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The Dynamics of Heat Exchange During Exercise

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THE DYNAMICS OF HEAT EXCHANGE DURING EXERCISE

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ABSTRACT

Purpose: The primary aim of this thesis was to examine the changes in body heat content (ΔH_b) during exercise. Specifically, Study #1 compared ΔH_b and changes in mean body temperature ($\Delta \bar{T}_b$) and ΔH_b from thermometry with direct calorimetry. Study #2 sought to examine the effect of ΔH_b on different time-responses of measures of body temperature. Methods: Study #1 – Forty-one subjects (23 females) performed 60 - 90 min of cycling exercise at 40% $\dot{V}O_{2peak}$. ΔH_b, core, muscle and skin temperatures were measured by direct calorimetry, and ΔH_b was also estimated from conventional thermometry equations. Study #2 - Sixteen subjects (8 females) performed 60 min of cycling exercise at 70 W. Changes in ΔH_b as a function of heat gain and heat loss, core and skin temperatures were measured. Results: Study #1 – Measurements of ΔH_b and $\Delta \bar{T}_b$ by direct calorimetry were significantly greater than by conventional thermometry ($p < 0.01$). Study #2 – Esophageal and tympanic temperatures and whole-body heat loss achieved steady values at a significantly earlier time than rectal temperature ($p < 0.01$). Conclusions: Study #1 – The calculation of ΔH_b by thermometry underestimates body heat content when compared to direct calorimetry, and estimates of ΔH_b by thermometry, must be revised to a three compartment model that includes muscle temperature. Study #2 – As rectal temperature achieved steady state later than all other measures of temperature and heat flow, it best indicates when whole-body thermal steady-state has been reached.

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ABBREVIATIONS

bpm	Beats per minute	R	Radiative
CO_2	Carbon dioxide	C	Conductive
O_2	Oxygen	E	Evaporative
HR	Heart Rate	T_{tb}	Triceps brachii (lateral head) temperature
mL	Milliliters	T_{up}	Upper trapezius temperature
Kg	Kilogram	T_{vl}	Vastus lateralis temperature
$\bar{T}_{sk}$	Skin temperature	$\dot{V}O_{2peak}$	Maximal oxygen consumption
T_{re}	Rectal temperature	DEXA	Dual energy x-ray absorption
T_{es}	Esophageal temperature	m_f	Fat mass
T_{ty}	Tympanic temperature	m_l	Lean mass
T_c	Core temperature	m_b	Bone mass
BM	Body mass	RER	Respiratory exchange ratio
LBM	Lean body mass	kJ	Kilojoules
H_b	Body heat content	W	Watts
$\bar{T}_b$	Mean body temperature	C_p	Specific heat capacity

CHAPTER 1: INTRODUCTION

Introduction

During thermoregulation in humans, control of body temperature is in a large part dependent upon internal heat exchange between tissues and compartments of the body, and externally between the body surface and the ambient environment. Body temperature change is ultimately affected by the rate of heat loss from the surface of the body, therefore in assuming a constant ambient temperature and humidity, the active control of heat loss responses will be influenced by the body's internal physiological activity.

During exercise or physical work, the rate of heat production increases above its level at rest because of heat produced as a by-product of skeletal muscle contraction due to both chemical mechanical efficiency with the active muscle tissue. As the heat producing event of exercise continues the increase in convective heat transfer between muscle and blood produces a subsequent and sustained rise in core temperature. Thus, core temperature rises during dynamic exercise subsequent to a sustained increase in muscle heat accumulation. In response to the increase in heat production, heat loss response mechanisms are activated, resulting in an increase in the rate of whole-body heat loss. Once the rate of heat loss is sufficient elevated to dissipate heat at the rate at which it is being produced, thermal balance is restored such that core temperature stops rising and reaches a steady-state level. Of note, even when physical work is performed in a cool environment which would tend to result in a decrease in mean skin temperature, an increase in core temperature is needed to stimulate an increase in heat loss albeit occurring at a higher core temperature than in a warm environment. The resultant increase in skin blood flow is necessary to increase heat delivery to the skin (i.e., increase in dry heat loss), thereby preventing the rise of core temperature.

Although human thermoregulatory control has typically been defined based on a regulated central temperature (29, 60) there continues to be significant controversy about what is the actual regulated variable. Whereas some ascribe to the theory that temperature or a function of various temperatures is the controlled variable (7), others support the notion that body heat content is the controlled variable (33) or that rate of heat outflow is adjusted to balance metabolic heat production (73). Based on the classical set-point theory of temperature regulation the hypothalamus is considered the primary control centre for thermoregulation. Within the hypothalamus, as with other regions such as the medulla, spinal cord, skin and various regions in the body there exists temperature sensitive cells. When stimulated through a thermal disturbance, a thermoregulatory response is initiated by the hypothalamus. The magnitude of the response is dependent on the degree of thermal disturbance as reference against the hypothalamic set-point temperature. For example, during exercise or physical work, brain temperature rises above a set-point and the resultant load error initiates a reflex response directed at increasing heat dissipation via an increase in skin blood flow and sweating. In contrast, when skin or core temperature is reduced, skin vasoconstriction occurs and if the decrease continues, shivering is triggered. Signal processing between the anterior and posterior hypothalamus ensures that the system is not working against itself thereby preventing any unnecessary oscillation.

Changes in body heat content can be measured by calorimetry or thermometry. Direct calorimetry is the measurement of total body heat loss through both the measurements of dry (radiative and conductive) and evaporative heat loss. In combination with the measurement of metabolic heat production (assessed indirectly by the measurement of oxygen consumption), changes in body heat content can be measured. Our Snellen calorimeter uses the "can within a can" design in a pressurized environmental chamber which ensures that a zero air temperature

gradient is maintained between the inside chamber and the environment. This permits the measurement of dry heat loss by the subject, measured as a change in temperature of the air passing through the calorimeter.

Changes in body heat content can be determined from the following equation:

$$\Delta H_b = \int_{t=0}^{t_i} \left[\dot{M} - \left(\dot{R} + \dot{C} \right) - \dot{E} - \dot{W} \right] dt \qquad \text{eq 1}$$

where ΔH_b = change in body heat content, $\dot{M}$ = metabolic rate, $(\dot{R} + \dot{C})$ = rate of dry heat loss (radiation and conduction), $\dot{E}$ rate of evaporative heat loss, and $\dot{W}$ = rate of external work being performed.

By measuring the metabolic heat production ($\dot{M}$), along with rates of dry heat loss (radiation and conduction, $(\dot{R} + \dot{C})$), and evaporative heat loss ($\dot{E}$), rate of heat storage can be quantified during exercise as an example.

In contrast to direct calorimetry, thermometry provides a much simpler approach to estimating body heat content. Thermometry is widely used to estimate changes in body heat content and is typically used to develop guidelines in the assessment of human tolerance to adverse environments. It is based on a weighted two-compartmental model of skin and core. These tissue temperature estimates are used to derive a mean body temperature ($\Delta \overline{T}_b$). Using this calculated mean body temperature, changes in body heat content can be calculated based on a function of body mass (BM), and whole-body specific heat capacity (C_p), as shown in the following equation:

$$\Delta H_b = \Delta \overline{T}_b \cdot BM \cdot C_p \qquad \text{eq 2}$$

However, it is difficult to accurately estimate mean body temperature during different conditions such as during rest and exercise due to the fact that the fractional contribution of skin or core temperature varies under different ambient conditions. As such, different weightings of skin and core have been developed. However, such estimates can result in either an over- or under-estimation of changes in body heat content. Furthermore, factors such as ambient conditions, tissue insulation by subcutaneous fat, surface insulation (clothing), physical fitness, hydration status and acclimatization and many other factors can significantly affect the estimation of mean body temperature, and therefore estimates of body heat content. Finally, the use of thermometry can only be used in steady state conditions. In other words, it is assumed that tissue temperatures of the body are in thermal steady state. Typically, rectal temperature is used to define the point at which steady state is achieved during exercise for example. At the point at which rectal temperature achieves steady state, it is further assumed that the rate of heat loss is equal to the rate of heat gain, and therefore net heat exchange (or flux) between the environment and the subject is zero. If steady state has not been reached, then body heat content is still changing.

As stated earlier, there remains significant disagreement related to whether or not a central reference temperature is used to regulate body temperature. On the other hand, there is some evidence to suggest that body heat content per se is the regulated variable. However, the assessment of body heat content is problematic given the limitations associated with the conventional use of thermometry in the measurement of body heat content as outlined above. Direct calorimetry does provide a Gold standard from which total body heat loss can be assessed and therefore changes in body heat content can be accurately measured during different conditions of thermal stress.

The purpose of the following research study was as follows:

1. To compare the measurement of using conventional thermometry with direct calorimetry during dynamic exercise.

This comparison was used to develop a new equation aimed at improving the indirect estimate of body heat content. The conventional thermometry equation originally proposed by Burton (9) was based on a two-compartmental model defined by a weighted average of core and skin temperature to estimate mean body temperature. As discussed earlier, such an approach can lead to erroneous measures of body heat content. On the other hand, direct calorimetry allows for the direct measurement of body heat storage. Therefore, values for body heat content obtained using the gold standard measurement of direct calorimetry were compared with those values obtained by conventional thermometry. Finally, in our study, we measured changes in rectal, esophageal, tympanic, skin and muscle temperatures. These values were used to develop a three-compartment model approach in estimating body heat content.

2. To compare the time-line response of esophageal, tympanic, and muscle temperatures during continuous prolonged dynamic exercise in comparison to that measured for rectal temperature.

As previously stated, rectal temperature is typically used to define the point at which steady state is achieved during exercise. Estimates of body heat content by thermometry are valid only when steady-state is achieved. However, a previous study by Kenny et al. (2003) (39) has shown that different core temperature indices, such as rectal, esophageal and tympanic temperatures, as well as both active and inactive muscle temperatures vary significantly during

exercise. Thus, it is possible that when T_{re} is constant, it can be assumed that the whole body is in a thermal steady state. This can lead, however, to significant error in the estimation of body heat content. Although rectal temperature is thought to be a good index to assess body heat storage, there have been few studies that have evaluated the use of other temperatures such as esophageal, tympanic and muscle temperatures as an indicator of 'steady-state'. Given that studies have shown that different tissue temperatures vary significantly during exercise, our study also examined the use of other non-conventional variables (i.e., muscle temperature, rate of heat loss to heat gain, etc.) to identifying steady state.

Hypothesis

1. We hypothesized that measurements of body heat content by direct calorimetry would be greater than those estimated by thermometry.

2. We hypothesized that rectal temperature would continue to change when the body was in a whole-body thermal steady-state (i.e., the rate of body heat storage is zero).

Relevance

1. This study examined the accuracy of predictive equations for changes in body heat content based on thermometry, and allowed for development of a new equation to better predict changes in heat content.

2. This study examined the use of other tissue temperatures as indices in assessing whole-body thermal steady-state during exercise.

Delimitations

The results of these studies can be generalized to the population of the same characteristics as used in this study, and under the same conditions (i.e. environmental conditions, exercise intensity, exposure times). Core temperatures must be stable at rest, and reach steady state levels during exercise to measure body heat content.

Limitations

Heat production from metabolism were calculated from a non-protein respiratory exchange ratio, and therefore all fuel oxidized during exercise was assumed to be due only to fat and carbohydrate oxidation.

CHAPTER 2: LITERATURE REVIEW

Introduction

Heat balance within mammals, including humans, is a function of heat transfer. Human temperature regulation during exercise reflects a control system with effector responses being proportional to afferent input, particularly the temperature of core and skin (25). Thermal balance is deemed to occur when the rate of heat loss is equal to the rate of heat load. Generally, heat storage is controlled in the body, and changes in heat stores, or total body heat content (H_b) produces changes in body temperatures. Different theories exist on human temperature control, such as the classic set-point theory, the theory of heat content. Based on the classical set-point theory of temperature regulation, the hypothalamus is considered the primary control centre for thermoregulation (7, 23, 28, 60). Within the hypothalamus, as with other regions such as the medulla, spinal cord, skin and various regions in the body, exists temperature sensitive cells (32). When stimulated through a thermal disturbance, a thermoregulatory response is initiated by the hypothalamus. The magnitude of the response is dependent on the degree of thermal disturbance as reference against the hypothalamic set-point temperature. For example, during exercise or physical work, brain temperature rises above a set-point and the resultant load error initiates a reflex response directed at increasing heat dissipation via an increase in skin blood flow and sweating. In contrast, when skin or core temperature is reduced, skin vasoconstriction occurs and if the decrease continues, shivering is triggered. Signal processing between the anterior and posterior hypothalamus ensures that the system is not working against itself thereby preventing any unnecessary oscillation.

However, during exercise, there is a re-setting of the temperature set-point to an elevated value while rate of heat loss remains stable. In other words, core temperature remains elevated

above 37°C at a steady value, with the rate of heat loss remaining at a steady-state level such that the excess stored heat is not removed until the termination of exercise. As a result, while some researchers ascribe to the theory that temperature or a function of various temperatures is the controlled variable (7), others support the notion that body heat content is the controlled variable (33) or that rate of heat outflow is adjusted to balance metabolic heat production (73). Webb (71) states that heat flux between the body and the environment is detected, and physiological responses defend the body heat content, and the changes in heat content drive changes in deep body temperature. At the onset of exercise, Webb (71) found that the quick response of increased metabolic rate corresponded to an increased rate of heat loss before there was a change in core temperature, and only minor changes in skin temperature. In other words, when there was an imbalance between the rate of metabolic heat production and rate of whole-body heat loss, there was a resultant change in core temperature. However, changes in compartmental tissue temperature may have still be occurring due to heat transfer by conduction between the tissue compartments, albeit there was no change in rate of whole-body heat loss.

