BM], 73.4±8.7 kg; height, 178.7±6.8 cm; %body fat, 10.8±5.2%; VO$_{2\text{max}}$, 57.1±7.2 ml·kg$^{-1}$·min$^{-1}$) participated in this study. Following an explanation of study procedures, which was approved by the Institutional Review Board at <<removed for review>>, participants provided written and informed consent to participate in this study.

Participants completed a maximal oxygen consumption test with a graded running exercise on a standardized treadmill to collect VO$_{2\text{max}}$ consumption and the velocity of VO$_{2\text{max}}$ (T150; COSMED, Traunstein, Germany). The participant completed 5 minutes of self-selected pace warm-up before the test. During the test, the speed was increased either 0.5 or 1.0 mile·h$^{-1}$ after 2 minutes of each stage. Participants continued exercise until reaching to their maximal effort.

Before participants received any heat exposures in the lab and the outside, they performed a test to measure physiological responses to the heat in the lab (baseline: test$^\#1$). The test consisted of 60 minutes exercise at 59±2 % vVO$_{2\text{max}}$ in the heat (M±SD; ambient temperature [T$_{\text{amb}}$], 35.2±0.6 °C; relative humidity [%RH], 47.5 ± 0.4%; Wet Bulb Globe Temperature [WBGT], 29.5±0.6 °C; wind speed 4.0±0.1 mile·h$^{-1}$). Participants provided urine samples to measure their
hydration status before the test and they were ensured to start test with euhydrated status (M±SD; urine specific gravity [USG], 1.010±0.009; color, 2±0). (16) If the USG was above 1.020 and below 1.025, participants consumed 500mL of water prior to the start of test. During the test, rectal temperature (T_{rec}) (MP160; BIOPAC Systems Inc., Goleta, CA, USA), HR (H10®, Polar Electro™, Kempele, Finland), and mean skin temperature (T_{sk}) using on four-sites including the thigh, chest, upper arm (17) (iButton; iButton Link LLC., Whitewater, WI, USA), and sweat rate were measured. Sweat rate was calculated based on pre and post exercise nude body mass. Additionally, VO$_2$ and RER were collected using a standard metabolic cart at 5-10, 30-35, and 55-60 minutes (TrueOne(R) Metabolic Measurement System; PARVO MEDICS Inc., Sandy, UT, USA).

Following test#1, participants performed self-directed summer training. After summer training, participants performed the same test (post-HAz: test#2). Then, participants performed 5 days of HA to induce hyperthermia for 60 minutes, which refers to hyperthermic zone HA (HZHA, 38.50-39.75°C) in the heat (M±SD; T$_{amb}$, 38.7±1.1 °C; %RH, 51.2± 2.3%; WBGT, 33.8±1.1°C). Then, the test was performed to investigate adaptations following “dual heat acc” (DHA), which was defined as the combination of HAz and HA (post-DHA: test#3).

Metabolic heat production ($H_{prod}$) was calculated by subtracting the rate of external work performed (running) (Wk) from the concurrent rate of metabolic energy expenditure dividend by surface area ($A_D$) for each participant (M)(5):
\[ H_{\text{prod}} \ (W \cdot m^{-2}) = (M - W_k) \div (A_D) \]

\[ M = \text{VO}_2 \cdot \left\{ \left[ \left( \frac{\text{RER} - 0.7}{0.3} \right) \cdot 21.13 \right] + \left[ \left( \frac{1.0 - \text{RER}}{0.3} \right) \cdot 19.62 \right] \right\} \times 1000 \ (W) \]

The average rate of evaporative heat loss from the skin surface \( H_{\text{evap,skin}} \) and sweat efficiency \( S_{\text{eff}} \) was calculated with following equation (5):

\[ H_{\text{evap,skin}} \ (W) = \text{Whole body sweat rate} \cdot 2426 \cdot \frac{s_{\text{eff}}}{60} \]

\[ S_{\text{eff}} = 1 - \frac{\omega_{\text{req}}^2}{2} \]

Sweat efficiency was calculated by skin wettedness required \( (\omega_{\text{req}}) \) for heat balance with using total evaporation required to maintain heat balance as zero \( (E_{\text{req}}) \) and the rate of maximal evaporation when the skin is completed wet \( (E_{\text{max}}) \). (5) When \( \omega_{\text{req}} > 1 \), a sweat efficiency value of 1 was assumed. (18) Dry heat exchange at the skin surface \( (H_{\text{dry,skin}}) \) is consisted of convection \( (C_{\text{skin}}) \), radiation \( (R_{\text{skin}}) \), and conduction \( (K_{\text{skin}}) \). (5) Respiratory heat loss \( (H_{\text{res}}) \) achieves via convection and evaporation. (5) The vapor pressure at the skin surface when saturated with sweat \( (P_{\text{skin,sat}}) \), the partial pressure of water vapor in ambient air \( (P_a) \), the evaporative resistance of clothing \( (R_{\text{e,cl}}) \), the evaporative heat transfer coefficient \( (h_e) \), and the clothing area factor \( (f_{\text{cl}}) \) involve in \( E_{\text{max}} \). (5) Additionally, running economy \( (\text{RE}) \), which referred to the amount of oxygen utilized at the given exercise intensity, was measured by \( \text{VO}_2 \).

\[ \omega_{\text{req}} = \frac{E_{\text{req}}}{E_{\text{max}}} \]

\[ E_{\text{req}} \ (W) = H_{\text{prod}} - H_{\text{dry,skin}} - H_{\text{res}} \]

\[ H_{\text{dry,skin}} = C_{\text{skin}} + R_{\text{skin}} + K_{\text{skin}} \]
\[ E_{\text{max}} = \frac{(P_{\text{skin,sat}} - P_a)}{(R_{e,cl} + \frac{1}{h_{e,F}Cl})} A_D \]

Repeated measures ANOVAs with LSD pairwise comparisons were performed to assess differences between mean metabolic heat production, evaporative heat loss, dry heat loss, total evaporation required for heat balance (E_{req}), the rate of maximal evaporation (E_{max}), and running economy (RE) in test\(^1\), test\(^2\), and test\(^3\). Effect sizes (ES) were calculated using Hedges’ g with the resulting effects identified as either small (0.2-0.49), medium (0.5-0.79), or large (> 0.8) effects. (19) Data are reported as M±SD, mean differences (MD)± standard error (SE), 95% confidence intervals (95%CI) and ES. Stepwise linear regression was used to predict maximum T_{rec} from metabolic heat production, evaporative heat loss, dry heat loss, T_{sk}, sweat rate, and minimum T_{rec}. All statistical analyses were completed using SPSS Statistics for Mac, version 25 (IBM Corp., Armonk N.Y., USA). Significance was set at p ≤ 0.05.

**Results**

Data in metabolic heat production, evaporative heat loss, and dry heat loss are described in table 1. There were no differences in metabolic heat production between test\(^1\), test\(^2\), and test\(^3\) (p=0.866) (Figure 1). However, evaporative heat loss was significantly increased at test\(^3\) compared to test\(^2\) (MD±SE; 84±38 W, p=0.038) and test\(^1\) (MD±SE; 104±45 W, p=0.032) (Figure 2). Additionally, dry heat loss was significantly lower at test\(^2\) (MD±SE; -3.3±1.2 W·m\(^{-2}\), p=0.013) and test\(^3\) (MD±SE; -7.5±1.8 W·m\(^{-2}\), p<0.001) compared to test\(^1\) (Figure 3). Also, dry heat loss at test\(^3\) was lower than test\(^2\) (MD±SE; -4.2±2.0 W·m\(^{-2}\), p=0.049).
Data for running economy, rate of maximal evaporation, and total evaporation required for heat balance are demonstrated in table 2. Running economy and total evaporation required for heat balance ($E_{req}$) were unchanged at test#1, test#2 and test#3 ($E_{req}$, $p=0.921$; running economy, $p=0.441$) (Figure 4). However, the rate of maximal evaporation ($E_{max}$) increased at test#3 (MD±SE; 16.2±5.4 W·m⁻², $p=0.007$) compared to test#2.

Only metabolic heat production predicted maximum $T_{rec}$ ($r^2=0.192$, $p=0.041$) among metabolic heat production, evaporative heat loss, dry heat loss, $T_{sk}$, sweat rate, and minimum $T_{rec}$ at test#1. However, lower $T_{sk}$, minimum $T_{rec}$, and metabolic heat production significantly predicted lower maximum $T_{rec}$ with $r^2=0.503$ ($p<0.001$) from results of test#2 and test#3. Furthermore, decreases in $T_{sk}$ by itself significantly predicted lower maximum $T_{rec}$ ($r^2=0.308$ $p<0.001$). Maximum $T_{rec}$ and $T_{sk}$ were significantly lower at test#3 compared to test#2 and test#1. Sweat rate was significantly higher at test#3 to test#2.