Body Heat Content

Body heat content is a function of body mass, mean body temperature, and the specific heat capacity of the body. Changes in body heat content (H_b) can be estimated based on the following from Burton (9):

$$\Delta H_b = \Delta \overline{T}_b \cdot BM \cdot C_p \qquad \text{eq 1}$$

where m_b is body mass (kg), C_p ($kJ \cdot kg^{-1} \cdot {}^oC^{-1}$) is average specific heat of all the tissues of the body, and $\overline{T}_b$, is body temperature (°C). A C_p value of 3.47 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$ was initially proposed, but it is an estimate based on average fat and fat-free mass of the body. Further research has allowed for more accurate determination of whole-body C_p by partitioning body composition into fat, tissue and bone, and using the C_p of each, i.e.:

$$C_p \text{ (whole body)} = (m_f \cdot C_{p\,f}) + (m_t \cdot C_{p\,t}) + (m_b \cdot C_{p\,b}) \qquad \text{eq 2}$$

where m_f, m_t, and m_b are fat, tissue and bone mass, and $C_{p\,f}$, $C_{p\,t}$, and $C_{p\,b}$ are the specific heat capacities for fat, tissue and bone, respectively.

By convention, body temperature is estimated using a two-compartment model (core-shell) based on a weighted sum of mean core temperature (traditionally rectal) and shell temperature (skin) where core accounts for 50% - 90% of body temperature and skin for the rest.

Changes in Heat Content

Heat content within the body is important for temperature regulation. To determine changes in heat content, which result in changes in whole body temperature, the following equation is used:

$$\Delta H_b = \int_{t=0}^{t_i} \left[\dot{M} - \left(\dot{R} + \dot{C} \right) - \dot{E} - \dot{W} \right] dt \qquad \text{eq 3}$$

ΔH_b = change in body heat content

$\dot{M}$ = metabolic rate

$\dot{C}$ = rate of heat loss through conduction

$\dot{R}$ = rate of heat loss through radiation

$\dot{E}$ = rate of heat loss through evaporation

$\dot{W}$ = rate of work being performed

From this equation, it is clear that if all variables are known, then rate of heat storage can be calculated. A negative storage indicates heat loss, while positive indicates a net heat gain. The direct calorimeter allows for determination of net heat loss through conduction, radiation and evaporation. Metabolic rate is determined through indirect calorimetry. The work rate is the power output during the exercise.

Prediction in Changes in Body Heat Content from Thermometry

As previously discussed, changes in body heat content (H_b) can be estimated based on the following :

$$\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot C_p \qquad \text{eq 4}$$

where BM is body mass (kg), C_p ($kJ \cdot kg^{-1} \cdot {}^oC^{-1}$) is average specific heat of all the tissues of the body, and $\Delta \bar{T}_b$ is the change in mean body temperature (°C). A C_p value of 3.47 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$ was initially proposed, but it is an estimate based on average fat and fat-free mass of the body. Burton proposed using rectal temperature as the index of core body temperature. Since then, many different estimates for $\bar{T}_b$ have been developed based on a weighted average of core and skin, where core accounts for 50% - 90% of body temperature. The ratios are based on ambient

conditions and clothing, which affect heat loss mechanisms. Standardization between subjects is often done by using body surface area, body mass, fat mass or lean mass, to account for differences in overall body composition.

Effect of a Heat Load on Body Temperature Regulation

The zone of thermoneutrality is, by definition, the ambient temperature under standard conditions at which a nude resting body is at its basal metabolic rate (14). In other words, the basal metabolic rate is sufficient to maintain a constant core temperature (T_c) as the rate of thermogenesis is equal to the rate of thermolysis in the zone. When a heat load is applied to the body, the response of cutaneous vasodilation and sweating is activated to prevent the rise in core temperature. During exposure to high temperatures, sweating allows for large rates of heat loss that can not be achieved solely by vasodilation of the skin blood vessels to allow for increased rates of radiative heat loss. However, in situations of uncompensable heat stress, when rate of heat load exceeds that of the rate of heat loss, core temperature rises (14).

Heat Production through Exercise

When a person begins to exercise, there is an increase in heat production due to the increase in fuel oxidation by the active muscles. Immediately with the start of exercise, oxygen uptake and utilization increases exponentially, and within minutes new steady state levels are achieved. The oxidation of glucose and fats is not 100% efficient, but rather ~50% of the energy released from the glucose is used for ATP formation, while the rest is converted to heat. Furthermore, cycling mechanical efficiency is ~25%, meaning 75% of the overall energy utilized is converted to heat. Therefore, during exercise, large amounts of heat are produced compared to

the amount of external work performed. Rate of heat load is calculated as the difference between rate of heat production and rate of external work.

Heat loss, after the onset of exercise, lags behind, known as inertia or temporal dissociation. Steady state levels of heat loss are often not reached until > 20 minutes after the onset of exercise, but can take up to 50 – 60 minutes to plateau. The curve is exponential in shape, with a time constant of 10 minutes, meaning that 50% of the maximum response is achieved within this time (71). Until steady state for heat loss is reached, there is a period of heat storage as a result of the delay in both dry and evaporative heat loss, as heat load is greater than heat loss. This increase in body heat content is released upon the termination of the exercise.

Heat Flow Sensors Within the Body

Detection of heat flux in the body is detected by central and peripheral thermoreceptors. The peripheral thermoreceptors are located in the dermis and subcutaneous tissue between the arterial and venous plexuses. It is believed that the subcutaneous receptors are stimulated when the mixed venous blood returning from the skin and muscle exceeds that of the arteries, thus creating a reversed temperature gradient, as arterial blood is warmer than venous blood when in thermal balance (5). The sensors work as a feedback system, signaling to the central nervous system when heat production is greater than heat loss. The receptors in the dermis, located at a depth of 0.3 to 0.6 mm, respond to temperatures by burst neural activity, such that as temperature increases, activity burst rate increases (32).

Changes in Body Heat Content with the Environment

Heat transfer from the body to the environment occurs in three ways, with the rate of each depending primarily on environmental conditions. Radiation is the exchange of heat between two bodies/surfaces without direct contact, but rather through electromagnetic radiation (52). Net radiative heat exchange is dependent on the radiative surface area and the temperature difference between the two bodies and/or surrounding objects. It is independent of the heat content of the two objects (i.e.: only the temperature difference between the two surfaces affects the net flow of radiative heat transfer). For humans, whenever the temperature of the objects in the environment are greater than $\bar{T}_{sk}$, there is a net heat absorption by radiation. Conduction is the transfer of heat from one substance to another through direct contact. The rate of heat transfer is dependent on thermal conductivity and temperature difference between the two substances (52). Within the body, conduction occurs with contact between the tissues and blood of different temperatures. The rate of total heat exchange by conduction and radiation is dependent on effective exposed body surface area, the temperature gradient between the air and the skin, and convective air flow. When air temperature is below that of skin temperature, radiation and conduction account for up to 85% of heat loss for a nude, standing human in quiet air (19-21). The final mechanism of which heat is lost from the body is evaporation of water from the skin and pulmonary surface. In changing the physical state of water from a liquid to a gas, energy is absorbed from the skin and pulmonary surface and the air in contact with the water (52). The latent heat of vaporization is 2427 J, which is the energy required to evaporate one gram of liquid sweat to a gas. Evaporative of fluid occurs on all wet external surfaces of the body exposed to the external air. The rate of heat loss through evaporation from the body depends on the exposed

body surface area, the rate of vaporization, the partial pressure of the water content of the air, and air flow rate. At rest in quiet air, 25% of heat loss is due to evaporation, but is the predominant means of heat loss during exercise and exposure to extreme temperatures and high convective flow (51, 62). It is only possible for the body to lose heat by evaporation, whereas radiative and conductive heat can be transferred in either direction with the environment (heat gain or heat loss).

Rate of heat exchange from the core is affected by air temperature, partial pressure of the water content of the air, convective fluid flow, skin temperature and core body temperature. As the gradient between core, skin and air increases, rate of dry heat loss increases. As the partial pressure of the water content of the air increases, the capacity for evaporative heat loss is decreased due to already elevated saturation levels of the air. As these change, the thresholds for sweating and vasodilation during exercise change to optimize heat loss mechanisms.

Indices of Core

Numerous sites have been utilized to represent core temperature, including the oral cavity, tympanic membrane, pulmonary artery and right heart, rectum, and esophagus. The use of the pulmonary artery and right heart for temperature measurement is not practical, due to the invasiveness involved (23).

Rectal Temperature as an Index of Core

Traditionally, rectal temperature has been used an index of core temperature based on the observation that the steady-state rectal temperature provides a good index to assess body heat storage (49). It provides uniform temperature measurements when inserted at a depth from 5-27

cm past the anal sphincter (47). Rectal temperature (T_{re}) is recognized to be a measurement of tissues of the abdominal region, and is less sensitive compared to other measures to fluctuations in body temperature under thermogenic or thermolytic conditions (26). This is due to the large tissue mass with a low rate of blood flow that must be heated, and thus a much slower response time (4, 6, 27, 47). At rest, T_{re} can be up to 0.3°C higher than T_{es} at rest and during exercise (4, 6, 49).

Esophageal Temperature as an Index of Core

Esophageal temperature (T_{es}) probably represents temperature of the blood returning to the heart via the pulmonary artery as it is placed next to the heart and aorta (8, 53). It is quick to respond due to its proximity to the heart, with a response time of about one minute, making it the best indicator of core temperature because of its rapid response to changes in temperature in mixed venous blood (18, 53). During exercise, esophageal temperatures have been shown to reach steady state levels within 15 – 20 minutes.

Recently, a study by Gass and Gass (23) examined the effect of how T_c measurement is influenced by predominantly upper- or low-body musculature (leg ergometry, arm ergometry, treadmill running at 65% of VO_2max). They observed that at rest, T_{re} was significantly higher than T_{es}. Furthermore, T_{re} was significantly higher at the termination of exercise with leg ergometry, but T_{re} was not significantly different with arm ergometry or with running. The response to cycling has been observed in other studies (41, 49).

Tympanic Temperature as an Index of Core

Tympanic temperature (T_{ty}) is viewed as the most sensitive measurement of core temperature since it should reflect the temperature of the blood perfusing to the brain (6). The correct placement of the sensor is crucial to the accuracy of the measurements, and it must be isolated from the environment (17, 42). During rest and exercise, it has been found that the use of the tympanic temperature to represent T_c provides dubious estimates (17, 23, 27, 43, 46). However, more recently there has been support that T_{ty} does provide an accurate measurement of T_c (50).

Skin Temperature as an Index of Shell

Skin temperature is measured to represent shell temperature, and is used as an indicator of heat transfer capacity at the skin surface. Skin temperature is under the control of the blood flow to the skin and sweating response, the temperature gradients between the core and skin, and the environmental conditions between core and environment (air/water movement, temperature, radiation) (14). Traditionally, an average weighted skin temperature is calculated based on a weighted model from body surface (31). At the onset of exercise, there is a redistribution of blood away from the cutaneous surface to the working muscles as a means to meet metabolic demands of the active tissues while maintaining cardiac output (44). This results in a decreased capacity for heat loss at the skin surface. However, at approximately 5 – 8 minutes into exercise (37), vasodilation at the skin surface allows for an increased rate of heat loss, at the expense of maintaining central blood volume (central venous pressure) and therefore blood flow to the active tissues. However, until this occurs, there is an increased rate of heat storage due to the decreased radiative heat loss at the skin surface.

Determining Average Body Temperature

As previously discussed, body temperature is traditionally estimated using a two-compartment model (core-shell) based on a weighted sum of mean core temperature (usually rectal) and shell temperature (skin) where core accounts for 50% - 90% of body temperature and skin for the rest.

$$\bar{T}_b = (X \cdot T_{re}) + ((1 - X) \cdot \bar{T}_{sk}) \qquad \text{eq 5}$$

The ratios are based on ambient conditions and clothing, which affect heat loss mechanisms. Values of X ranging from 0.5 to 0.9 have been proposed by several researchers. A value of 0.5 was proposed for subjects in a cold environment, a value of 0.65 in a neutral environment (15), and a value of 0.8 was proposed for subjects exposed to neutral and hot environments, with or without clothing (15, 30, 59, 65). The value of 0.9 was also proposed for subjects in a hot environment when wearing clothing (3).

However, such estimates can result in either an over- or under-estimation of changes in body heat content. Furthermore, factors such as tissue insulation by subcutaneous fat, surface insulation (clothing), physical fitness, hydration status and acclimatization and many other factors can significantly affect the estimation of mean body temperature, and therefore estimates of body heat content. Finally, the average body temperature can only be predicted in steady state conditions, meaning that the tissue temperatures of the body are in thermal steady state and there is a zero net heat flux between the body and the environment. Typically, rectal temperature is used to define the point at which steady state is achieved during exercise for example. At the point at which rectal temperature achieves steady state, it is assumed that the rate of heat loss is

equal to the rate of heat gain, and therefore net heat exchange (or flux) between the environment and the subject is zero. If steady state has not been reached, then body heat content is still changing.

The development of a three-compartment model (core-shell-muscle) to estimate body temperature is necessary for better prediction of average body temperature due to the heat production within the active musculature, which is not accounted for in the conventional core-skin model. During exercise, it has been shown that there is a significant amount of heat stored within the active tissues, and muscle temperature can exceed that of rectal temperature (39). Conductive heat flow by the blood away from the active musculature allows for tissue heat content to be decreased, and leads to the rise in core temperature. In recovery, studies have shown that temperatures of previously active muscle remains elevated during recovery even after other temperatures have returned to baseline, indicating that heat is still being stored within the muscle tissue. Therefore, error in thermometric calculations of ΔH_b may result from not accounting for changes in muscle temperature (39).

Therefore, the need for a three-compartment model accounting for core, skin and muscle is necessary to provide a better estimate of average body temperature.

Effect of Body Composition on Body Heat Content

Body mass and relative body tissue composition are determinants of body heat content, and there is a wide individual variation in these parameters. Fat tissue has a specific heat capacity of 2.973 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$, while muscle tissue is 3.639 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$ (22, 24, 54). Therefore, the amount of heat stored in a unit mass of muscle is greater than that of fat for a given temperature change. For two people with an identical body weight, the one with a relatively

larger fat mass will have a greater temperature rise for a given amount of heat load. It is necessary to determine individual average whole-body specific heat capacity (C_p) based on relative tissue x-ray density. Thus, dual energy x-ray absorption (DEXA) can used to partition body mass into tissue fractions of: a) fat soft tissue mass (C_p = 2.973 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$); b) lean soft tissue mass; and c) bone mass (C_p = 1.256 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$) based on relative tissue x-ray density. Lean tissue mass is further calculated to be composed of the following averages, listed in Table 1 (22, 24, 54).

Table 1: *Fractional composition and specific heat capacity of lean tissue mass.*

Tissue	Percent of Lean Tissue Mass (%)	Tissue C_p ($kJ \cdot kg^{-1} \cdot {}^oC^{-1}$)
Muscle	51	3.639
Skin	11	3.662
White and grey matter	5	3.664
Eye	0.5	3.664
Nerve tissue, lens, cartilage	7.4	3.664
Blood	25	3.894
Cerebral spinal fluid	0.1	4.182

Types of Direct Calorimeters

Direct calorimeters allow the measurement of heat loss through the measurement of dry and evaporative heat loss. Direct calorimeters exist in the form of flow calorimeters, gradient calorimeters, storage calorimeters, and calorimeters with compensating heaters (69). *Flow calorimeters* consist of a climatic chamber for air flow that continuously monitor changes in air temperature and humidity, or by using a liquid-conditioned suit, which measures heat loss through the skin while preventing any heat loss through sweating. A *gradient calorimeter* requires an insulative gradient layer between the subject and the chamber, and changes in

temperature on either side of the metal layer determine the temperature difference across the gradient. Air flow between the gradient and the chamber walls carries away water vapor, which is then analyzed for evaporative heat loss. A variation of a gradient calorimeter is the use of heat flow sensors attached to the skin, which measure dry heat loss based on the gradient between the skin and air. *Storage calorimeters* consist of a water bath calorimeter, in which changes in water temperature is due to heat transfer between the subject and the water. *Compensating heater calorimeters* work by maintaining a stable temperature within and chamber or bath, and heat loss by the human is determined by the decrease in power by the heater to maintain the same environmental temperature, due to the heat loss from the subject. For further description of these calorimeters, refer to Webb (1985).

University of Ottawa Modified Snellen Calorimeter

The modified Snellen whole-body air flow calorimeter is located at the Laboratory of Bioenergetics and Environmental Physiology at the University of Ottawa. The original Snellen calorimeter, which was modified for the purposes of the laboratory, has been previously described (57). It is a whole-body, zero-temperature gradient air calorimeter. The zero-temperature gradient refers to the injection of a constant flow of conditioned air partly into the calorimeter and partly into the space surrounding the calorimeter at such a rate that there exists no thermal gradient and therefore no heat flux across the calorimeter wall. Thus, all the heat dissipated by the subject in the chamber is reflected in the temperature difference (dry heat) and humidity difference (evaporative heat) between the incoming and outgoing air measured from temperature and humidity sensors placed to measure air as it enters and exits the chamber. The temporal summation of metabolic heat production and dry and evaporative heat exchange when

the system is equilibrated yields the net heat storage. A chair and an electronically-braked ergometer are also installed within the chamber, to allow for exercise at a known constant workload to be performed. The chair is designed specifically to maximize air flow around the subject to prevent sweat from staying on the skin surface, while still allowing for comfort.

Air temperature is regulated at a fixed point by a heater and air conditioner, and has an operating temperature from +5°C to +40°C. Temperature is monitored to ±0.01°C, and is controlled by a feed-back system that allows for very controlled temperatures. Humidity is monitored using a dew-point system, measuring the concentration of water in the air to an accuracy of ±0.01 $g \cdot kg^{-1}$.

In summary, by knowing the rate of air flow, dry and evaporative heat loss can be calculated through the following equations:

Rate of dry heat loss = Δ temperature · specific heat of air · $\dot{m}$ eq 6

Rate of evaporative heat loss = Δ humidity · heat of vaporization · $\dot{m}$ eq 7

Rate of total heat loss = rate of dry + rate of evaporative eq 8

where Δ temperature is the temperature of the effluent air minus influent air in K°, Δ humidity is the absolute humidity of the effluent air minus influent air (g water · kg air^{-1}), $\dot{m}$ is mass flow ($kg \cdot min^{-1}$), and specific heat of air and evaporative heat of vaporization are constants (1005 $J \cdot kg\ air^{-1} \cdot {}^{o}C$ and 2427 $J \cdot g\ water^{-1}$).

Indirect Calorimetry

Direct calorimeters are only able to measure rates of dry and evaporative heat loss. In order to calculate rate of heat storage, rate of heat load (heat production minus external work performed) must also be known. Metabolic heat production, or energy expenditure, is estimated stoichiometrically by analysis of oxygen and carbon dioxide content of inspired and expired air. Metabolic heat production, determined by oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio (RER), are measured by an open-circuit technique. Expired gases are sampled from a fluted mixing box.. Expired air from the mixing box is vented back into the chamber to allow for measurement of respiratory water loss. $\dot{V}O_2$ ($L \cdot min^{-1}$) and RER are averaged on a minute-basis and used to calculate energy expenditure ($\dot{M}$) in Watts from the following equation:

$$\dot{M} \equiv \Sigma \left(\dot{V}O_2 \bullet \left[\frac{RER - 0.7}{0.3} e_f + \frac{1 - RER}{0.3} e_c \right] \right) \qquad \text{eq 9}$$

where $\dot{M}$ = rate of energy expenditure, e_f is the caloric equivalent per liter of oxygen for fat (kJ), and e_c is the caloric equivalent per liter of oxygen for carbohydrates (kJ).

Application of the Haldane equation to determine $\dot{V}O_2$ and RER is acceptable, as during low-intensity exercise, protein is not considered a significant fuel source. Therefore, all energy production is assumed to come from the metabolism of fat and carbohydrate.

Hemodynamic Response to Dynamic Exercise

Stretch receptors, also known as baroreceptors, are located in the arterial walls of the carotid sinus and aortic arch. During exercise, the increase in blood pressure activates the baroreceptors, causing them to signal the central nervous system and medulla, which inhibits the

vasoconstrictor centre of the medulla (48, 66). During exercise, a rise in stroke volume and heart rate causes a corresponding increase in cardiac output. If there is not a corresponding decrease in total peripheral resistance, blood pressure rises. If blood pressure rises, then baroreceptor activity increases. Some of the blood flow increase is routed to the skin due to the need for heat loss during exercise, resulting in an increase in dry heat loss. The cutaneous vasodilation response during exercise is regulated also by non-thermal factors, as exercise also creates a need for a redistribution of blood to active muscle. The end response is the effect on skin blood flow, which regulates heat loss by radiation and conduction.

Post-Exercise Heat Storage

After long duration dynamic exercise of moderate intensity, during the post-exercise recovery period body temperature can remain elevated at up to ~0.5°C above resting temperature for up to 65 minutes, even after much of the increase in body heat content is released upon the termination of exercise (38, 39, 63). The reason for this elevated temperature is the transfer of heat from the previously active musculature to the other body compartments via conductive heat flow from the blood. During rest, there have been numerous studies describing limb thermal profiles. A most recent study by Kenny et al. (39) measured superficial, mid-, and deep- muscle temperature using embedded thermal probes. They observed that at rest, muscle temperature (T_{mu}) profile is parabolic, with deep tissue muscle being warmer than superficial muscle. The proposed differences for the observed variations in resting muscle temperature are inconsistency of probe placement, proximity of bone and large arteries, differences in specific heat capacity of muscle tissue, differences in blood flow (and therefore conductive effect), and the influence of rate of temperature change in adjacent regions of the muscle. By the end of exercise, the muscle

temperature gradient is nonexistent, such that the mid- and superficial muscle temperature rises to that of the deep muscle. All the T_{mu} temperatures recorded were greater than the core temperature, opposite of what exists at rest, when core temperature is greater. It is also important to note that during exercise, they observed that the rate of temperature rise of the core was slower than that of muscle, suggesting that the rate of heat accumulation within the core is not offset completely by the increase in rate of heat loss mechanisms. Much of the heat produced by the active muscles is lost by conductive heat loss through the transportation of the heat to the surface veins of the active areas, or by conductive heat flow by the blood to other compartments of the body. Limb sweat rate, cutaneous blood flow and muscle-to-skin temperatures increased during exercise, allowing for enhanced mechanisms of heat loss.

Immediately after exercise during passive recovery, deep muscle temperature decreases to that of esophageal temperature, and remains relatively the same throughout the remainder of the exercise. Kenny et al. (39) suggested that this was due to equilibrium of heat distribution within the body, and therefore changes in surface heat by dry and evaporative heat loss mechanisms will change the rate of whole body cooling.

Gender Differences in Thermoregulatory Response to Dynamic Exercise

Four main factors that potential affect thermoregulatory control in men and women are: physiological differences (i.e.: female hormones, body water regulation, exercise capacity, etc), anthropometric characteristics (i.e.: body mass and size), body composition (muscle and fat content), and physical behavior (i.e.: daily physical activity) (36).

Factors such as fat content, body surface area, body mass, and surface-to-mass ratio contribute only partly to thermal responses to heat stress. However, when body size-related

variables are adjusted for according to $\dot{V}O_{2max}$, many of the differences between men and women are not evident. In calculating individual whole-body specific heat values, difference in body mass and body composition are accounted for, as those with difference amounts of fat and tissue mass, even with the same body mass, will have significantly different specific heats. Except for sweat rate, men and women have been reported to be quite similar for thermoregulatory control (10). For sweating, men have been shown to have a lower core and skin temperature at which the onset of sweating occurs, therefore for a given relative heat load ($kJ \cdot kg^{-1}$), less heat is stored in men before evaporative cooling is activated (61). Also, while women have a greater proportion of sweat glands, they secrete less sweat compared to men (36). In regards to sex hormones, estrogen and progesterone have been shown to affect body temperature and skin blood flow in women (12, 13). Estrogen promotes cutaneous dilation and therefore an increase in heat dissipation, while progesterone inhibits the same cutaneous dilation (11).

Limitations to comparing men and women

Identifying physiological differences that are due solely to gender is very difficult. Gender-related factors such as lean body mass, fitness, lifestyle, weight and height may lead to differences, along with possible menstrual cycle phase effects on cardiovascular control. As a disadvantage, women generally have a lower blood volume due to being smaller, therefore a lower relative circulating blood volume in females due to venous pooling would contribute to a more rapid reduction of cardiac filling and therefore failure to maintain MAP (61). They also have a higher relative fat content, resulting in a lower thermal conductivity (2). However, the advantages for women are having a greater relative surface area, and therefore a greater capacity

for heat loss through sweating, radiation and conduction, and also a lower muscle mass to generate heat with a corresponding large heat sink due to a higher fat content (1, 36, 61).

Menstrual cycle in women must be controlled for by testing during the follicular phase to control for estrogen and progesterone levels, which affects cutaneous dilation and therefore rate of heat dissipation (61).

CHAPTER 3: METHODOLOGY

Population and sample

The subjects for this study included 57 healthy volunteers between the ages of 18 and 40 years. Those on any form of medications with any history of cardiovascular or respiratory disease were excluded. Female subjects were not to be pregnant or trying to conceive at the time of testing. Female subjects were to experience a regular menstrual cycle and were doing nothing to compromise the regularity of their menstrual cycle (i.e. excessive training, under eating, under excessive stress).

Instrumentation

Indirect Calorimetry.

$\dot{V}_E$, $\dot{V}_{O_2}$, and carbon dioxide production ($\dot{V}_{CO_2}$) were determined by open-circuit spirometry from measurements of inspired minute volume and inspired and mixed expired gas concentrations sampled from a 6-litre fluted mixing box. Expired gas was analyzed using calibrated electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA). Expired air was recycled back into the environmental chamber to allow for respiratory heat loss to be included in measurement of evaporative heat loss. Fractional O_2, CO_2 and ventilation rate were collected and digitized at 15-sec intervals, simultaneously displayed and recoded in spreadsheet format on a hard disk (Dell OPTIPLEX GX270). $\dot{V}_{O_2}$ and RER were averaged on a minute-basis and used to calculate energy expenditure ($\dot{M}$) from the following equation:

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

where e_f is the caloric equivalent per liter of oxygen for fat (kJ), and e_c is the caloric equivalent per liter of oxygen for carbohydrates (kJ).

Direct Calorimetry.

The modified Snellen calorimeter was used to measure dry (radiative and conductive) heat loss by changes in influent and effluent air temperature. Temperature was measured using copper/constantan thermometers positioned at the entrance and exit of the chamber (1560 Black Stack, Hart Scientific, American Fork, UT). Input and output temperatures can be measured to within ± 0.002 °°. Data was collected and digitized at 8 second intervals, displayed graphically in real time and recorded in spreadsheet format on a hard disk. Evaporative heat loss was measured by changes in influent and effluent absolute humidity. Absolute humidity was measured by water content analysis of the air at the entrance and exit of the chamber by dew-point measures with an accuracy of ± 0.01 $g \cdot kg^{-1}$ of air (Dew Point Mirror 373H, RH Systems, Albuquerque, NM). Data was collected and digitized at 8 second intervals displayed graphically in real time and recorded in spreadsheet format on a hard disk.