**Discussion**

The purpose of this study was to examine the changes in metabolic heat production, evaporative heat loss, and dry heat loss following HAz and HA. The current study found that there was no change in metabolic heat production following HAz and HA, however, evaporative heat loss increased following HA. Also, dry heat loss was decreased following HA. Additionally, lower $T_{sk}$, minimum $T_{rec}$, and metabolic heat production predicted lower maximum $T_{rec}$ following HAz and HA. These findings add to current literature that helps to understand the principals of adaptations in body heat exchanges following HA.
Metabolic heat production is one of the factors determining internal body temperature during exercise. In the current study, there was no difference in metabolic heat production following HA in trained athletes. This finding conflicted with previous findings, which demonstrated metabolic heat production decreased following HA in untrained athletes. (20) This previous study concluded that the primary factor was lower metabolic heat production to induce lower internal body temperature following HA. (20) However, in this previous study, running economy was improved following HA. (20) Thus, metabolic heat production might be reduced at the given exercise intensity due to an improvement of running economy. However, in the current study, participants were endurance trained athletes and did not show the improvement of running economy following HA. This was the same finding from the previous study showing running economy was not improved in regularly trained runners following HA. (21) It is not clear if the improvement of running economy was induced by training or HA, however, this could be the reason to decrease metabolic heat production in previous study. Therefore, changes in metabolic heat production was not observed and it was not the factor to induce lower $T_{rec}$ in endurance trained athletes following HA.

Evaporative heat loss was increased following HA in the current study, which could be the main factor to achieve lower $T_{rec}$ following HA. A previous study indicated a different finding in untrained participants, which did not show change in evaporative heat loss following HA. (20) However, participants reached to plateau in the internal body temperature during exercise, which indicated the amount of heat dissipation was matched to heat production. Thus, evaporative heat
loss did not increase following HA while internal body temperature was decreased due to lower metabolic heat production associated with improved running economy in the previous study. (20) In the current study, evaporative heat loss was improved accompanied with increase in sweat rate and decrease in $T_{sk}$, which induced lower $T_{rec}$. This result was supported by the previous study indicating increase in evaporative heat loss following HA when metabolic heat production was controlled during exercise (22). Thus, increase evaporative heat loss was the primary factor to induce lower $T_{rec}$ following HA in endurance trained athletes, which is known to decrease fatigue and increase exercise performance in the heat. (15)

Lower $T_{sk}$, minimum $T_{rec}$, and metabolic heat production significantly predicted lower maximum $T_{rec}$ ($r^2=0.503$) from results of test#2 and test#3. Additionally, lower $T_{sk}$ by itself significantly predicted lower maximum $T_{rec}$ ($r^2=0.308$). The evaporation of sweat from the skin surface results in a cooling effect of 2426 J·g$^{-1}$ and leads to lower $T_{sk}$. (23) This subsequently decreases redistribution of blood to the cutaneous circulation, which receives up to 50-70% of cardiac output during heat stress. (23, 24) This helps to deliver oxygen to exercising muscles. (13)

The dry heat loss was decreased following HA in the current study. This could be due to lower $T_{sk}$ induced by greater evaporative heat loss. Lowering $T_{sk}$ decreased a gradient between the skin surface and the ambient air, which led to smaller amount of dry heat loss following HA. (22) However, the rate of decrease in dry heat loss following HA was smaller compared to the rate of increase in evaporative heat loss, thus, the net heat storage and $T_{rec}$ were decreased following HA.
This study was not without limitations. While the indirect measurements of metabolic heat production, evaporative heat loss, and dry heat loss are widely used and well accepted in the previous studies, the most accurate method to determine whole-body evaporative and dry heat exchange was using direct calorimetry. (5, 22, 25) However, this method requires the complete evaporation of all sweat from the skin and is typically performed in a calorimeter with a high and turbulent air flow. (26) Another limitation of this study was evaporative heat loss and dry heat loss can be depending on environmental conditions of testing as well as the method of HA induction. For example, evaporative heat loss is limited when exercise in the high humidity and dry heat loss is primary mechanism to dissipate heat in this case. Additionally, previous study demonstrated that greater adaptation in sweat rate was achieved following HA in dry condition compared to in humid condition. (27) Also, while the findings from the current study are applied to endurance trained athletes, studying in other populations might indicate different results. Furthermore, fluid loss was not replaced during testing and dehydration level at the end of testing was greater following HA due to the higher sweat rate while everyone started testing with euhydrated status. Dehydration can impair sweat rate and if fluid was replaced to the amount of sweat and evaporative heat loss could be even higher following HA. (28)

**Conclusion**

Metabolic heat production was not changed, however, evaporative heat loss was increased following HA. While dry heat loss was decreased due to lower $T_{sk}$ following HA, the rate of change was smaller compared to increase in evaporative heat loss. Thus, the primary factor to
induce lower T_{rec} following HA was adaptations of increasing evaporative heat loss in endurance trained athletes. Thus, it is critical to achieve greater amount of hyperthermia and sweat during HA induction to induce this adaptation. The factors changing adaptations in sweat, such as exercise intensity, duration and environmental conditions, are important when creating optimal HA induction protocol.

References


Figure 1. Changes in metabolic heat production following heat acclimatization and acclimation.

Test\(^1\) indicates baseline-unacclimatized, test\(^2\) indicates post-heat acclimatization, test\(^3\) indicated post heat acclimation (dual heat acc)
Figure 2. Changes in evaporative heat loss following heat acclimatization and acclimation. * indicates statistical significance from following heat acclimation, p≤0.05. Test #1 indicates baseline-unacclimatized, test #2 indicates post-heat acclimatization, test #3 indicated post heat acclimation (dual heat acc)
Figure 3. Changes in dry heat loss following heat acclimatization and acclimation. * indicates statistical significance from following heat acclimation and # indicates statistical significance from following heat acclimatization, p≤0.05. Test#1 indicates baseline-unacclimatized, test#2 indicates post-heat acclimatization, test#3 indicated post heat acclimation (dual heat acc)
Figure 4. Changes in running economy following heat acclimatization and acclimation. Test#1 indicates baseline-unacclimatized, test#2 indicates post-heat acclimatization, test#3 indicated post heat acclimation (dual heat acc)
Table 1. Metabolic heat production, evaporative heat loss, and dry heat loss at baseline/unacclimatized (test #1), post-heat acclimatization (test #2), and post-heat acclimation/dual HA (test #3). Data are presented as mean (M) ± standard deviation (SD), effect size (ES), 95% confidence intervals (95% CI). * indicates statistical significance, p ≤ 0.05.

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Table 2. Running economy, rate of maximal evaporative heat loss, and total evaporation required for heat balance at baseline/un-acclimatized (test #1), post-heat acclimatization (test #2), and post-heat acclimation/dual HA (test #3). Data are presented as mean (M) ± standard deviation (SD), effect size (ES), 95% confidence intervals (95%CI). * indicates statistical significance, p≤0.05.

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Chapter 4. The Effect of Dual Heat Acc and Intermittent Exercise Heat Training on Endurance Performance in the heat in the Trained Individuals

Abstract

Exercise in the heat can cause negative impacts on exercise performance and establishing practical methods to mitigate those negative implications are critical. Thus, the purposes of this study were to investigate 1): the effect of heat acclimation (HA) following heat acclimatization (HAz) (HAz plus HA, “dual heat acc” [DHA]) on time trial performance and 2): the effect of heat training (HT) following DHA on time trial performance in endurance trained athletes.