Air mass flow rate was measured as the mass of air moved through the chamber per minute (in $kg \cdot min^{-1}$). It was determined based on the following equation:

$$\dot{m} = \frac{\Delta T}{P_{IN} C_P K} \qquad \text{eq 2}$$

where $\dot{m}$ is mass flow, ΔT is temperature difference across heater, P_{IN} is input power to heater, C_p is specific heat of (dry) air at 30°C (1.005 $kJ \cdot (kg \cdot °C)^{-1}$), and K is a system-related constant (~1) dependent on the temperature profile across the duct.

Tissue Temperatures.

Esophageal (T_{es}), rectal (T_{re}) and tympanic (T_{ty}) temperatures were measured continuously as indices of central body temperature. To measure T_{es}, a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO) was used, which was inserted through the nares to a depth of approximately one-fourth of the standing height of the subject placing the tip of the thermocouple at the level of the left atrium. T_{re} was measured using a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO) was inserted at least 12 cm past the rectal sphincter. T_{ty} was measured with a tympanic thermocouple (Mon-a-therm Tympanic, Mallinckrodt Medical, St. Louis, MO) was inserted into the aural canal until it reached the tympanic membrane, and then withdrawn slightly. It was held into this position with cotton, and covered with ear protectors to isolate it from the outside environment. Skin temperature was monitored at 12 sites by using Type T thermocouples integrated into heat-flow sensors (Concept Engineering, Old Saybrook, CT), and the area-weighted mean skin temperature was calculated using the following regional percentages (31): head 7%, hand 4%, upper back 9.5%, chest 9.5%, lower back 9.5%, abdomen 9.5%, bicep 9%, forearm 7%, quadriceps 9.5%, hamstring 9.5%, front calf 8.5%, and back calf 7.5%. Temperature data was collected and digitized (HP data acquisition module, model 3497 A) at 8-sec intervals, simultaneously displayed and recorded in spreadsheet format on a hard disk (IBM ThinkCentre M50).

Regional muscle temperature of the: 1. vastus lateralis (T_{vl}), 2. lateral head of triceps brachii (T_{tb}), and 3. upper trapezius (T_{ut}) was measured by using a flexible thermocouple probe inserted at an angle of 30 – 40° from the skin, and inserted to a depth of one centimeter into the

muscle. The implant side for the vastus lateralis was approximately midway between, and lateral to, a line joining the anterior superior iliac spine and the superior aspect of the centre of the patella. The triceps brachii implant site was approximately midway between, and lateral to, a line joining the greater tubercle of the humerus and the superior aspect of the olecranon of the ulna. Upper trapezius muscle temperature was measured ~3 cm superior to the center point between the acromion process and superior angle of the scapula. With the use of aseptic technique, the skin, subcutaneous tissue, and muscle were anesthetized to a maximum depth of 40 mm by infiltrating ~ 3 mL of 2% lidocaine with epinephrine. An 18-gauge, 45-mm non radiopaque FEP polymer I.V. catheter (Medex Medical, Ltd.) was then inserted into the anesthetized tract to the required depth. The catheter stylet was then withdrawn, and the temperature probe was inserted into the catheter shaft. The probe assembly, including the catheter shaft, was secured to the skin with sterile, waterproof transparent dressing.

Twelve thermocouples integrated into heat-flow sensors will be taped to the skin surface measured skin temperature. The area-weighted mean skin temperature ($\bar{T}_{sk}$) was estimated by calculating the weighted mean value whereby the following regional percentages are assigned (31): head 7%, hand 4%, upper back 9.5%, chest 9.5%, lower back 9.5%, abdomen 9.5%, bicep 9%, forearm 7%, quadriceps 9.5%, hamstring 9.5%, front calf 8.5%, and back calf 7.5%. Temperature data was collected and digitized (Agilent Data Acquisition/Switch Unit module, model 34970A) at 15 second intervals, displayed graphically in real time and recorded in spreadsheet format on a hard disk (IBM ThinkCentre M50).

Calculations to Determine Body Heat Content by Direct Calorimetry.

The modified Snellen air calorimeter was used to measure evaporative and dry heat loss by changes in humidity and air temperature entering and exiting the chamber. Absolute humidity was measured using sensors positioned at the inlet and outlet circulation air vents of the chamber (Dew Point Mirror 373H, RH Systems, Albuquerque, NM). Air temperature was measured using thermometers positioned at the inlet and outlet circulation air vents of the chamber (1560 Black Stack, Hart Scientific, American Fork, UT). Mass flow rate (kg air $\cdot$ min^{-1}) was calculated immediately prior to the start of each trial. Direct calorimetry data was collected and digitized at 8 second intervals, and displayed graphically in real time and recorded in spreadsheet format on a hard disk. Evaporative heat loss per minute was calculated using the following equation:

$$\text{Evaporative Heat Loss} = \text{mass flow} \cdot (\text{humidity}_{out} - \text{humidity}_{in}) \cdot 2.427 \qquad \text{eq 3}$$

where ($humidity_{out}$ – $humidity_{in}$) was the absolute humidity difference across the chamber (g water·kg air^{-1}), and 2.427 is the latent heat of vaporization of sweat (kJ·kg $sweat^{-1}$) (76). Dry (radiative and conductive) heat loss per minute was calculated per minute by the following equation:

$$\text{Dry Heat Loss} = \text{mass flow} \cdot (\text{temperature}_{out} - \text{temperature}_{in}) \cdot 1.005 \qquad \text{eq 4}$$

where ($temperature_{out}$ – $temperature_{in}$) is the temperature difference across the chamber (°C), and 1.005 is the specific heat of air (kJ·(kg air·°C)$^{-1}$).

The cumulative change in heat storage over the 60 minutes of exercise was calculated from the following:

$$\Delta H_b = \int_{t=0}^{t_i} \left[\dot{M} - \left(\dot{R} + \dot{C} \right) - \dot{E} - \dot{W} \right] dt \qquad \text{eq 5}$$

where $\dot{M}$ =metabolic rate, $(\dot{R}+\dot{C})$ = rate of dry heat loss (radiation and conduction), $\dot{E}$ = rate evaporative heat loss, and $\dot{W}$ = rate of external work being performed.

Calculations to Determine Body Heat Content from Thermometry.

Changes in body heat storage were modeled-based from Burton (9) using X = 0.5, 0.65, 0.80 and 0.90. For all equations, the value of 3.47 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$ was used for whole-body specific heat capacity. Therefore, the equation was (in kJ):

$$\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot 3.47 \qquad \text{eq 6}$$

where ΔH_b = change in body heat content, $\Delta \bar{T}_b$ = mean body temperature, and BM is whole body mass. $\Delta \bar{T}_b$ was calculated as follows:

$$\Delta \bar{T}_b = (X \cdot T_{re}) + ((1\text{-}X) \cdot \bar{T}_{sk}) \qquad \text{eq 7}$$

Criteria for Tissue Temperature Steady State

Steady state criteria was set based on the following (45, 74, 75): a) metabolic rate varied by no more than ± 3%; b) total heat loss varied by no more than ± 3%; c) rectal, esophageal and tympanic temperature varied by no more than ± 0.1°C; and d) mean skin temperature varied by

no more than ± 0.2°C . Time was determined based on minute-by-minute changes in temperatures or rate (for heat loss).

Experimental Protocol

Pre-experimental testing. During the first hour-long visit to the environmental physiology laboratory at the University of Ottawa, potential participants were informed of the experimental procedures and given the opportunity to ask questions. Those who were interested in taking part in the study and fit the criteria completed informed consent, the health questionnaire and the PAR-Q and You forms. A signed copy of the documents was given to them. At this point, the subjects' age, height, and body mass were obtained. Body composition was estimated by DEXA analysis. Following body composition analysis, peak oxygen consumption ($\dot{V}O_{2peak}$) was determined with the use of an automated metabolic cart (MOXUS) by a progressive test on a cycle ergometer. The test was terminated when the participant could no longer sustain the required power output, at which point they continued pedaling at 25 W until heart rate and breathing had returned to near resting levels. Heart rate was continuously monitored using a Polar Heart Monitor.

Experimental Testing. The experimental sessions were conducted following a 24-hour period of no heavy or prolonged physical activity, and the last 12 hours included abstinence from stimulants and alcohol. Experimental sessions were separated by a minimum of 24 hours. All thermal and metabolic stimuli were minimized as much as possible on this day. Upon arriving at the laboratory, subjects were instrumented with the thermal probes and a heart rate monitor. They then entered the climatic chamber that was set at the appropriate temperature of either 24°C

or 30°C. Once all thermal sensors were connected to the data acquisition system and the participant was connected to the mouthpiece, the pre-exercise resting period of 45 minutes was started, during which metabolic and thermal data was collected continuously. Following this, the participant cycled at 40% of their $\dot{V}O_{2peak}$ for 60 to 90 minutes to allow rectal temperature to stabilize, and then underwent an inactive recovery period for 60 minutes. During the exercise and recovery period, metabolic, cardiovascular and thermal data was again collected continuously. Once the post-exercise period was over, the participant exited the chamber.

CHAPTER 4

ARTICLES 1 AND 2

ABSTRACT

Changes in body heat content (ΔH_b) can be measured by direct calorimetry as a function of changes in heat gain and heat loss, or estimated by thermometry, in which predictive equations relate changes in mean body temperature ($\Delta \bar{T}_b$) with changes in ΔH_b . However, it has been suggested the ΔH_b may be underestimated using conventional thermometry [i.e., $\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot C_p$, where $\bar{T}_b = (X\% \cdot T_{re}) + ((1 - X\%) \cdot \bar{T}_{sk})$, which is based on a linear two-compartment model. The following study was conducted to compare estimates of ΔH_b from direct calorimetry to that calculated by thermometry using core-shell weighting factors (i.e.: coefficient X) of 0.5, 0.65, 0.8, and 0.9. Using a modified Snellen calorimeter set at 24 or 30°C, following a resting period, 41 subjects (23 females) exercised on a semi-recumbent cycle ergometer at ~40% of their pre-determined $\dot{V}O_{2peak}$ until steady state rectal temperature was achieved (less than 90 minutes). Oxygen consumption, dry and evaporative heat loss and core, muscle and skin temperatures were measured continuously. Since direct calorimetry measures only changes in heat storage, which can be converted to $\Delta \bar{T}_b$, all body temperatures are expressed as changes from a constant baseline resting conditions. Specific heat capacity for each subject was calculated by partitioning body weight into fat, lean and bone using dual energy x-ray absorption, and assigning specific heat capacities to each component. The calculated ΔH_b and $\Delta \bar{T}_b$, as measured by direct calorimetry, were significantly greater than those values derived from thermometry using the conventional method with the 4 values for X. Furthermore, we proposed a model using core, skin and muscle to estimate ΔH_b. Our results yielded a significantly improved estimate of ΔH_b

compared to conventional thermometry, as it predicted better than 0.3°C in 70% of the cases. These results lend further support to the concept of a three compartment model approach (i.e., core, skin and muscle tissue temperatures) to estimate ΔH_b as compared to the conventional linear two-compartment approach.

Key words: Heat storage, thermometry, direct calorimetry, body heat content

INTRODUCTION

Many safety standards for heat tolerance are based on changes in body heat content (ΔH_b), and accurate determination of this change in heat content is crucial. resulting in erroneous estimates of changes in ΔH_b. For example, an underestimation of ΔH_b can potentially put a worker at risk of developing a heat-related injury especially if work standards are established based on an estimated ΔH_b. Changes in body heat content (or body heat storage) can be measured either directly using a calorimeter, or by estimation by conventional thermometry which is based primarily on an estimate of rectal and skin temperature change as described below. With direct calorimetry, it is possible to measure with a high degree of accuracy changes in body heat storage and therefore ΔH_b, provided that both mean and regional body temperatures are stable at the beginning and during the period of thermal stress such as during exercise (55). However, due to the fact that direct calorimeters are both expensive and complex to construct, there exists very few in the world today capable of measuring rapid changes in body heat storage. As such, owing to its simplicity of use, conventional thermometry is often used to estimate body heat content.

Using conventional thermometry, ΔH_b can be calculated based on the change in mean body temperature ($\Delta \bar{T}_b$) from a weighted average of core and skin, total body mass (BM), and a whole-body specific heat capacity (C_p) of the body equal to 3.47 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$ (9).

$$\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot C_p \qquad \text{eq 1}$$

From Burton's model, $\bar{T}_b$ is calculated by: $\bar{T}_b = (X\% \cdot T_{re}) + ((1 - X\%) \cdot \bar{T}_{sk})$.

Traditionally, rectal temperature has been used as the indices of core temperature based on the previous demonstration that the steady-state rectal temperature provides a good index to assess body heat storage (49) However, tissue temperature at any given time is ultimately determined by the relative rates of heat production and heat loss. Thus, the idea that a single core temperature measurement, such as T_{re}, can provide an index of body temperature is problematic from both a theoretical and practical point of view. For example, estimates of ΔHb may be underestimated during intermittent work activities whereby changes in T_{re} are to slow to respond to rapid changes in blood temperature. In such conditions, esophageal temperature and tympanic temperatures, which has been shown to be related to changes in blood temperature (8, 53) would be a more appropriate estimate of core temperature.

Based on Burton's model, it is assumed that the body is conceptually divided into two compartments: the core and the shell (outer tissues of the body – the skin). A change in mean body temperature is estimated by taking X % of the body (assumed to representative of the core) as represented by rectal temperature and the remainder, (100-X) % of the body, which is considered the 'shell' by a weighted average skin temperature ($\bar{T}_{sk}$). The value of X being dependent upon ambient temperature and which therefore may range from a value of 50% in a cold environment, 65% in a thermoneutral environment and 90% in a hot environment (15). Furthermore, other factors such as the level of clothing insulation must be considered when applying such factors. For example, a value of 80% (15, 30, 59, 65) and 90% (3) has been proposed for subjects exposed to neutral or hot environments, with or without clothing.