Twenty-six endurance athletes (mean (M)±SD; age, 35±12 y; body mass, 72.8±8.9 kg; height, 178.7±6.3 cm; VO_{2max}, 57.3±6.7ml·kg^{-1}·min^{-1}) completed five 4km time trials (baseline-unacclimatized, test#1; post-HAz, test#2; post-HA/DHA, test#3; 4 weeks post-DHA, test#4; 8 weeks post-DHA, test#5) in the heat (M±SD; ambient temperature [T_{amb}], 35.5±0.7 °C; relative humidity [%RH], 46.3±2.2%; Wet Bulb Globe Temperature (WBGT), 29.2±0.7 °C). After test#1, participants performed self-directed summer training followed by test#2. Then, they completed a five-days of HA sessions over eight days in the heat (M±SD; T_{amb}, 39.2±0.4 °C; %RH, 51.1±2.6%; WBGT, 33.2±0.7 °C). During the HA sessions, participants exercised to induce hyperthermia for 60 minutes, which is defined as hyperthermic zone HA (HZHA, 38.50 °C and 39.75°C). Participants were then divided into three groups: maximal heat training group (HT_{MAX}), minimum heat training (HT_{MIN}), and the control group (HT_{CON}). HT_{MAX} completed a twice per week of HT and HT_{MIN} completed once a week of HT over the course of eight weeks. The exercise used for the HT matched the HA sessions. Percent 4km time change (TT_p) was calculated. TT_p was significantly faster at test#3 (M±SD; -3.7±8.5% compared to test#1 (p=0.036)
and test#2 (M±SD; -0.9±10.0 %, p=0.046). TT_p was significantly faster in HT_MAX (M±SD; -4.2±5.4 %) compared to HT_MIN (M±SD; 1.9±6.5 %, p=0.044) and HT_CON (M±SD; 10.7±17.0 %, p=0.024) at test#5. There were no differences of TT_p in HT_MIN between test#3, test#4 (M±SD; 0.95±5.55%), and test#5 (M±SD; 1.93±6.45%) (p>0.05). These results indicate that HT conducted twice per week demonstrates improvements after 8 weeks following DHA, while no HT results in a loss of some adaptations in 4 weeks with greater losses after 8 weeks. Additionally, HT once per week may maintain adaptations for 4 weeks and potentially for 8 weeks.

**Introduction**

Sport scientists, coaches, and medical professions are given the task of preparing athletes to compete in a wide range of environmental conditions, including exercise in the heat. Major sport events at both National (i.e. National Collegiate Athletic Association: NCAA) and International levels (i.e., the FIFA World Cup Soccer, the world championship, and the Olympics) are often held in locations where heat comes into play. It is well described exercising in the heat leads to greater physiological strains, including increased heart rate (HR) and internal body temperature. (1)

These physiological stressors can cause performance decrement and increased fatigue. (2, 3) For example, during the cycling world championships, 85% of elite cyclists reached an internal body temperature of at least 39°C and 25% of them exceeded 40°C, which was associated with higher
fatigue. (3, 4) In addition to the effect of heat on performance, excessive heat exposure poses an increased risk for heat illness. (5) In the NCAA, 232 exertional heat illness events were reported during five years. (6) These findings stress the importance for practical and effective heat mitigation strategies to optimize exercise performance and safety in the heat.

Heat acclimation (HA) and heat acclimatization (HAz) are suggested as one of the impactful and practical strategies to induce positive adaptations and ensure the peak physical condition for the athlete exercising in the heat. (7) This processes of systematic and repeated heat exposures elicits key physiological and protective adaptations. HA refers to training in a hot artificial environment, while HAz refers to training in a natural hot environment. HA and HAz require sufficient heat stress to elicit profuse sweating and elevate skin and internal body temperature, which results in positive physiological and performance adaptations. (8)

Adaptations known to improve exercise performance in the heat include decreases in HR, internal body temperature, skin temperature ($T_{sk}$), rating of perceived exertion (RPE), sweat sodium and chloride concentrations, and increases in plasma volume and sweat rate. (9, 10) These adaptations independently and collectively enhance exercise performance in a hot environment by improving the body’s thermoregulatory efficiency while decreasing the overall physiological strain. (11) Lorenzo et al., demonstrated $VO_{2\text{max}}$ and time trial performance were enhanced following 10 days of HA in a cool (13°C) and hot (38°C) environment, while the control group did not. (12)
A recent meta-analysis indicated the magnitude of performance change and factors contributing those changes following HA. (13) The biggest performance enhancement was observed in time to exhaustion followed by time trial, mean power, VO$_{2\text{max}}$, and peak power. The magnitude of performance improvement in time to exhaustion was the largest when a controlled work rate method was utilized and participants had higher fitness levels. The time trial performance was improved the most when low exercise intensity was utilized for HA, which could be associated with lower fatigue level experiencing from HA. Longer HA induction duration (i.e. 10 days) improved mean power more than short HA induction duration (i.e. 5 days). Most of the studies examining exercise performance utilized HA. While the controlled nature of HA may result in greater adaptations, HAz may be more widely accessible and feasible. No study to date has examined the combined impact of HA following a period of HAz (referred to dual heat acc [DHA]) for the purposes of achieving optimal physiological adaptations and enhanced exercise performance.

Further, when an individual discontinues heat exposure, physiological and performance adaptations are typically lost. This process is known as HA decay. While the data are limited, performance enhancements following HA seem to persist for approximately 1-2 weeks without heat exposures. (14) Arguably, decay is one of biggest obstacles when HA is implemented in sport settings. Examining the methods to maintain adaptations following HA is critical to maximize performance for specific competitions without interfering with sport-specific training and imposing stress to the body.
One study has investigated the strategy of maintaining benefits from HA for an extended duration. (15) This strategy involved intermittent exercising-heat exposure, or heat training (HT), every five days for 25 days and demonstrated positive physiological benefits compared to a control group. (15) Even though the intermittent-heat exposure group showed benefits in HR, internal body temperature, and sweat rate compared to the control group, the decay was still observed. Additionally, the effect of HT on exercise performance was not investigated. Thus, the purpose(s) of this study was 1): to investigate the effect of short-term HA following HAz (DHA) on time-trial performance, 2): the effect of HT on time trial performance following DHA, 3) the factors associated with improvement of performance following HAz and HA.

**Materials and Methods**

Twenty-six endurance athletes (mean (M)±SD; age, 35±12y; body mass, 72.8±8.9kg; height, 178.7±6.3 cm; VO$_{2\text{max}}$, 57.3±6.7ml·kg$^{-1}$·min$^{-1}$; % body fat (%BF) 10.8±5.1%) participated in this study. Following an explanation of study procedures, which was approved by the Institutional Review Board at <<removed for review>>, participants provided written and informed consent to participate in this study.

Participants performed a maximal oxygen consumption (VO$_{2\text{max}}$) test with a graded running exercise on a standardized treadmill to measure VO$_{2\text{max}}$ #1 and the velocity of VO$_{2\text{max}}$ (vVO$_{2\text{max}}$) at the beginning of the study (T150; COSMED, Traunstein, Germany). The participant completed a self-selected pace warm-up before the test. During the test, the speed was increased either 0.5 or 1.0 mile·h$^{-1}$ after 2 minutes of each stage. Participants continued exercise until
reaching to their maximal effort. \(\text{VO}_{2\text{max}}\) were also measures at approximately one week before Test\(^2\) (\(\text{VO}_{2\text{max}}\) \(^2\)), Test\(^4\) (\(\text{VO}_{2\text{max}}\) \(^4\)), and Test\(^5\) (\(\text{VO}_{2\text{max}}\) \(^5\)), and one week after Test\(^3\) (\(\text{VO}_{2\text{max}}\) \(^3\)).

At baseline, prior to any heat exposures either in the laboratory or outside environment, the baseline (test\(^1\)) occurred (May and early June). One importance aspect to note is that this research was part of larger study which included 60 minutes of exercise at 59.1±1.8 % \(\text{vVO}_{2\text{max}}\) before 4km time trial on the treadmill in the heat (M±SD; ambient temperature [\(\text{T}_{\text{amb}}\)], 35.5±0.7 °C; relative humidity [%RH], 46.3±2.2%; WBGT, 29.2±0.7 °C; wind speed 4.0±0.1 mile·h\(^{-1}\)). Participants provided urine samples to assess their hydration status before the 60 minutes of exercise to start testing with euhydrated state (M±SD; urine specific gravity, 1.009±0.004; color, 2±1). (16) Following the 60 minutes of exercise, fluid was given to participants to replace fluid losses to start 4km time trial at < 1% body mass loss (M±SD; test\(^1\), 0.61±0.26%; test\(^2\), 0.58±0.33%; test\(^3\), 0.73±0.33%; test\(^4\), 0.78±0.20%; test\(^5\), 0.64±0.34%) from the beginning of 60 minutes exercise during the minimum of 30 min break (M±SD; 33.7±7.2 min). Rectal temperature (\(\text{T}_{\text{rec}}\)) was also lowered during this break (M±SD; test\(^1\), 37.5±0.3°C; test\(^2\), 37.4±0.4°C; test\(^3\), 37.3±0.4°C; test\(^4\), 37.3±0.3°C; test\(^5\), 37.5±0.3°C) before starting 4km time trial. This strategy allowed participants to recover from 60 minutes exercise. (17, 18) During 4km time trial, \(\text{T}_{\text{rec}}\) (MP160; BIOPAC Systems Inc., Goleta, CA, USA) and HR (H10®, Polar Electro™, Kempele, Finland) were collected every 1km. Additionally, RPE, thermal sensation (TS), and fatigue level were measured before and at the end of 4km time trial.
Following test#1, participants were instructed to complete self-directed summer training. Training loads, including total distance covered, training time, and average HR, were monitored (Garmin, [Forerunner® Fenix® Vivoactive® Garmin™ Ltd., Olathe, Kansas, USA]; Polar H10 and Polar Beat application, [H10®, Polar Electro™, Kempele, Finland]; Wahoo ELEMNT Bolt, [ELEMNT Bolt, Wahoo Fitness®, Atlanta, GA, USA], Garmin Edge, [Edge®, Garmin Ltd., Olathe, Kansas, USA], Bryton Rider 15, [Rider 15®, Bryton™ Inc., Taipei City, Taiwan]). (19) Tamb, %RH, heat index (HI), and WGBT were reported for each session. Daytime WBG Ts (7 a.m. - 7 p.m.) were modeled using Heat Stress Advisor software package (version 2005; Zunis Foundation, Tulsa, OK; Coyle 2000)(20, 21).

After summer, participants completed the second identical session of 60 minutes of exercise followed by the 4km time trial (post-HAz: test#2). This occurred in late August and early September. After test#2 participants performed 5 days of HA in the lab. During HA, participants performed exercise in the heat (M±SD; Tamb, 39.2±0.4 °C; %RH, 51.1±2.6%; WBG T, 33.2±0.7 °C) to induce hyperthermia for a minimum of 60 minutes. This method is referred to as hyperthermic zone HA (HZHA), where hyperthermia is defined as the maintenance of internal body temperature between 38.50-39.75°C. After the 5 sessions of HA, again the same testing was performed to investigate adaptations following DHA (post-DHA: test#3). The HA following HAz is defined as “dual heat acc” (DHA).

Then, participants were randomly assigned into three groups, maximal heat training group (HTMAX), minimum heat training group (HTMIN), and the control group (HTCON) and were
matched for VO$_{2max}$, body mass, and age; (M±SD; VO$_{2max}$, HT$_{CON}$ 58.6±4.7 ml·kg$^{-1}$·min$^{-1}$; HT$_{MIN}$ 58.1±9.7 ml·kg$^{-1}$·min$^{-1}$; HT$_{MAX}$ 56.5±5.6 ml·kg$^{-1}$·min$^{-1}$; p=0.800; age, HT$_{CON}$ 33±8 yrs; HT$_{MIN}$ 34±13 yrs; HT$_{MAX}$ 37±14 yrs; p=0.706; body mass, M±SD HT$_{CON}$ 72.0±9.8 kg; HT$_{MIN}$ 72.4±7.2 kg; HT$_{MAX}$ 73.2±10.1 kg; p=0.961). HT$_{MAX}$ completed a total of sixteen visits, (approximately twice per week of HT) and HT$_{MIN}$ completed a total of eight visits over the course of eight weeks, (approximately once per week of HT). HT$_{CON}$ did not perform any HT. The days between HT sessions for HT$_{MAX}$ was 3.5±1.5 days and HT$_{MIN}$ was 7.0±2.2 days. The exercise used for the HT matched the HA sessions. Additionally, participants performed a 4km time trial on the treadmill 4 weeks (post-4 weeks of DHA: test$^#4$) and 8 weeks (post-8 weeks of DHA: test$^#5$).

Repeated measures ANOVAs with independent and dependent t-tests were performed to assess differences of 4km time trial performance, HR, T$_{rec}$, RPE, TS, and fatigue level in test$^#1$, test$^#2$, test$^#3$, test$^#4$, and test$^#5$. Effect sizes (ES) were calculated using Cohen’s d or Hedges' g with the resulting effects identified as either small (0.2-0.49), medium (0.5-0.79), or large (> 0.8) effects (22). Data are reported as M±SD, mean differences (MD)±standard error (SE), 95% confidence intervals (CI), and ES. Stepwise linear regression was used to predict 4km performance improvement, which was defined as the differences of 4km time between pre- and post- tests. VO$_{2max}$, weekly distance (km), sum of weekly distance (km), weekly training time (min), average HR (bpm), WGBT, T$_{amb}$, %RH, and HI during the summer training were used to predict performance improvement at test$^#2$. Areal under the curve of T$_{rec}$ (AUC) and area under the curve of T$_{rec}$ above 38.5 °C (AUC$^{38.5}$) were calculated by the integral of T$_{rec}$ during HA sessions. AUC,
AUC^{38.5}, average HR, the amount of sweat during HA induction, and VO_{2\text{max}}, \%BF, age, body mass, and 4km time at test^{#2} were utilized to predict performance improvement at test^{#3}. Independent t-tests were performed to examine the differences between the variables that improved 4km time trial (Improved) and those that did not (Not-improved). Furthermore, individual z-score was calculated to account individual training differences, and a repeated measures ANOVA was performed to investigate the changes in training (inclusive of both inside and outside of the lab) for each group. All statistical analyses were completed using SPSS Statistics for Mac, version 25 (IBM Corp., Armonk N.Y., USA). Significance was set at p ≤ 0.05.

Results

There were no differences in VO_{2\text{max}} throughout this study (M±SD; VO_{2\text{max}}^{#1}, 57.5±7.0 ml·kg^{-1}·min^{-1}; VO_{2\text{max}}^{#2}, 59.7±7.92 ml·kg^{-1}·min^{-1}; VO_{2\text{max}}^{#3}, 59.0±7.9 ml·kg^{-1}·min^{-1}; VO_{2\text{max}}^{#4}, 60.0±7.9 ml·kg^{-1}·min^{-1}; VO_{2\text{max}}^{#5}, 59.2±8.8 ml·kg^{-1}·min^{-1}, p>0.05).

Heat acclimatization did not, but subsequent 5-day heat acclimation and dual heat acc did improve 4km performance among endurance trained athletes

Assessing performance by administering a 4km time trial revealed that there were differences in 4 km time (TT) and percent change in 4km time (TT_{p}) following different intervention phases in this study (Table 1). TT_{p} was significantly faster at test^{#3} (M±SD; -3.7±8.5 \%) compared to both test^{#1} (p=0.038) and test^{#2} (M±SD; -0.9±10.0 \%, p=0.046) (Figure 1). TT at test^{#3} (M±SD;
18.0±2.2 min) was significantly faster than test\textsuperscript{#1} (M±SD; 18.8±3.3 min, p=0.028) and approached to be significantly faster than test\textsuperscript{#2} (M±SD; 18.5±3.1 min, p=0.060).

*Not only did heat acclimation improved 4-km time trial performance but also improved the athletes’ subjective feeling during the test (lower RPE, reduced thermal sensation, reduced fatigue)*

There were no differences in HR (p=0.146) and \(T_{\text{rec}}\) (p=0.061) at the end of 4km between test\textsuperscript{#1} (M±SD; HR, 180.7±12.6 bpm; \(T_{\text{rec}}\), 38.8±0.5 °C), test\textsuperscript{#2} (M±SD; HR, 176.9±15.8 bpm; \(T_{\text{rec}}\), 38.8±0.5 °C), and test\textsuperscript{#3} (M±SD; HR, 178.2±12.2 bpm; \(T_{\text{rec}}\), 38.6±0.5 °C). RPE was significantly lower at the end of 4km at test\textsuperscript{#3} (M±SD; 16±3) compared to test\textsuperscript{#1} (M±SD; 18±3, p=0.018), while RPE at test\textsuperscript{#3} approached to significantly lower compared to test\textsuperscript{#2} (M±SD; 17±3, p=0.082). Additionally, TS and fatigue level were significantly lower at test\textsuperscript{#3} (M±SD; TS, 6.1±0.8; Fatigue, 5±2), compared to test\textsuperscript{#1} (M±SD; TS, 6.9±0.6, p<0.001; Fatigue, 7±2, p<0.001) and test\textsuperscript{#2} (M±SD; TS, 6.6±0.7, p<0.001; Fatigue, 7±1.6, p<0.001).