It has been suggested that estimates of ΔH_b by conventional thermometry produce incorrect values of ΔH_b (15, 56). Conventional thermometry, which is defined based on a linear two-compartment model, does not consider changes in muscle temperature, despite the fact that

segmental lean body mass comprises almost 40% of total lean body mass (67). Previous studies have shown that muscle temperature vary significantly between different muscle groups and between the different measures of core (i.e., esophageal, tympanic and rectal) (39, 72). Given the fact that muscle has the capacity to store large amounts of heat for a given temperature rise, it would be logical to consider the changes in muscle temperature in estimating $\Delta \bar{T}_b$ (and therefore ΔH_b). Previous studies have advanced the notion that a three-temperature or three-compartment model approach, which includes muscle tissue temperature (72), should be considered in estimating changes in ΔH_b. To the best of our knowledge, Snellen (55) is only study that compared estimates of mean body temperature by conventional thermometry with direct calorimetry. His comparison was based on multiple tissue temperature measurements which included an indirect estimate of muscle temperature albeit using zero-flux devices. Although his model showed an improvement in predicting changes in mean body temperature, their observations were limited to data collected from 7 male subjects only within in a range of ambient temperature conditions.

Therefore, the following study was conducted to 1) compare ΔH_b measured by direct calorimetry to that estimated by conventional thermometry using a coefficients for X of 50, 65, 80 and 90% under temperate (24°C) and hot (30°C) ambient conditions; and 2) to develop a new model to estimate changes in ΔH_b which includes measurements of core, skin and muscle.

METHODOLOGY

Subjects

Forty-one healthy subjects (23 females) volunteered and gave written consent to participate in this study. The study was approved by the Research Ethics Board of the University

of Ottawa. Male subjects were (mean ± SD) 29 ± 10 yrs, 1.71 ± 0.09 m tall, weighed 69.7 ± 13.8 kg, and $\dot{V}O_{2peak}$ was 59.43 mL·kg LBM^{-1}·min^{-1}. Female subjects were 24 ± 6 yrs, 1.66 ± 0.06 m tall, weighed 62.4 ± 9.9 kg, and $\dot{V}O_{2peak}$ was 53.45 mL·kg LBM^{-1}·min^{-1}. Dual energy x-ray absorptiometry (DEXA) was used to determine body composition. DEXA is a gold-standard method, partitioning body weight into the components of fat soft tissue mass (m_f), lean soft tissue mass (m_l), and bone mass (m_b), based on the differential attenuation by tissues of two levels of x-rays. Lean tissue mass was further subdivided as follows: muscle mass (51.0% of m_l), skin mass (11.0%) white matter, grey matter, eye, nerve, lens, and cartilage mass (12.9%), blood mass (25.0%), and cerebral spinal fluid mass (0.1%). For each of these components, a specific C_p value was assigned (22, 24, 54).

Instrumentation

Tissue Temperatures:

Esophageal, rectal and tympanic temperatures were measured continuously. Esophageal temperature was measured using a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO) which was inserted through the nares to a depth of approximately one-fourth of the standing height of the subject placing the tip of the thermocouple at the level of the left atrium. Rectal temperature was measured using a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO) was inserted at least 12 cm past the rectal sphincter. Tympanic temperature was measured with a tympanic thermocouple (Mon-a-therm Tympanic, Mallinckrodt Medical, St. Louis, MO). The tip of the sensor was inserted into the aural canal until it reached the tympanic membrane, and then withdrawn slightly. It was held into this

position with cotton, and covered with ear protectors to isolate it from the outside environment. Skin temperature was monitored at 12 sites by using Type T thermocouples integrated into heat-flow sensors (Concept Engineering, Old Saybrook, CT), and the area-weighted mean skin temperature was calculated using the following regional percentages (31): head 7%, hand 4%, upper back 9.5%, chest 9.5%, lower back 9.5%, abdomen 9.5%, bicep 9%, forearm 7%, quadriceps 9.5%, hamstring 9.5%, front calf 8.5%, and back calf 7.5%. Temperature data was collected and digitized (HP data acquisition module, model 3497 A) at 8-sec intervals, simultaneously displayed and recorded in spreadsheet format on a hard disk (IBM ThinkCentre M50).

Regional muscle temperature of the vastus lateralis (T_{vl}), lateral head of triceps brachii (T_{tb}), and upper trapezius (T_{ut}) was measured by using a flexible thermocouple probe inserted at ~ 3 cm from the skin surface. The implant site for the vastus lateralis was approximately midway between, and lateral to, a line joining the anterior superior iliac spine and the superior aspect of the centre of the patella. The triceps brachii muscle sensor was inserted approximately midway between, and lateral to, a line joining the greater tubercle of the humerus and the superior aspect of the olecranon of the ulna. Upper trapezius muscle temperature was measured ~3 cm superior to the center point between the acromion process and superior angle of the scapula. With the use of an aseptic technique, the skin, subcutaneous tissue, and muscle were anaesthetized to a maximum depth of 40 mm by infiltrating ~ 3 mL of 2% lidocaine with epinephrine. An 18-gauge, 45-mm non radiopaque FEP polymer I.V. catheter (Medex Medical, Ltd.) was then inserted into the anaesthetized tract to the required depth. The catheter stylet was then withdrawn, and the temperature probe was inserted into the catheter shaft. The probe assembly, including the catheter shaft, was secured to the skin with sterile, waterproof transparent dressing.

Indirect Calorimetry:

$\dot{V}_E$, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ were determined by open-circuit spirometry from measurements of inspired minute volume and inspired and mixed expired gas concentrations sampled from a 6-litre fluted mixing box. Expired gas was analyzed using calibrated electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA). Expired air was recycled back into the environmental chamber to allow for respiratory heat loss to be included in measurement of evaporative heat loss. Fractional O_2, CO_2 and ventilation rate were collected and digitized at 15-sec intervals, simultaneously displayed and recoded in spreadsheet format on a hard disk (Dell OPTIPLEX GX270). $\dot{V}_{O_2}$ and RER were averaged on a minute-basis and used to calculate energy expenditure ($\dot{M}$) from the following equation:

$$\dot{M} \equiv \Sigma \left(\dot{V}O_2 \bullet \left[\frac{RER - 0.7}{0.3} e_f + \frac{1 - RER}{0.3} e_c \right] \right) \qquad \text{eq 2}$$

where e_f is the caloric equivalent per liter of oxygen for fat (kJ), and e_c is the caloric equivalent per liter of oxygen for carbohydrates (kJ).

Direct Calorimetry:

A modified Snellen air calorimeter was used to measure evaporative and dry heat loss by changes in humidity and air temperature entering and exiting the chamber. Absolute humidity was measured using sensors positioned at the inlet and outlet circulation air vents of the chamber (Dew Point Mirror 373H, RH Systems, Albuquerque, NM). Air temperature was measured using thermometers positioned at the inlet and outlet circulation air vents of the chamber (1560 Black Stack, Hart Scientific, American Fork, UT). Mass flow rate (kg air $\cdot$ min^{-1}) was calculated

immediately prior to the start of each trial. Direct calorimetry data was collected and digitized at 8 second intervals, and displayed graphically in real time and recorded in spreadsheet format on a hard disk. Evaporative heat loss per minute was calculated using the following equation:

$$\text{Evaporative Heat Loss} = \text{mass flow} \cdot (\text{humidity}_{out} - \text{humidity}_{in}) \cdot 2.427 \qquad \text{eq 3}$$

where (humidity_{out} – humidity_{in}) was the absolute humidity difference across the chamber (g water·kg air^{-1}), and 2.427 is the latent heat of vaporization of sweat (kJ·kg sweat^{-1}) (76). Dry (radiative and conductive) heat loss per minute was calculated per minute by the following equation:

$$\text{Dry Heat Loss} = \text{mass flow} \cdot (\text{temperature}_{out} - \text{temperature}_{in}) \cdot 1.005 \qquad \text{eq 4}$$

where (temperature_{out} – temperature_{in}) is the temperature difference across the chamber (°C), and 1.005 is the specific heat of air (kJ·(kg air·°C)$^{-1}$).

The cumulative change in heat storage over the 60 minutes of exercise was calculated by the following equation:

$$\Delta H_b = \int_{t=0}^{t_f} \left[\dot{M} - \left(\dot{R} + \dot{C} \right) - \dot{E} - \dot{W} \right] dt \qquad \text{eq 5}$$

where $\dot{M}$ = metabolic rate, $(\dot{R} + \dot{C})$ = rate of dry heat loss (radiation and conduction), $\dot{E}$ = rate evaporative heat loss, and $\dot{W}$ = rate of external work being performed.

Experimental Protocol

Subjects performed an incremental cycle ergometer $\dot{V}O_{2peak}$ test on the first day. The experimental trials were conducted at the same time on different days, separated by a minimum of 72 hours. Subjects were asked to refrain from exercise for 24 hours prior to the start of each trial. On each day, care was taken to avoid major thermal stimuli or a substantial increase in metabolic rate between awakening and the start of the experiment. Subjects were clothed in shorts, sports bra (women) and running shoes and were then instrumented appropriately. They then entered the calorimeter set at either 24.0 or 30.0°C, and began the 45-min habituation period in a semi-recumbent position. Subjects then cycled for 60 to 90 minutes on a semi-recumbent constant load cycle ergometer at 40% of their $\dot{V}O_{2peak}$ until steady state rectal temperature was (45, 74, 75) , followed by a resting recovery period in the semi-recumbent position.

Data Analysis:

Changes in body heat storage from conventional thermometry were modeled based from Burton (9) using X = 50, 65, 80 and 90%. For all thermometry equations, the value of 3.47 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$ was used for whole-body specific heat capacity. Therefore, the equation was (in kJ):

$$\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot 3.47 \qquad \text{eq 6}$$

where ΔH_b = change in body heat content, $\Delta \bar{T}_b$ = mean body temperature, and BM is whole body mass. $\Delta \bar{T}_b$ was calculated from $(X\% \cdot T_{re}) + ((1 - X\%) \cdot \bar{T}_{sk})$.

Changes in $\Delta \bar{T}_b$ estimated from thermometry were also compared to that measured by direct calorimetry. $\Delta \bar{T}_b$ from direct calorimetry was calculated from the following:

$$\Delta \bar{T}_b = \Delta H_b / (BM \cdot C_p) \qquad \text{eq 7}$$

where C_p was the individual subjects' calculated specific heat capacity.

For development of a new model for thermometry, multilinear regression analysis was applied to determine the coefficients for each predictor of ΔH_b. Due to the limitation in the number of subjects, only 4 variables were used to predict ΔH_b. Variables were added into the model using the stepwise method in SPSS 11.0 (58), and their effect on explained variance for ΔH_b determined whether they were significant for the model.

RESULTS

Core, muscle and skin temperature response.

Tissue temperature responses for core, muscle and skin temperatures, respectively, are presented in Table 1. Final exercise T_{re}, T_{re} and T_{ty} temperatures increased by 0.64 ± 0.36°C, 0.66 ± 0.33°C, and 0.45 ± 0.43°C from baseline resting. Final exercise muscle temperatures for T_{vl}, T_{tb} and T_{ut} increased by 2.36 ± 0.69°C, 2.00 ± 0.71°C, and 0.79 ± 0.44°C from baseline resting. Average skin temperature increased 0.49 ± 0.46°C from baseline resting. All temperatures were significantly greater after exercise compared to rest ($p < 0.01$).

Comparison between Calorimetry and Thermometry.

Refer to Table 2 for individual results of ΔH_b from direct calorimetry and thermometry. Overall, direct calorimetric results were significantly higher than those obtained from all three original thermometry models. ΔH_b at the end of the exercise period was highly variable between individual subjects, resulting in an average of 203.3 ± 77.6 kJ. From the original thermometry equations, using X = 0.5 yielded consistently lower values that from calorimetry by 63.8 kJ, X =

0.65 was lower by 59.4 kJ, X = 0.80 was lower by 55.0 kJ, and X = 0.90 was lower by 52.1 kJ. These were all significantly lower than that from calorimetry ($p < 0.01$).

Results from the Multilinear Regression Analysis.

Due to limitations from the number of cases, only 4 variables in the end were selected for the multilinear regression equation. The use of ΔT_{tb}, C_p and T_{es} and $\Delta \bar{T}_{sk}$ gave a significant model for ΔH_b ($p < 0.01$), with an $r^2 = 0.921$. Therefore, 92% of ΔH_b is explained by these variables. The final equation to predict ΔH_b in kJ based on the multilinear regression analysis was:

$$\Delta H_b = (97.907 \cdot \Delta T_{tb}) + (47.670 \cdot \Delta \bar{T}_{sk}) + (22.305 \cdot C_p) - (146.157 \cdot \Delta T_{es}) \qquad \text{eq 8}$$

Using Burton's model with values of X of 0.5, 0.65, 0.8 and 0.9 gave r^2 values of 0.057, 0.049, 0.026 and 0.014. Therefore, there was an improvement of our new model over previously proposed models. Figure 1 shows the graphed results of each model compared to direct calorimetry.

Results of calculation of mean body temperatures

Table 3 shows the results of the individual calculated $\Delta \bar{T}_b$ using conventional thermometry and also from Model #1. These values were compared to those calculated from direct calorimetry to determine the efficacy of each model to predict $\Delta \bar{T}_b$. Results showed that on average, thermometry underestimated $\Delta \bar{T}_b$ by 0.27 ± 0.40°C, 0.25 ± 0.45°C, 0.23 ± 0.44°C

and 0.21 ± 0.45°C for an X coefficient of 0.5, 0.65, 0.8, and 0.9, respectively. From Model #1, using the individual C_p values as opposed to 3.47 kJ·(kg air·°K)$^{-1}$, calculated $\Delta\bar{T}_b$ was -0.01 ± 0.36°C. Prediction of $\Delta\bar{T}_b$ from Model #1 was not significantly different than that from direct calorimetry, while all values from thermometry were all significantly lower than direct calorimetry ($p < 0.01$).