*Twice a week of heat training induced better 4km time trial performance than once a week of heat training and no heat training in 8 weeks.*

Table 2 depicts differences in TT and \(TT_p\) between HT\textsubscript{MAX}, HT\textsubscript{MIN}, and HT\textsubscript{CON} at test\textsuperscript{#3}, test\textsuperscript{#4}, and test\textsuperscript{#5}. \(TT_p\) was significantly faster in HT\textsubscript{MAX} (M±SD; -4.2±5.4 %) compared to HT\textsubscript{MIN} (M±SD; 1.9±6.5 %, p=0.044) and HT\textsubscript{CON} (M±SD; 10.7±17.0 %, p=0.024) with large effects at
TT_p approached statistical significance for HT_MAX (M±SD; 1.9±6.5 %) being faster than HT_CON and with a large effect (M±SD; 3.4±7.1 %, p=0.059) at test#4. There were no differences between HT_MAX, HT_MIN, and HT_CON on at the end of 4km HR (p=0.857), T_rec (p=0.168), RPE (p=0.966), TS (p=0.287), and fatigue (p=0.166).

Twice a week of heat training improved and once a week of heat training maintained 4km time trial performance while no heat training resulted in decrease in 4km time trial performance after 4-8 weeks despite continued their normal training.

Table 3 described differences of TT and TT_p between test#3, test#4, and test#5 within HT_MAX, HR_MIN, and HT_CON. TT_p in HT_MAX at test#5 was significantly faster than test#3 with large effect (p=0.046). There were no differences of TT_p in HT_MIN between test#3, test#4 (M±SD; 0.95±5.55%), and test#5 (M±SD; 1.93±6.45%). While there was no statistical difference, TT_p in HT_CON at test#3 was slower than test#4 and test#5 and demonstrated a moderate and large effect, respectively.

Total training volume did not change throughout the study and WBGT was lower during heat training.

There were no differences training time (z-scores), including both inside and outside of the lab between HT_MAX, HT_MIN, and HT_CON (p=0.115) (Figure 3). WGBT throughout the study was described in figure 4. WGBT in weeks 1-4, 5-8, 9-12, and 13-16 during self-directed summer training were M±SD, 19.5±2.8°C, 24.2±2.6°C, 24.4±2.6°C, and 21.0±2.5°C, respectively.
WBGT was lower during HT period compared to self-directed summer training (M±SD; HT week 1-4, 16.0±0.8°C; HT week 5-8, 8.7±10.0°C).

Factors impact on an adaptation in 4km time trial performance resulted from heat acclimatization

Performing summer training in higher %RH condition significantly predicted the larger improvement of TT at test#2 ($r^2=0.249$, $p=0.013$). Additionally, VO$_{2\text{max}}$ (M±SD; Improved, 52.9±5.6; Not-improved, 60.7±6.1, ES=1.33, $p=0.004$), $T_{\text{amb}}$ (M±SD; Improved, 22.2±1.7; Not-improved, 23.7±1.6, ES=0.91, $p=0.035$), WBGT (M±SD; Improved, 22.1±1.4; Not-improved, 23.2±1.1, ES=0.93, $p=0.033$) were significantly lower and %RH (M±SD; Improved, 68.5±8.1; Not-improved, 61.6±5.5, ES=1.02, $p=0.021$) was higher for participants who improved TT at test#2. There were no differences in weekly average distance (M±SD; Improved, 40.3±24.0; Not-improved, 42.6±33.6 km, ES=0.08, $p=0.849$), sum of weekly distance (M±SD; Improved, 341.7±167.8 km; Not-improved, 399.1±142.1 km, ES=0.37, $p=0.374$), average training time (M±SD; Improved, 67.5±25.1 min; Not-improved, 63.8±22.0 min, ES=0.16, $p=0.699$), average HR (M±SD; Improved, 134.6±12.0 bpm; Not-improved, 135.4±10.4 bpm, ES=0.08 $p=0.854$), and HI (M±SD; Improved, 29.9±1.1; Not-improved, 30.0±0.8, ES=0.17 $p=0.672$).

Factors impact on the adaptation in 4km time trial performance resulted from heat acclimation

Slower TT at test#2 significantly predicted larger TT improvement at test#3 ($r^2=0.339$, $p=0.002$). Despite statistical significance, participants who improved at test#3 demonstrated larger AUC$^{38.5}$
compared to who did not and a large effect was observed (M±SD; Improved, 222.1±33.0 °C·min; Not-improved, 192.0±44.2 °C·min, ES=0.83, p=0.072). However, there were no differences in AUC (M±SD; Improved, 15462.9±928.9 °C·min ; Not improved, 15959.3±716.9 °C·min, ES=0.56, p=0.2145), average HR (M±SD; Improved, 131.2±11.1 bpm; Not-improved, 136.2±12.8 bpm, ES=0.43, p=0.338), the amount of sweat (M±SD; Improved, 2.6±0.5 L; Not-improved, 2.8±0.42 L,ES=0.33, p=0.453), VO\textsubscript{2\text{max}} (M±SD; Improved, 59.0±9.1 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}; Not-improved, 59.3±7.6 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}, ES=0.04, p=0.932), %BF (M±SD; Improved, 10.8±4.9%; Not-improved, 11.1±6.1 %, ES=0.06, p=0.900), age (M±SD; Improved, 34±12yrs; Not-improved, 38±11 yrs, ES=0.32, p=0.481), and body mass (M±SD; Improved, 73.3±8.9 kg; Not-improved, 71.7±9.3 kg, ES=0.18, p=0.691).

**Discussion**

The purpose(s) of this study were to investigate 1) the effect of a short-term HA following HAz (DHA) on 4km time trial performance, 2) the effect of HT on 4km time trial performance following DHA, and 3) the factors associated with improvement of performance following HAz and HA in endurance trained athletes. TT\textsubscript{p} following DHA was significantly faster than both baseline and following HAz, while there was no difference between baseline and following HAz. Furthermore, TT\textsubscript{p} in when HT was performed twice per week was significantly faster than once per week and no HT after 8 weeks. TT\textsubscript{p} with HT twice per week approached statistically significant faster times with large effects compared to no HT after 4 weeks. This study provided
information to improve endurance performance resulted in a short-term HA and HT with a time-efficient and practical way.

TT_p was improved at test#3 compared to test#1 and test#2 while there was no difference between test#1 and test#2. This indicated HAz did not improve 4km time trial performance in this study, however, a short-term HA following HAz (DHA) induced improvement in 4km time trial. Additionally, a short-term HA independently improved 4km time trial performance. A meta-analysis examining the magnitude of time trial performance following HA reported that HA induced the improvement with average 0.485 of ES. (13) Also seven out of ten cases demonstrated improvement of time trial performance. The current study improved TT_p with an ES of 0.39 from HA following HAz and 0.61 with DHA. HAz is less controlled compared to HA, and the level of adaptations are different between cases. (23, 24) In the current study, HAz independently did not improve 4km time trial performance. Even though higher %RH during summer training predicted the performance improvement, the environmental conditions participants experienced during training might not be enough of a stress to induce adaptations (Figure 4). Thus, only HA and DHA induced improvement in 4km time trial performance in endurance trained athletes.

4km time at following DHA was 51.6 seconds faster than when in an unacclimatized state and 34.2 seconds faster than following HA in endurance trained individuals. These improvement levels are larger than previous study, indicating a short-term HA improved 4 seconds in 2km time trial in trained individuals. (25) This previous study used the isothermal method (38.5°C) to
induce HA. (25) One of the potential explanation for this difference in performance adaptation was the level thermal load of the heat exposures as explained by the AUC$^{38.5}$. The current study utilized the HZHA method to induce HA which resulted in a greater level of hyperthermia than previous studies. (25) Additionally, while not supported statistically, participants who improved 4km time trial performance reported a larger AUC$^{38.5}$ with a large effect compared to those who demonstrated no improvement. (25). Thus, greater hyperthermia might be necessary to induce adaptations in performance. (8)

$TT_p$ with HT twice per week was significantly faster than $HA_{CON}$ at test#5 with large effect. Also, $HA_{MAX}$ at test#5 was significantly faster than test#3. Furthermore, $HA_{MAX}$ at test#4 approached statistically significant faster compared to $HA_{CON}$ with large effect. Even though there was not statistically difference, $HA_{CON}$ at test#5 was slower than test#3 with large effect. Additionally, there were no differences in $TT_p$ between $HT_{MIN}$ test#3, test#4, and test#5, and TT at test#3 was 10 seconds faster than test#5 and 5 seconds faster than test#4. However, $HT_{MAX}$ in $TT_p$ was significantly faster than $HT_{MIN}$ at test#5. These results indicate that HT twice per week demonstrate improvements in 4km time trial after 8 weeks following DHA, while $HA_{CON}$ may lose adaptations in 4km time trial in 4 weeks and even greater losses after 8 weeks. Additionally, $HT_{MIN}$ may hold adaptations for 4 weeks and potentially for 8 weeks.

While there were limited studies related to decay in exercise performance, one study indicated time to exhaustion was shorter one week (13.7 min) and two weeks (12.7 min) following HA compared to right after HA (14.2 min). (26) Even though there is no previous study
demonstrated decay in time trial performance, limited data showed improvements in performance persists for 1-2 weeks without heat exposures. (14) A previous study indicates that heat exposure once every five days for 25 days leads to 0.47°C lower $T_{rec}$ and 28 bpm lower HR compared to the control group. (15) Additionally, the data reported from the same study indicated the benefits of HT of $H_{A{MAX}}$ and $H_{T{MIN}}$ during 60 min of steady exercise in the heat. The benefits from HT twice and once per week did not result in significant loss of the positive physiological adaptations for average HR, highest HR, average $T_{rec}$, ending $T_{rec}$ and $T_{sk}$ after 8 weeks once DHA was completed. These physiological adaptations might contribute to improvement in HT twice per week for 8 weeks and may support that HT once per week maintains the adaptations for 4 weeks and potentially for 8 weeks.

Training time in z-score was not different between $H_{T{MAX}}$, $H_{T{MIN}}$, and $H_{T{CON}}$ and training volume was not changed throughout this study. Training time included both in the lab and outside of the lab. Z-score was utilized to examine the changes in training time within individuals. Additionally, $V_{O2{max}}$ were not changed throughout the study. Thus, these results were not due to training volume. A previous study indicated that exercise duration and HR during training outside of the lab are not associated with $T_{rec}$ and HR following heat exposures once every 5 days following HA. (15)

One limitation of our study is the other factors than HT could change 4km performance. For example, sleep and nutrition have been shown to influence exercise performance. (27) However, to minimize the effect of other factors, participants were instructed to avoid strenuous exercise
the day before testing and eat similar foods from three days before testing to control nutrition. Even though there were no differences in training time throughout the study, including HT, training outside of HT was not controlled. Future studies should attempt to control the training more. Additionally, further studies are needed to determine the factors impacting endurance performance improvement following HAz and HA. Lastly, HT was performed for 8 weeks, and the effects of twice and once per week of HT on 4km time trial performance after 8 weeks is still unknow.

Conclusion

TT_p following HA and DHA was significantly faster than when participants completed HAz alone and were unacclimatized. Thus, HA and DHA improved 4km time trial performance. Additionally, TT_p with HT twice per week was significantly faster than both HT once per week and no HT 8 weeks following DHA. TT_p with HT twice per week approached statistically significant faster times and demonstrated a large effect compared to no HT after 4 weeks following DHA. There were no differences in HT once per week following DHA at 4 weeks or 8 weeks. These results indicate HT twice per week still showed improvement in 4km time trial after 8 weeks following DHA, while no HT results in a loss of adaptations in 4km time trial after 4 weeks and greater losses after 8 weeks. Additionally, HT_MIN may hold adaptations for 4 weeks and potentially for 8 weeks. Sport scientist, coaches, and medical professions can use these results to optimize athlete performance and safety with time-efficient and practical ways.

References


Figure 1. Percent 4km time change in test\textsuperscript{#1} (baseline-unacclimatized), test\textsuperscript{#2} (post-heat acclimatization), and test\textsuperscript{#3} (post-heat acclimation). * indicates statistical significance from following heat acclimation, p<0.05.
Figure 2. Percent 4km time change in test#4 (week 4 of heat training) and test#5 (week 8 of heat training). (HTMAN, twice per week of heat training group; HTMIN, once per week of heat training group; HTCON, the control group). * indicates statistical significance between control and maximal heat training. *' indicates approaching to be significant between control and maximal heat training. = indicates statistical significance between minimum and maximum heat training. # indicates statistical significance between test#3 and test#5 in maximum heat training. Significance was set at p ≤ 0.05
Figure 3. Training time z score throughout the study (HAz, heat acclimatization; HT1, heat training week 1-4; HT2, heat training week 5-8, HT\textsubscript{CON}, heat training control; HT\textsubscript{MIN}, heat training minimum; HR\textsubscript{MAX}, heat training maximum).
Figure 4. WGBT throughout the study. (HAz, heat acclimatization; HT1, heat training week 1-4; HT2, heat training week 5-8).
Table 1. 4km time, %4km time change, end of 4km heart rate, internal body temperature, skin temperature, RPE, thermal sensation, and fatigue in un-acclimatized (test#1), following heat acclimatization (test#2), and acclimation (test#3). * indicates statistical significance, p<0.05.

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<tr>
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<th>ES</th>
<th>95% CI</th>
<th>p-value</th>
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<tr>
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Table 2. Differences in 4km time and % 4km time change between maximal heat training group (HT\text{MAX}), minimum heat training (HT\text{MIN}), and the control group (HT\text{CON})* indicates statistical significance, p<0.05.

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<td>vs <strong>HT\text{MIN}</strong></td>
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Table 3. Differences in 4km time and % 4km time change between test\textsuperscript{#3} (post-heat acclimation), test\textsuperscript{#4} (4 weeks of post-heat acclimation), and test\textsuperscript{#5} (8 weeks of post-heat acclimation) in maximal heat training group (HT\textsubscript{MAX}), minimum heat training (HT\textsubscript{MIN}), and the control group (HT\textsubscript{CON}). * indicates statistical significance, p<0.05.

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Chapter 5. A Practical Method to Examine Adaptations Following Heat Acclimatization, Heat Acclimation, and Dual Heat Acc

Abstract
Heat acclimation (HA) and heat acclimatization (HAz) are the impactful strategies to mitigate negative implications and outcomes resulted from exercising in the heat. There is a need to create a practical and noninvasive tool to monitor the adaptations from HA and HAz. Thus, the purpose of this study was to investigate the relationships between heart rate (HR), sweat rate (SR), thermal sensation (TS), and rectal temperature (T\textsubscript{rec}) following HAz, HA, and dual heat acc (DHA) independent of the induction methods. DHA describes the combination of HAz and HA.

Twenty-five male endurance athletes (mean[M]±standard deviation [SD]; age, 36±12 y; height, 178.81±6.39 cm; body mass, 73.03±8.97 kg; VO\textsubscript{2max} 57.48±7.03 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}) completed three tests (baseline-unacclimatized, test\textsuperscript{#1}; post-HAz, test\textsuperscript{#2}; post-HA, test\textsuperscript{#3}), which consisted of 60 min running at 59.31±1.73% vVO\textsubscript{2max} in a hot environment (M±SD; ambient temperature [T\textsubscript{amb}], 35.11±0.62°C; relative humidity [%RH], 47.61±0.38%; Wet Bulb Globe Temperature [WBGT], 29.53±0.63°C). During the test, max HR, ending T\textsubscript{rec}, max TS, and SR were recorded. Following test\textsuperscript{#1}, participant performed self-directed summer training (HAz) followed by test\textsuperscript{#2}. Then, participants completed the five-day HA protocol over eight days in the heat (M±SD; T\textsubscript{amb}, 38.67±1.03°C; %RH, 51.34±2.42%; WBGT, 33.82±1.20 °C). During the HA sessions, participants exercised to induce hyperthermia for 60 minutes, which is defined as hyperthermic zone HA (HZHA, 38.50°C and 39.75°C). To examine the adaptations for HR, SR, T\textsubscript{rec}, and TS, the differences between test\textsuperscript{#1} and test\textsuperscript{#2}, test\textsuperscript{#2} and test\textsuperscript{#3}, test\textsuperscript{#1} and test\textsuperscript{#3} were calculated. Then, data from different timepoints were combined for analysis for each variable. A Decision tree,
which is the predictive modeling technique to classify outcomes by subdividing the set of observations, indicated cut-points of HR (<-13bpm), SR (0.3 L·h⁻¹), and TS (<-0.5) being associated with improved $T_{rec}$. When two or three variables met the cut-points, the probability of accuracy to show improvement of $T_{rec}$ was 95.24%, while one (59.52%) or zero (41.67%) variables indicated lower probabilities of accuracy. The differences of $T_{rec}$ between pre and post-test indicated significantly greater improvement when two or three variables met the cut-points (M±SD; -0.68±0.50) compared to when one (M±SD; -0.15±0.41, p<0.001) or zero variable (M±SD; 0.03±0.39, p<0.001) met the cut-point. Furthermore, sensitivity was 0.900 when two or three variables met cut-points while sensitivity was 0.400 when one variable met cut-points and 0.00 when zero variables met cut-points. A Venn Diagram consisted of HR, SR, and TS was a useful, practical tool to assess the adaptations in $T_{rec}$.