DISCUSSION

In the following study, we compared measurements of ΔH_b obtained from direct calorimetry to that using conventional thermometry based on the equation developed by Burton (9). Furthermore, we also compared changes in $\Delta\bar{T}_b$ from direct calorimetry and thermometry. From these results, we attempted to develop a new equation to predict ΔH_b based on using a three-compartmental model approach incorporating changes in core, skin and muscle temperatures.

We did not measure a significant difference between the values of ΔH_b calculated from Burton's equation using the different coefficients of X equivalent to 50, 65, 80 and 90% respectively. However, all four of these measurements of ΔH_b were significantly lower than that measured by direct calorimetry ($p < 0.01$). Results of our multilinear regression analysis showed significant improvement in predicting ΔH_b using a model (i.e., Model #1) which incorporated the following variables: ΔT_{tb}, C_p and T_{es} and $\Delta\bar{T}_{sk}$. Changes in body heat content measured by direct calorimetry was 203.0 ± 77.6 kJ as compared to 212.4 ± 53.7 kJ measured from our proposed Model #1. When relating $\Delta\bar{T}_b$ from calorimetry to thermometry, the calculated $\Delta\bar{T}_b$ by direct

calorimetry was significantly greater than those values estimated from thermometry (i.e., 0.84 ± 0.44°C vs. 0.56 ± 0.30°C, 0.59 ± 0.29°C, 0.61 ± 0.31°C, and 0.63 ± 0.32°C with X equal to 50, 65, 80 and 90% respectively, $p > 0.01$). Compared to Model #1, there was no difference between the values for $\Delta \bar{T}_b$ (0.84 ± 0.44°C vs 0.91 ± 0.29°C, $p < 0.01$).

A key limitation in the use of thermometry is that a steady state core temperature must be achieved. Steady-state is defined as the point at which: 1) rectal temperature achieves a stable value (equal to 0.1°C for a minimum period of 5 minutes); and 2) the rate of heat gain and heat loss is matched, and therefore the rate of body heat storage remains unchanged (i.e.: body heat content is stable) (40, 55, 68). However, we observed that rectal temperature stabilized significantly later than T_{es}, T_{ty}, and $\bar{T}_{sk}$. Of note, a steady state rectal temperature was recorded well after a balance in the rate of heat gain and heat loss had been achieved (i.e., H_b remained unchanged). This observation itself brings into question the validity of using a single core temperature indicator to represent internal core temperature steady state.

Tissue temperature at any given time is ultimately determined by the relative rates of heat production and heat loss. For example, regional muscle temperature is the result of regional differences in metabolic rate, conductive heat loss to adjacent tissue and deep and peripheral convective blood flow (20). As such, regional temperature profile and the rate of temperature change will differ accordingly. Thus, it would seem evident that any estimate of ΔH_b should consider changes in muscle tissue temperature in addition to changes in core and skin temperatures. A three-compartment model (i.e., which includes muscle temperature) approach would most likely improve the estimate of $\Delta \bar{T}_b$ and therefore ΔH_b. Snellen (55) attempted to propose an new model to estimate $\Delta \bar{T}_b$ which incorporated multiple tissue temperature

measurements, including muscle tissue temperatures. However, muscle temperature was measured by an indirect method only using a zero heat flux device. Moreover, his model included variables other than tissue temperatures such as body surface area, percent body fat, and air temperature to estimate $\Delta \bar{T}_b$.

We showed that changes in mean body temperature calculated by conventional thermometry were significantly lower than that from direct calorimetry. Based on Burton's model, it is assumed that the body is conceptually divided into two compartments: the core and the shell. However, the temperature within a given body region depends upon: 1. tissue metabolic rate, 2. deep and peripheral convective blood flow, and; 3. conductive heat loss to adjacent tissue. As such, considerable temperature gradients exist between and within different orifices, body cavities and blood vessels. Estimating $\Delta \bar{T}_b$ based solely on a linear two-compartment model, as defined by changes in an estimated temperature of core and skin alone, would likely produce significant errors. The idea that a single core temperature measurement can provide an index of body temperature is problematic. For example, the response characteristic (i.e., response time) of a particular core temperature measurement site is influenced by such factors as the environmental conditions (72), tissue metabolic rate, deep and peripheral convective blood flow, conductive heat exchange between adjacent tissue changes in tissue blood flow, and local tissue density. Similarly, skin temperature is also subject to the same influences (72). Thus, a three-compartment model which considers the changes in muscle tissue temperature, along with those of core and skin temperatures, would likely provide a better estimate of a body temperature.

In order to relate changes in $\Delta \bar{T}_b$ to changes in ΔH_b using conventional thermometry, a standard value for whole-body specific heat capacity (C_p) of tissue of 3.47 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$ is used. This value assumes a similar relative body composition between subjects. In our study, we calculated the whole-body C_p for each subject by partitioning the body mass into the following components: fat tissue mass, lean tissue mass, and bone tissue mass using DEXA. Lean body mass was further partitioned into the following components: muscle, cartilage, blood, skin, white and gray matter, eye, nerve, lens, and cerebral spinal fluid. As such, we were able to calculate each individual subject's whole-body C_p which ranged between 3.34 to 3.55 $kJ \cdot kg^{-1} \cdot {}^oC^{-1}$. The increased accuracy in our measured value for C_p would have reduced the error of our calculated value of $\Delta \bar{T}_b$ as derived from direct calorimetry.

As previously indicated, we observed a significantly greater ΔH_b measured by direct calorimetry as compared to the ΔH_b estimated by conventional thermometry. The difference may be due to an underestimation of the external work performed (45, 75), specifically the "non-thermal energy" associated with the external mechanical work. For example, Webb (75) suggested that the energy transferred from the foot to the moving treadmill belt whereby the force causes the shoe to compress and bend produces a "non-thermal energy" is typically unaccounted for. Similarly, Nagle (45) suggested that the energy associated with the displacement of the body's centre of mass against gravity during uphill treadmill walking is unaccounted. In either case, the underestimation of the non-thermal energy could possibly result in erroneous estimates of ΔH_b and may therefore account for the discrepancy in our measurements. Although it is plausible that there may be a "non-thermal energy" component associated with the mechanical work of cycling, this source of energy is likely insufficient to explain our observed differences.

It is also possible that the greater values for ΔH_b measured by direct calorimetry were the result of an underestimation of whole-body heat loss. However, our measurement devices used to quantify both dry heat loss and latent heat loss were highly precise. Changes in humidity and temperature can be detected to a precision of 0.01 g water·kg air^{-1} and 0.001°C respectively. During the experiments, mass flow (i.e., air flow through the calorimeter) was maintained at a moderately high flow rate of ~12 kg/min in order to reduce skin wettedness. This ensured that the latent heat loss was due to evaporation from the skin surface only (i.e., as opposed to that associated with water dripping on the bike or floor). However, by maintaining a high mass flow, the level of accuracy related to the measurement of air temperature may have been reduced. Regardless, given the high level of precision of our modified Snellen calorimeter for measuring dry heat loss and latent heat loss it is likely that the error in the estimate of whole-body heat loss was negligible.

In summary, changes in $\Delta \bar{T}_b$ and therefore ΔH_b measured by thermometry are significantly underestimated when compared to those values measured by direct calorimetry. Furthermore, we showed that the addition of muscle temperature significantly improved the estimate of ΔH_b.

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TABLE LEGEND

Table 1. Individual physical characteristics of the subjects.

Table 2. Mean (±SD) and individual calculated changes in body heat content measured during exercise (all values in kJ).

Table 3. Mean (±SD) and individual calculated changes in mean body temperature measured during exercise (all values in kJ).

Table 4. Regression equations and statistics; conventional thermometry method. $Y = \bar{T}_b$; $X = (X \cdot \Delta T_{re}) + ((1 - X) \cdot \Delta \bar{T}_{sk})$.

FIGURE LEGEND

Figure 1. Thermometry prediction values vs. direct calorimetry values for body heat content (all are in kJ). Values were calculated using X = 0.5, 0.65, 0.8 and 0.9 (A, B and C). Model #1 was based on our proposed equation.

Table 1: Individual physical characteristics of the subjects.

Subject	Gender	Age	VO_2max	VO_2max	Fat Mass	Lean Mass	Bone Mass	C_p
		yr	*mL*min*	*mL/(kg LBM*min)*	*kg*	*kg*	*kg*	$kJ \cdot kg^{-1} \cdot °C^{-1}$
1	F	23	2073	53.0	15.9	39.1	2.5	3.40
2	F	24	2925	65.9	18.7	44.4	2.8	3.40
3	F	25	1875	51.6	16.5	36.3	2.1	3.40
4	M	27	3212	51.7	10.0	62.1	3.0	3.51
5	M	33	3728	59.2	31.7	62.9	3.2	3.39
6	M	26	3687	58.8	9.6	62.7	3.4	3.51
7	F	20	2031	46.7	12.4	43.5	2.5	3.45
8	M	26	4989	69.0	23.4	72.3	3.5	3.45
9	M	47	3198	58.9	14.1	54.3	2.8	3.47
10	M	21	3025	55.2	7.6	54.8	3.1	3.51
11	F	19	2020	47.0	20.2	43.0	2.9	3.38
12	F	28	2870	51.7	38.5	55.5	3.1	3.34
13	F	22	2972	60.3	17.5	49.3	3.2	3.47
14	F	23	2880	57.2	10.3	50.4	3.1	3.47
15	F	20	2570	59.4	19.1	43.2	2.3	3.40
16	F	22	2226	48.9	15.2	45.5	2.8	3.43
17	F	20	2646	65.0	12.8	40.7	2.6	3.43
18	M	37	3432	62.7	8.5	54.7	2.8	3.51
19	F	22	1729	44.6	20.3	38.8	2.7	3.36
20	F	19	2020	47.0	20.2	43.0	2.9	3.38
21	F	23	2073	53.0	15.9	39.1	2.5	3.40
22	M	19	3042	60.3	10.4	50.5	2.8	3.48
23	M	28	4071	69.8	8.7	58.3	2.9	3.51
24	F	23	2845	61.4	21.2	46.3	2.8	3.39
25	F	20	2570	59.4	19.1	43.2	2.3	3.40
26	F	22	1906	51.9	18.6	36.7	2.5	3.37
27	F	26	2853	62.8	10.3	45.4	2.5	3.47
28	F	31	2667	57.7	18.2	46.2	2.6	3.42
29	M	47	2894	51.5	18.9	56.2	3.8	3.42
30	M	51	3562	57.7	12.4	61.7	3.2	3.47
31	M	23	3290	44.5	28.8	74.0	4.0	3.47
32	F	21	1473	44.1	6.2	33.4	1.9	3.49
33	F	21	1640	47.0	16.0	34.9	2.1	3.39
34	M	40	3727	56.2	10.0	66.3	3.5	3.51
35	M	21	3787	66.7	6.8	56.8	3.0	3.52
36	M	20	3956	61.7	6.8	64.1	2.9	3.55
37	M	26	3103	54.4	16.4	57.0	3.1	3.45
38	F	26	3037	65.3	10.3	46.5	2.5	3.48
39	M	21	4103	56.9	14.0	72.1	3.8	3.49
40	F	49	1208	28.7	14.4	42.1	2.6	3.42
41	M	23	4639	74.3	23.6	62.4	3.3	3.42
MEAN		**26**	**2892**	**56.1**	**15.8**	**51.0**	**2.9**	**62**
SD		**9**	**861**	**7.1**	**6.9**	**10.9**	**4.7**	**18**

m_f: fat mass; m_b – bone mass; m_l – lean mass; Cp - calculated individual specific heat capacity.

Table 2: Mean (±SD) and individual calculated changes in body heat content measured during exercise (all values in kJ).