**Introduction**

Sport events at both national and international levels are often hosted in locations with extreme heat. Training and competing in the heat have negative performance and health outcomes, including a higher internal body temperature, heart rate (HR), rating perceived exertion (RPE), and thermal sensation (TS). (1–3) These negative outcomes represent physiological strains, which can lead to greater fatigue, poor exercise performance and safety. (4, 5) Heat acclimation (HA) and heat acclimatization (HAz) are examples of impactful strategies utilized to mitigate these negative health and performance implications and outcomes. (6)
HA refers to training in a hot artificial environment (i.e., laboratory) and HAz involves training in a naturally hot environment. During HA and HAz induction, sufficient heat stress to elicit profuse sweat and elevated skin and internal body temperature is critical to induce positive physiological and performance adaptations. (7) The most rapid positive adaptations observed following HA and HAz are increased plasma volume and decreased HR, which can directly help an individual mitigate negative impact of exercise in the heat (7, 8) PRE and TS also improve rapidly. (8–10) Additionally, one of the most important adaptation to HA and HAz is a decrease in internal body temperature. Lower internal body temperature during both resting and exercising allows for lower effort and fatigue at the given exercise intensity that can lead to more effective training or enhanced performance. (4) Furthermore, sweat rate increases at the later phase of HA and HAz. The majority, or 75%–80%, of adaptations resulted from HA occur within 4-7 days, however, these adaptations are dependent on the level of hyperthermia induced by heat exposures. (10–12) Adaptations induced by HA and HAz independently and collectively enhance exercise performance and safety in a hot environment by improving the body’s thermoregulatory efficiency and decreasing the overall physiological strain. (13) HAz and HA are methodologically different, however, the adaptatations observed following HAz and HA are typically similar.

Monitoring adaptations resulted from HA and HAz can be challenging and often require expensive and/or technically advanced methods. For example, adaptations in each variable (e.g., HR, sweat rate, perceptual measurements [RPE and TS], and internal body temperature) are often assessed following HA and HAz. (9) HR, sweat rate, and perceptual measurements are
relatively easier measures to collect compared to internal body temperature, which requires either rectal probes, esophageal probes, and ingestible pills. Esophageal temperature is invasive method and not practical to use during exercise. (14) Even though rectal temperature (T_{rec}) is widely used in laboratory settings, this method might not be practical or externally valid to use for continuous monitoring during exercise in field settings. (14) These measurements require connections between thermistor and connecting devices, which would be a problem for continuous monitoring. (14) Ingestible pills are relatively easy to use in the field settings, however, these pills may be cost-prohibitive. Thus, there are some limitations to monitor internal body temperature continuously in field settings. While there is an association between skin temperature and the internal body temperature, skin temperature is affected by the surrounding environment and not appropriate to use as “internal body temperature”. Assessing an adaptation of internal body temperature is critical following HAz and HA since it is associated with athlete performance and safety, but more feasible and valid methods need to be identified. (4, 5)

Considering the importance of adaptations resulting from HA and HAz, sport scientists, coaches, and medical professionals need a method to monitor adaptations, especially in field settings, without using internal body temperature measurements. Thus, the purpose of this study was to investigate the relationships between HR, sweat rate, TS, and T_{rec} adaptations to predict adaptations in T_{rec} independent of the induction methods.

**Materials and Method**
Endurance trained athletes were recruited from the local community through study flyers. A total of 57 people were screened for inclusion using the following criteria: 1) a VO2max >45 ml·kg\(^{-1}\)·min\(^{-1}\), 2) 18-55 years old, 3) no history of heat illness, and 4) no current injury limiting physical activity participation. 35 participants were enrolled in the study with twenty-five male endurance athletes (mean[M]±standard deviation [SD]; age, 36±12 yrs; height, 178.81±6.39cm; body mass, 73.03±8.97kg; VO2max 57.48±7.03 ml·kg\(^{-1}\)·min\(^{-1}\); % body fat 10.73±5.14%) completing the study. Following an explanation of study procedures, which were approved by the Institutional Review Board at <<removed for review>>, participants provided informed written consent to participate in this study.

Study timeline was described in figure 1. Participants performed 60 minutes of steady state exercise testing (59.31±1.73% vVO2max) on a standard treadmill (T150; COSMED, Traunstein, Germany) in an artificial environmental laboratory (M±SD; ambient temperature [T\(_{\text{amb}}\)], 35.11±0.62°C; relative humidity [%RH], 47.61±0.38%; Wet Bulb Globe Temperature [WBGT], 29.53±0.63°C; wind speed, 4.02±0.12 mph) at baseline (Test\(^{#1}\)), post-HAz (Test\(^{#2}\)), and post-HA/dual heat acc (test\(^{#3}\)). The HA following HAz is defined as “dual heat acc” (DHA).

Test\(^{#1}\) was performed when participants were un-acclimatized. Participants provided urine samples to measure their hydration status before the 60 minutes exercise testing to confirm euhydration (M±SD; urine specific gravity, 1.010±0.008; urine color, 2±0). (15) No fluid was provided throughout the 60 minutes. During testing, HR (H10®, Polar Electro™, Kempele,
Finland), $T_{\text{rec}}$ (MP160; BIOPAC Systems Inc., Goleta, CA, USA), TS were recorded every five minutes. Thermal sensation scale utilized in this study was demonstrated in figure 2. (16) Nude body mass were collected prior to and after exercise to calculate sweat rate (Pre body mass – post body mass = sweat rate). In the current, maximum HR and TS for 60 minutes exercise, $T_{\text{rec}}$ at the end of 60 minutes exercise, and sweat rate from the entire 60 minutes exercise were utilized.

Following test #1, participants performed self-directed summer training (HAz). After self-directed summer training, test #2 was performed to examine adaptations following HAz. Then, participants completed a HA protocol, which consisted of five-days of HA sessions over eight days in the heat (M±SD; $T_{\text{amb}}$, 38.67±1.03°C; %RH, 51.34±2.42%; WBGT, 33.82±1.20°C). During the HA sessions, participants exercised to induce hyperthermia for 60 minutes, which is defined as hyperthermic zone HA (HZHA). Hyperthermia was defined as temperatures between 38.50°C and 39.75°C. Then, test #3 was performed to examine the adaptations following HA.

To examine the adaptations for HR, sweat rate, TS, and $T_{\text{rec}}$, following HAz, HA, and DHA, the differences between test #1 and test #2 (Adaptations from HAz), test #2 and test #3 (Adaptations from HA), test #1 and test #3 (Adaptations from HAz plus HA, “dual heat acc” [DHA]) were calculated. There were methodological differences between HAz, HA, and DHA to induce adaptatations. However, methods to induce adaptatations should not matter when examining relationships between the adaptations in $T_{\text{rec}}$ and HR, sweat rate, and TS. Thus, the data of adaptations resulting from HAz, HA, and DHA were combined and analyzed together. Minus values for HR,
TS, and $T_{\text{rec}}$, and positive values for sweat rate indicated improvements. Furthermore, $T_{\text{rec}}$ for each participant and testing was categorized into either improved or not.

Then, a predictive modeling decision tree was used to determine the cut-points of HR, sweat rate, and TS to indicate if $T_{\text{rec}}$ was improved or not. The decision tree is a technique to classify outcomes by subdividing the set of observations into different subsets. (17) This process provides the most uniform subsets of observations possible. (17) The steps of the decision tree analysis included: 1) set the data to establish the relationships between values of each variable (HR, sweat rate, and TS) and if $T_{\text{rec}}$ was improved or not, 2) split values to minimize entropy with the variable. (17) After one split, the model provided the probability of improvement in $T_{\text{rec}}$ when values for each variable were higher or lower than the splitting values. This process was repeated and determined the best splitting values to use based on the number of probability and the cases of observations for $T_{\text{rec}}$ improvement. For example, when the splitting value was 5 bpm (e.g., HR at post-test was lower than 5 bpm at pre-test), the probability of $T_{\text{rec}}$ improvements was 79% with 41 cases of observations. However, when splitting value was 13 bpm, the probability of $T_{\text{rec}}$ was 82% with 22 cases. The cut-point for each variable was determined based on the balance between probability and the number of observations to avoid overfitting of the model and to achieve the best overall probability when three variables were used together, which is explained below.