Subject	Calorimetry	X = 0.5	Δ	X = 0.65	Δ	X = 0.8	Δ	X = 0.9	Δ	Model #1	Δ
1	203.5	54.1	149.4	81.8	121.7	109.5	93.9	128.0	75.5	n/a	n/a
2	181.3	69.5	111.8	91.5	89.8	113.5	67.7	128.2	53.1	106.4	-74.8
3	163.8	72.3	91.5	59.9	103.9	47.5	116.3	39.2	124.5	192.7	28.9
4	74.2	91.1	-16.8	131.3	-57.1	171.6	-97.3	198.4	-124.2	119.4	45.1
5	317.4	235.6	81.9	221.1	96.3	206.6	110.8	197.0	120.4	238.8	-78.6
6	216.7	135.9	80.8	163.6	53.1	191.2	25.5	209.6	7.1	188.1	-28.6
7	287.8	77.7	210.1	107.8	180.0	137.9	149.9	157.9	129.8	262.0	-25.8
8	471.9	309.5	-309.5	275.5	-275.5	241.5	-241.5	218.8	-218.8	n/a	n/a
9	67.9	92.6	-24.7	135.3	-67.4	178.0	-110.1	206.5	-138.6	175.8	107.9
10	209.6	208.2	1.5	202.8	6.8	197.5	12.1	193.9	15.7	200.8	-8.8
11	191.9	121.4	70.5	126.3	65.6	131.3	60.7	134.5	57.4	186.0	-5.9
12	219.0	231.5	-12.5	229.8	-10.8	228.1	-9.0	226.9	-7.9	209.2	-9.8
13	223.8	72.8	151.0	76.7	147.1	80.5	143.2	83.1	140.6	199.7	-24.0
14	269.6	94.0	175.6	108.3	161.3	122.5	147.1	131.9	137.7	n/a	n/a
15	56.3	58.5	-2.2	77.3	-21.0	96.1	-39.8	108.6	-52.3	198.6	142.3
16	214.2	135.6	78.6	134.9	79.2	134.2	79.9	133.8	80.4	286.2	72.0
17	305.0	82.4	222.6	109.8	195.2	137.2	167.8	155.5	149.5	200.6	-104.4
18	213.1	214.3	-1.1	200.6	12.6	186.9	26.3	177.7	35.4	211.5	-1.6
19	104.5	113.1	-8.7	118.8	-14.3	124.5	-20.0	128.3	-23.8	276.5	172.0
20	116.2	97.8	18.4	84.0	32.2	70.3	46.0	61.1	55.2	97.1	-19.1
21	225.9	170.2	55.7	143.3	82.6	116.4	109.5	98.4	127.5	n/a	n/a
22	229.8	105.0	124.8	127.8	102.0	150.6	79.2	165.9	64.0	n/a	n/a
23	160.0	200.6	-40.6	186.3	-26.3	172.0	-12.0	162.5	-2.5	275.8	115.8
24	245.5	266.3	-20.9	235.8	9.7	205.2	40.2	184.8	60.6	308.4	63.0
25	190.1	90.9	99.1	84.3	105.8	77.6	112.5	73.1	116.9	247.9	57.9
26	533.8	103.1	-103.1	99.8	-99.8	96.4	-96.4	94.2	-94.2	n/a	n/a
27	190.4	85.3	105.1	79.7	110.7	74.1	116.3	70.4	120.0	n/a	n/a
28	68.6	112.8	-44.2	99.3	-30.8	85.9	-17.3	76.9	-8.4	n/a	n/a
29	204.3	106.0	98.3	112.0	92.3	117.9	86.4	121.9	82.4	224.8	20.5
30	234.7	171.7	63.0	172.6	62.1	173.5	61.3	174.0	60.7	n/a	n/a
31	162.7	186.5	-23.8	163.8	-1.1	141.0	21.6	125.9	36.8	n/a	n/a
32	303.7	149.6	154.1	167.4	136.2	185.2	118.4	197.1	106.6	177.2	-126.5
33	333.1	269.4	63.7	274.6	58.5	279.7	53.3	283.2	49.9	282.5	-50.6
34	192.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	214.7	22.4
35	236.2	86.1	150.1	87.6	148.6	89.2	147.0	90.2	146.0	245.6	9.4
36	199.4	188.8	10.6	184.4	15.0	180.1	19.3	177.2	22.2	262.5	63.1
37	333.9	93.6	240.3	86.3	247.6	78.9	255.0	74.1	259.8	163.9	-170.0
38	119.4	72.0	47.4	97.0	22.4	122.0	-2.6	138.6	-19.2	138.8	19.4
39	283.6	124.4	159.2	141.5	142.1	158.6	125.0	170.1	113.6	255.0	-28.6
40	58.6	239.4	-180.8	271.6	-213.0	303.8	-245.2	325.2	-266.7	n/a	n/a
41	309.2	176.7	132.5	190.1	119.1	203.6	105.6	212.5	96.7	224.9	-84.3
MEAN	203.0	*139.2	54.0	*143.6	49.6	*148.0	45.2	*150.9	42.2	212.4	3.3
SD	77.6	67.0	107.4	59.8	102.8	58.5	101.8	61.1	103.2	53.7	77.9

'X' refers to the weighting value for thermometry, where $\Delta \bar{T}_b = (X \cdot \Delta T_{re}) + ((1 - X) \cdot \Delta \bar{T}_{sk})$. Model #1 is from our proposed equation. 'Δ' refers to the difference between the individual value from direct calorimetry minus the predicted value from the respective equation. *n/a,* denotes not applicable due to missing temperature values. *, denotes significantly different than values obtained by calorimetry ($p < 0.01$).

Table 3: Mean (±SD) and individual calculated changes in mean body temperature measured during exercise (all values in °C).

Subject	Calorimetry	X = 0.5	Δ	X = 0.65	Δ	X = 0.8	Δ	X = 0.9	Δ	Model #1	Δ
1	1.04	0.27	0.77	0.41	0.63	0.55	0.49	0.64	0.40	n/a	n/a
2	0.81	0.30	0.51	0.40	0.41	0.50	0.31	0.56	0.25	0.48	0.33
3	0.88	0.38	0.50	0.31	0.56	0.25	0.63	0.21	0.67	1.03	-0.16
4	0.28	0.35	-0.07	0.50	-0.22	0.66	-0.38	0.76	-0.48	0.45	-0.17
5	0.96	0.69	0.26	0.65	0.31	0.61	0.35	0.58	0.38	0.72	0.24
6	0.82	0.52	0.30	0.62	0.19	0.73	0.09	0.80	0.02	0.71	0.11
7	1.43	0.38	1.05	0.53	0.90	0.68	0.75	0.78	0.65	1.30	0.13
8	0.00	0.90	-0.90	0.80	-0.80	0.70	-0.70	0.64	-0.64	n/a	n/a
9	0.27	0.37	-0.10	0.55	-0.27	0.72	-0.45	0.84	-0.56	0.71	-0.44
10	0.91	0.92	0.00	0.89	0.02	0.87	0.04	0.85	0.06	0.88	0.04
11	0.86	0.53	0.33	0.55	0.31	0.57	0.29	0.59	0.27	0.83	0.03
12	0.68	0.69	-0.01	0.68	-0.01	0.68	0.00	0.67	0.00	0.64	0.03
13	0.92	0.30	0.62	0.32	0.61	0.33	0.59	0.34	0.58	0.82	0.10
14	1.22	0.42	0.79	0.49	0.73	0.55	0.66	0.60	0.62	n/a	n/a
15	0.26	0.26	0.00	0.34	-0.09	0.43	-0.17	0.48	-0.23	0.90	-0.65
16	0.98	0.62	0.37	0.61	0.37	0.61	0.38	0.61	0.38	1.32	-0.33
17	1.59	0.42	1.16	0.56	1.02	0.70	0.88	0.80	0.79	1.04	0.54
18	0.92	0.93	-0.02	0.87	0.04	0.81	0.10	0.78	0.14	0.91	0.01
19	0.50	0.53	-0.02	0.55	-0.05	0.58	-0.08	0.60	-0.10	1.33	-0.83
20	0.52	0.43	0.09	0.37	0.15	0.31	0.21	0.27	0.25	0.44	0.09
21	1.16	0.85	0.30	0.72	0.44	0.58	0.57	0.49	0.66	n/a	n/a
22	1.04	0.48	0.56	0.58	0.46	0.68	0.35	0.75	0.29	n/a	n/a
23	0.65	0.83	-0.18	0.77	-0.12	0.71	-0.06	0.67	-0.02	1.12	-0.47
24	1.03	1.09	-0.06	0.97	0.06	0.84	0.19	0.76	0.27	1.29	-0.26
25	0.86	0.41	0.46	0.38	0.49	0.35	0.52	0.33	0.54	1.13	-0.26
26	0.00	0.51	-0.51	0.50	-0.50	0.48	-0.48	0.47	-0.47	n/a	n/a
27	0.94	0.42	0.52	0.39	0.55	0.37	0.57	0.35	0.59	n/a	n/a
28	0.30	0.48	-0.19	0.43	-0.13	0.37	-0.07	0.33	-0.03	n/a	n/a
29	0.76	0.39	0.37	0.41	0.35	0.43	0.33	0.45	0.31	0.83	-0.08
30	0.88	0.64	0.23	0.64	0.23	0.65	0.23	0.65	0.23	n/a	n/a
31	0.44	0.50	-0.06	0.44	0.00	0.38	0.06	0.34	0.10	n/a	n/a
32	2.10	1.04	1.06	1.16	0.94	1.29	0.81	1.37	0.73	1.23	0.87
33	1.85	1.46	0.39	1.49	0.36	1.52	0.33	1.54	0.31	1.57	0.28
34	0.69	-0.12	0.81	-0.08	0.77	-0.05	0.73	-0.02	0.71	0.77	-0.08
35	1.01	0.37	0.64	0.38	0.63	0.39	0.62	0.39	0.62	1.05	-0.04
36	0.76	0.74	0.02	0.72	0.04	0.70	0.06	0.69	0.07	1.00	-0.24
37	1.26	0.35	0.91	0.32	0.94	0.30	0.97	0.28	0.99	0.62	0.64
38	0.58	0.35	0.23	0.47	0.11	0.59	-0.01	0.67	-0.10	0.67	-0.09
39	0.90	0.40	0.51	0.45	0.45	0.51	0.40	0.55	0.36	0.81	0.09
40	0.29	1.17	-0.88	1.33	-1.04	1.48	-1.19	1.59	-1.30	n/a	n/a
41	1.01	0.57	0.44	0.61	0.40	0.66	0.35	0.69	0.33	0.73	0.28
MEAN	0.84	*0.56	0.27	*0.59	0.25	*0.61	0.23	*0.63	0.21	0.91	-0.01
SD	0.44	0.30	0.46	0.29	0.45	0.30	0.44	0.32	0.45	0.29	0.36

'X' refers to the weighting value for thermometry, where $\Delta\bar{T}_b = (X \cdot \Delta T_{re}) + ((1 - X) \cdot \Delta\bar{T}_{sk})$. Model #1 is from our proposed equation. 'Δ' refers to the difference between the individual value from direct calorimetry minus the predicted value from the respective equation. *n/a,* denotes not applicable due to missing temperature values. *,denotes significantly different than values obtained by calorimetry ($p < 0.01$).

Table 4: Regression equations and statistics; conventional thermometry method. $Y = \bar{T}_b$; $X = (X \cdot \Delta T_{re}) + ((1 - X) \cdot \Delta \bar{T}_{sk})$

X	(1 - X)	Regression Equation	r^2
0.5	0.5	y = 1.7016x + 90.718	0.090
0.65	0.35	y = 1.5698x + 98.145	0.091
0.80	0.2	y = 1.4381x + 105.57	0.078
0.90	0.1	y = 1.3503x + 110.52	0.064

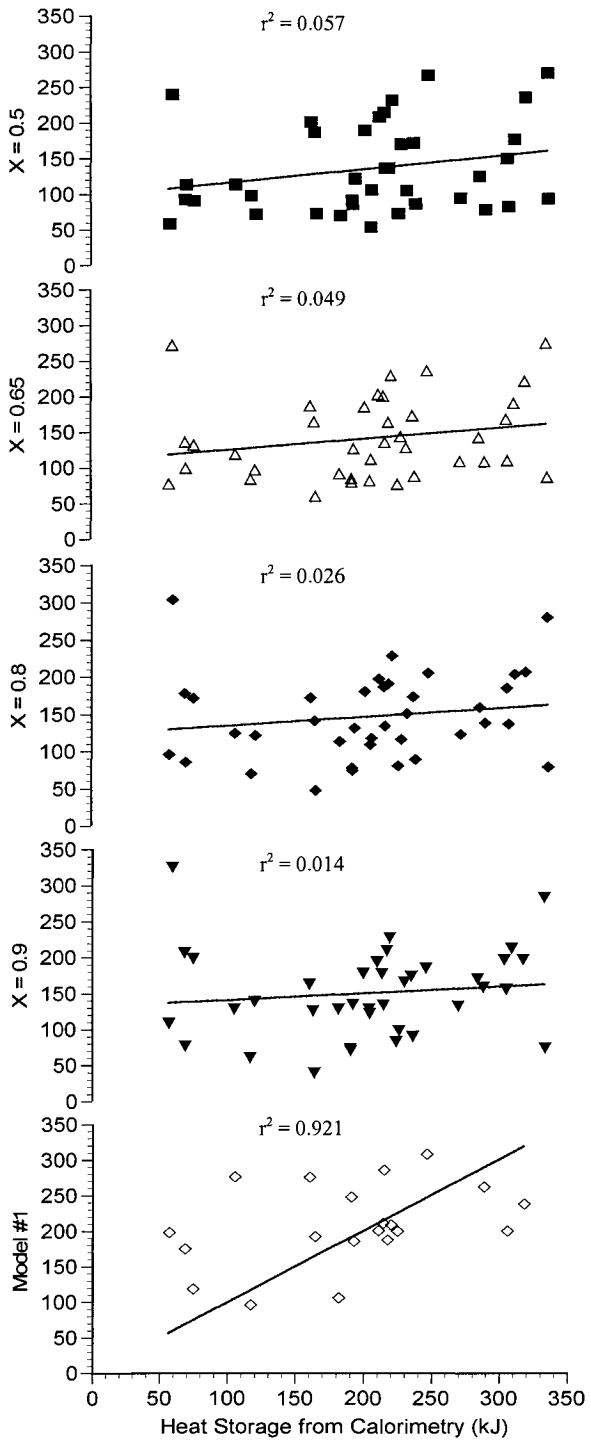

Figure 1: Thermometry prediction values vs. direct calorimetry values for body heat content (all are in kJ). Values were calculated using X = 0.5, 0.65, 0.8 and 0.9 (A, B and C). Model #1 was based on our proposed equation.

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ABSTRACT

The objective of this study was to examine the time required to a achieve steady state temperature in rectal as compared to other core and skin temperature. Specifically, the effect of changes in body heat content on different measures of body temperature, and the steady state time was evaluated. Additionally, time to steady state was recorded for rate of heat loss and heat gain, as determined by direct calorimetry using the modified Snellen Calorimeter. Sixteen subjects (8 females) underwent a 30-min baseline resting period, followed by a 60-min exercise period on a semi-recumbant cycle ergometer at 70 W to reach a steady state rectal temperature. This intensity was employed to ensure that the subjects achieved steady state rectal temperatures within the exercise period. Core temperatures were measured by esophageal, rectal, and tympanic. Skin temperature was calculated as an average of 12 sites (31). Rate of heat gain and heat loss was determined by whole-body calorimetry based on changes in air temperature and humidity. Our results showed that rectal steady state was the last temperature measurement to stabilize during the exercise period. Steady state times for esophageal (23.0 ± 6.7 min) and tympanic temperature (22.6 ± 7.7 min), along with rate of heat loss (35.5 ± 9.7 min), occurred significantly earlier ($p < 0.05$) than rectal temperature (45.2 ± 10.5 min). Our results showed that heat balance was achieved before rectal temperature stabilized, and that the rise in rectal temperature was due to the transfer of heat within the body, while heat flux with the environment was stable.