After the cut-points were determined, binary logistic regressions were used to predict changes in $T_{\text{rec}}$ from one variable. Then, the number of variables among HR, sweat rate, and TS to meet the
cut-points were counted. Independent t-tests were performed to examine the difference of $T_{rec}$ between the number of variables meeting cut-points. Additionally, likelihood ratios were calculated, and ROC analysis was performed to determine sensitivity for each number of variables met cut-points. Data are reported as M±SD, mean differences (MD)± standard error (SE), 95% confidence intervals (CI) and effect size (ES). ES were calculated using Hedges’ g with the resulting effects identified as either small (0.2-0.49), medium (0.5-0.79), or large (> 0.8) effects. (18) Statistical analyses were completed using SPSS Statistics, version 25 (IBM Corp., Armonk N.Y., USA) and JMP, version 15 (SAS Institute Inc., Caryn N.C., USA) (p ≤ 0.05).

**Results**

The cut-point of HR was determined as when HR in post test was 13bpm lower that HR in pre test (HR<-13bpm). This cut-point indicated the probability of 81.82% accuracy when indicating $T_{rec}$ was improved. Logistic regression demonstrated HR using this cut-point by itself was not a significant predictor of $T_{rec}$ improvements (p=0.064). The cut-point of sweat rate was determined to be a sweat rate greater than 0.3 L·h⁻¹ (sweat rate>0.3L·h⁻¹) at post-test compared to pre-test. This cut-point showed the probability of 88.24% accuracy. Logistic regression indicated this cut-point significantly predicted $T_{rec}$ improvements ($r^2=0.07$, p=0.033). The cut-point of TS was determined when TS was 0.5 lower (TS≤-0.5) at post test compared to pre test. This cut-point indicated the probability of 72.34% accuracy, however, TS by itself did not significantly predict $T_{rec}$ improvement (p=0.116).
When two or three of the HR, sweat rate, and TS variables met the identified cut-points, $T_{rec}$ was improved for 20 cases out of 21 cases, which coincided with a probability of 95.24% accuracy. When one variable met the cut-point, $T_{rec}$ was improved 25 cases out of 42 cases, which probability of accuracy was 59.52%. When no variable met the cut-point, $T_{rec}$ was improved 5 cases out of 12 cases, which probability of accuracy was 41.67%.

The differences of $T_{rec}$ between pre and post-test when two or three variables met the cut-points (M±SD; -0.68±0.50) indicated significantly greater improvement compared to when one (M±SD; -0.15±0.41, p<0.001) or no variables (M±SD; 0.03±0.39, p<0.001) meeting the cut-point with large effect (Figure 3). The differences of $T_{rec}$ between pre and post test when one variable and zero variables met the cut-points were not different (p=0.211) (Table 1).

Likelihood ratios indicated that when two or three variables met the cut-points, the chances to show improvement in $T_{rec}$ was 10.00 times greater compared to when one or zero variables met the cut-points. However, the chances were lower when one variable met cut-points (0.74) and when zero variables met cut-points (0.36). Additionally, sensitivity was 0.900 when two or three variables met cut-points while sensitivity was 0.400 when one variable met cut-points and 0.00 when zero variables met cut-points.

**Discussion**
The purpose of this study was to identify if evaluating changes in practical, inexpensive variables, such as HR, sweat rate, and TS, could predict changes in internal body temperature to monitor adaptations from HAz, HA, and DHA. When two or three variables met the cut-points (HR, <13 bpm; sweat rate, >0.3 L·h⁻¹; TS, ≤0.5), Tₑربط was improved 95% of the time with sensitivity of 0.900. Also, the level of adaptations in Tₑربط was significantly greater when two or three variables met the cut-points compared to one or zero variable with large effect. These results provide sport scientists, coaches, and medical professionals a practical method to monitor adaptations following HAz, HA, and DHA, especially in the field settings.

HR, sweat rate, and TS are easy metrics to measure during exercise even in field settings. HR requires only HR straps, sweat rate uses body mass to calculate, and TS needs only TS scale to collect data. However, monitoring internal body temperature has some restrictions to use, especially in the field settings. For example, while Tₑربط is widely used in the lab settings, it might not practical to utilize for continuous monitoring during exercise in the field settings. (14) However, monitoring adaptations of internal body temperature is critical to ensure improvement in athlete safety and exercise performance. Monitoring only one variable of HR, sweat rate, or TS does not provide greater than 90% of accuracy to indicate if Tₑربط was improved. However, measuring three variables together achieved 95% of accuracy with 0.900 of sensitivity when Tₑربط was improved. A Venn diagram consisted of HR, sweat rate, and TS is a useful tool to assume the adaptation in Tₑربط (Figure 4). This method allows to monitor adaptations with practical and cost and time effective matter.
The reasons that HR, sweat rate, and TS were used in the current study are multifaceted. First, as mentioned above, these variables are time and cost-efficient with good practicality in field settings. Second, adaptations in these variables are typically observed in the different timelines. (8–10) Adaptations in HR and TS were normally observed earlier than an adaptations in $T_{rec}$. (10) However, an adaptation in sweat rate is one of the last adaptations to be induced. (10) Third, responses of HR, sweat rate, TS, and $T_{rec}$ to exercise in the heat are related to each other and these variables represent both cardiovascular and thermoregulatory systems. (19, 20) Thus, these measurements can provide comprehensive information related to adaptations following HAz, HA, and DHA.

This study provided the suggestion to use the cut-points for HR<13 bpm, sweat rate>0.3 L·h$^{-1}$, and TS≤0.5 in endurance trained athletes with the wide range of age individuals (19-55 years old). These cut-points can be used to assess adaptations regardless of induction methods, such as HAz, HA, and DHA. However, the cut-points to predict an adaptation in $T_{rec}$ for different populations might be different. There are no thresholds for HR, sweat rate, TS, and $T_{rec}$ to indicate “enough” or “success” adaptations following HAz, HA, and DHA. Thus, the decision tree was used to determine the cut-points for HR, sweat rate, and TS in the current study. The cut-point used in the current study demonstrated the magnitude of improvement was 0.53°C greater in ending $T_{rec}$ when two or three variables met the cut-points compared to zero variable and 0.71°C was greater compared to one variable met with both large effects. Maximal HR and TS, sweat rate, and ending $T_{rec}$ were collected from 60 minutes exercise at 60% vVO$_{2\text{max}}$, which was performed $T_{\text{amb}}$ at 35.11±0.62°C, %RH at 47.61±0.38%, WBGT at 29.53±0.63°C. This
exercise intensity was corresponding to average of 77% HRmax. This testing procedure can be used to assess the adaptations. However, different environmental conditions and exercise intensity and duration for testing can provide different results for adaptations of each variable. Analyzing data at 30 minutes mark from current study did not provide better probabilities because the stress level during the testing was not enough to demonstrate the adaptations at the exercise intensity used in this study. Future study needs to investigate using shorter testing duration with higher exercise intensity protocol to induce enough stress for the testing.

**Conclusion**

A Venn Diagram consisted of maximal HR, sweat rate, and maximal TS with cut-points of HR<-13 bpm, sweat rate>0.3 L·h⁻¹, and TS<-0.5 between pre and post-test was a useful tool to assess the adaptations in T_{rec} at the end of exercise. When two or three variables met cut-points, the probability of accuracy to indicate improvement in T_{rec} was 95% with sensitivity of 0.900. When one and zero variable met the probability of accuracy was 62% and 42%, with low sensitivity 0.400 and 0.00, respectively. Additionally, the magnitude of adaptations were significantly greater when three or two variables met compared to one or zero. Theas results suggested to use Venn Diagram as practical and noninvasive method to indicate the adaptations in T_{rec}, especially in the field settings.

**References**


Figure 1. Study timeline
Figure 2. Thermal sensation scale (16)
Figure 3. The differences of rectal temperature between pre and post-test when two or three variables, one, and zero variables met the cut-points. * indicates statistical significance from two or three variable met the cut-points, p<0.05.
**Figure 4.** A Venn diagram consisted of heart rate, thermal sensation, and sweat rate to indicate if rectal temperature adaptation occurred or not. Cut-points were heat rate < -13 bpm, sweat rate > 0.3 L·h⁻¹, and thermal sensation ≤ -0.5 between pre and post-test. When three or two variables met cut-points, rectal temperature decreased at 95% of the cases.
Table 1. Difference of rectal temperature between pre and post-test when three or two, one, and zero variables met the cut-points. *indicates statistical significance, p<0.05.

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<th>ES</th>
<th>95%CI</th>
<th>p-value</th>
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