Key words: Temperature regulation, steady state, heat content, heat transfer

INTRODUCTION

Exposure to hyperthermic conditions is common for humans, and the importance of heat loss mechanisms maintaining body temperature cannot be overemphasized. Heat loss mechanisms of radiative, conductive and evaporative heat loss all allow for heat to be dissipated from the body to avoid a corresponding rise in body temperature and the associated health risks.

The ability to relate body temperature to changes body heat content is the purpose of thermometry. Burton initially proposed that changes in body heat content is the product of mean body temperature ($\bar{T}_b$), body mass (BM), and body specific heat capacity (C_p) (9).

$$\Delta H_b = \Delta \bar{T}_b \cdot BM \cdot C_p \qquad \text{(kJ)} \qquad \text{eq 1}$$

When there is an imbalance between rate of metabolic heat production and rate of total heat loss, there is a resultant change in mean body temperature (35). Traditionally, rectal temperature has been used as the indices of core temperature based on the observation that the steady-state rectal temperature provides a good index to assess body heat storage (49). Rectal temperature (T_{re}) is recognized to be a measurement of tissues of the abdominal region, and is less sensitive compared to other measures to fluctuations in body temperature under thermogenic conditions (26). Esophageal temperature (T_{es}) most closely represents temperature of the blood returning to the heart via the pulmonary artery as it is placed next to the heart and aorta (8, 53). It is quick to respond due to its proximity to the heart. T_{re} can be up to 0.3°C higher than T_{es} at rest and during exercise (4, 6, 49). In non-steady state conditions T_{es} is believed to be the best indicator of core temperature because of its rapid response to changes in mixed venous blood, with a response time of about one minute (16, 53). Tympanic temperature (T_{ty}) is viewed as the most sensitive measurement of core temperature since it reflects temperature of the blood perfusing to the brain (6). It has been observed that T_{re} tends to lag behind both T_{es} and T_{ty} under

thermogenic conditions, due to the large tissue mass that must be heated (26). Average skin temperature ($\bar{T}_{sk}$) is measured to represent shell temperature, and is used as an indicator of heat transfer at the skin surface. Skin temperature is under the control of the blood flow to the skin and sweating response, the temperature gradients between the core and skin, and the environmental conditions between core and environment (air/water movement, temperature, radiation) (14).

Mean body temperature can only be predicted in steady state conditions, meaning that tissue temperatures of the body are in thermal steady state and there is a zero net heat flux between the body and the environment. Previous studies have shown that predicting mean body temperature during non-steady states is invalid (15, 56). Typically, rectal temperature is used to define the point at which steady state is achieved during exercise for example. At the point at which rectal temperature achieves steady state, it is assumed that the rate of heat loss is equal to the rate of heat gain, and therefore net heat exchange (or flux) between the environment and the subject is zero. If steady state rectal temperature has not been reached, it is believed that body heat content is still changing. However, changes in compartmental tissue temperature may still be occurring due to heat transfer by conduction between the tissue compartments, albeit there is no change in rate of whole-body heat loss. Furthermore, it has been shown previously that during cold exposure, rates of heat loss and heat load stabilized before rectal temperature has reached steady state (64) and therefore any changes in body temperature after this is due only to thermal equilibrium of the tissues within the body, and not on changes in heat stores.

Therefore, the purpose of this study was to relate the relative rates of heat loss and heat load on core and skin body temperatures. It was hypothesized that when heat loss and heat load

have reached steady state levels, changes in rectal temperature would still be occurring due to the transfer of heat between and within the tissues of the body.

METHODOLOGY

Subjects

Sixteen subject (8 females) volunteered and gave written consent to participate in this study. The study was approved by the Research Ethics Board of the University of Ottawa. Male subjects were (mean ± SD) 28 ± 6 yrs, 1.81 ± 0.04 m tall, weighed 79.3 ± 9.1 kg, and mean $\dot{V}O_{2peak}$ was 50.08 ± 6.12 $mL \cdot kg^{-1} \cdot min^{-1}$. Female subjects were (mean ± SD) 28 ± 6 yrs, 1.61 ± 0.06 m tall, weighed 55.9 ± 8.9 kg, and mean $\dot{V}O_{2peak}$ was 43.54 ± 7.63 $mL \cdot kg^{-1} \cdot min^{-1}$. Dual energy x-ray absorption (DEXA) was used to determine body composition. DEXA is a gold-standard method, partitioning body weight into the components of fat soft tissue mass (m_f), lean soft tissue mass (m_l), and bone mass (m_b), based on the differential attenuation by tissues of two levels of x-rays.

Instrumentation

Esophageal (T_{es}), rectal (T_{re}) and tympanic (T_{ty}) temperatures were measured continuously as indices of central body temperature. To measure T_{es}, a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO) was used, which was inserted through the nares to a depth of approximately one-fourth of the standing height of the subject placing the tip of the thermocouple at the level of the left atrium. T_{re} was measured using a paediatric thermocouple probe (Mon-a-therm General Purpose

Temperature Probe, Mallinckrodt Medical, St-Louis, MO) was inserted at least 12 cm past the rectal sphincter. T_{ty} was measured with a tympanic thermocouple (Mon-a-therm Tympanic, Mallinckrodt Medical, St. Louis, MO) was inserted into the aural canal until it reached the tympanic membrane, and then withdrawn slightly. It was held into this position with cotton, and covered with ear protectors to isolate it from the outside environment. Skin temperature was monitored at 12 sites by using Type T thermocouples integrated into heat-flow sensors (Concept Engineering, Old Saybrook, CT), and the area-weighted mean skin temperature was calculated using the following regional percentages (31): head 7%, hand 4%, upper back 9.5%, chest 9.5%, lower back 9.5%, abdomen 9.5%, bicep 9%, forearm 7%, quadriceps 9.5%, hamstring 9.5%, front calf 8.5%, and back calf 7.5%. Temperature data was collected and digitized (HP data acquisition module, model 3497 A) at 8-sec intervals, simultaneously displayed and recorded in spreadsheet format on a hard disk (IBM ThinkCentre M50).

Indirect Calorimetry:

$\dot{V}_E$, $\dot{V}_{O_2}$, and $\dot{V}_{CO_2}$ were determined by open-circuit spirometry from measurements of inspired minute volume and inspired and mixed expired gas concentrations sampled from a 6-litre fluted mixing box. Expired gas was analyzed using calibrated electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA). Expired air was recycled back into the environmental chamber to allow for respiratory heat loss to be included in measurement of evaporative heat loss. Fractional O_2, CO_2 and ventilation rate were collected and digitized at 15-sec intervals, simultaneously displayed and recoded in spreadsheet format on a hard disk (Dell OPTIPLEX GX270). $\dot{V}_{O_2}$ and RER were averaged on a minute-basis and used to calculate energy expenditure ($\dot{M}$) from the following equation:

$$\dot{M} \equiv \Sigma \left(\dot{V}O_2 \cdot \left[\frac{RER - 0.7}{0.3} e_f + \frac{1 - RER}{0.3} e_c \right] \right) \quad \text{eq 2}$$

where e_f is the caloric equivalent per liter of oxygen for fat (kJ), and e_c is the caloric equivalent per liter of oxygen for carbohydrate (kJ).

Direct Calorimetry:

The modified Snellen thermal climatic chamber was used to measure evaporative and dry heat loss by changes in humidity and air temperature entering and exiting the chamber. Humidity (g water · kg air^{-1}) was measured using sensors positioned at the entrance and exit to the chamber (Dew Point Mirror 373H, RH Systems, Albuquerque, NM). Temperature (°C) was measured using thermometers positioned at the entrance and exit to the chamber (1560 Black Stack, Hart Scientific, American Fork, UT). Massflow rate (kg air · min^{-1}) was calculated immediately prior to the start of each trial. Direct calorimetry data was collected and digitized at 8 second intervals, and displayed graphically in real time and recorded in spreadsheet format on a hard disk. Evaporative heat loss per minute was calculated using the following equation:

$$\text{Evaporative Heat Loss} = \text{massflow} \cdot (\text{humidity}_{out} - \text{humidity}_{in}) \cdot 2.427 \quad \text{eq 3}$$

where (humidity_{out} – humidity_{in}) was the absolute humidity difference across the chamber (g water·kg air^{-1}), and 2.427 is the latent heat of vaporization of sweat (kJ·kg sweat^{-1}) (76). Dry (radiative and conductive) heat loss per minute was calculated per minute by the following equation:

$$\text{Dry Heat Loss} = \text{massflow} \cdot (\text{temperature}_{out} - \text{temperature}_{in}) \cdot 1.005 \qquad \text{eq 4}$$

where ($\text{temperature}_{out} - \text{temperature}_{in}$) is the temperature difference across the chamber (°C), and 1.005 is the specific heat of air (kJ·(kg air·°C)$^{-1}$).

The cumulative change in heat storage over the 60 minutes of exercise was calculated from the following equation:

$$\Delta H_b = \int_{t=0}^{t_i} \left[\dot{M} - \left(\dot{R} + \dot{C} \right) - \dot{E} - \dot{W} \right] dt \qquad \text{eq 5}$$

where $\dot{M}$ = metabolic rate, $(\dot{R} + \dot{C})$ = rate of dry heat loss (radiation and conduction), $\dot{E}$ = rate evaporative heat loss, and $\dot{W}$ = rate of external work being performed.

Experimental Protocol

Subjects performed an incremental cycle ergometer $\dot{V}O_{2peak}$ test on the first day. The experimental trials were conducted at the same time on different days, separated by a minimum of 72 hours. Subjects were asked to refrain from exercise for 24 hours prior to the start of each trial. On each day, care was taken to avoid major thermal stimuli or a substantial increase in metabolic rate between awakening and the start of the experiment. Subjects were clothed in shorts, sports bra (women) and running shoes and were then instrumented appropriately. They then entered the calorimeter set at 30.00 ± 0.05°C, and began the 30-min baseline resting period in a semi-recumbent position. Subjects then cycled for 60 minutes on a semi-recumbent cycle ergometer at 70 W followed by 60 minutes of resting recovery in the semi-recumbent position.

Steady State Criteria

Steady state criteria was set based on the following (45, 74, 75): a) metabolic rate varied by no more than ± 3%; b) total heat loss varied by no more than ±3 %; c) rectal, esophageal and tympanic temperature varied by no more than ±0.1°C; and d) mean skin temperature varied by no more than ± 0.2°C . Time was determined based on minute-by-minute changes in temperatures or rate (for heat loss).

RESULTS

Heat load and heat loss response. Figure 1 shows heat loss response during the 60 minutes of exercise. At the onset of exercise, heat load significantly exceeded heat loss, resulting in a large net heat gain. There were 2 males subjects who did not reach steady state heat loss by the end of the 60 minutes. For all other subjects, rate of heat load stabilized quickly after the onset of exercise (within 5 minutes), while heat loss took significantly longer to reach steady state levels (36 ± 10). However, once steady state was reached, heat loss remained stable, regardless of changes in core or skin temperatures.

Core and skin temperature response: Refer to Table 1 and Figure 1. Resting esophageal, rectal and tympanic temperatures were 36.90 ± 0.14°C, 37.13 ± 0.18°C and 36.74 ± 0.32°C, respectively. By the end of exercise, esophageal, rectal and tympanic temperatures were 37.53 ± 0.50°C, 37.82 ± 0.43, and 37.10 ± 0.57°C. All core temperatures were greater at the end of exercise compared to rest. Baseline resting $\bar{T}_{sk}$ was 33.26 ± 0.95°C. Steady state skin temperature was reached at 30 minutes at 33.90 ± 0.25°C, after which it began to fall until termination of exercise for a final $\bar{T}_{sk}$ value of 33.84 ± 1.10°C.

Comparison of steady state times. Refer to Table 1 for specific results for each subject. Overall, heat loss stabilization occurred significantly earlier than rectal stabilization by 9.8 minutes. Esophageal, tympanic and skin temperatures stabilized at similar times (23.0 ± 6.7 and 22.6 ± 7.7 minutes, respectively), and were significantly earlier than both rectal and heat loss stabilization times at 45.3 ± 10.5 and 35.5 ± 9.7 minutes. Its important to note that the two subjects that did not reach steady state rate of heat loss did not reach steady state of rectal temperature, and one subject did not reach steady state for any core temperatures, but heat loss did steady state at 47 minutes.

DISCUSSION

Based on our observations, it was evident that rectal temperature was slowest to reach a steady state temperature, compared to the other temperature indices and total heat loss. The fast rise in metabolic heat production at the onset of exercise was followed by an increase in rate of whole-body heat loss, before there was any measured rise in any of the core temperature indices. If the set-point theory was correct, there would be no increase in the rate of heat loss until there was a rise in core temperature.

We observed that steady state for esophageal and tympanic temperatures was reached first at 23 minutes, after which rate of heat loss plateaued at ~10 and ~15 minutes later. This was expected, as esophageal and tympanic temperatures mirrored each other, and showed similar rates and overall levels of increase during exercise. This response has been observed before during exercise (27). Heat loss stabilized earlier than rectal temperature, indicating that there was heat transfer occurring within the body from warmer tissues to those in the abdominal region, but

overall net heat balance was zero. It would appear that body heat content and not a set-point temperature per se is the regulated variable which is consistent with the previous findings of Houdas (7, 34). Further investigation of the changes in tissue temperatures and change in the rate of heat transfer to the other compartments of the body is necessary to determine how the heat of the active muscle is distributed within and from the body. Webb et al (70) discussed the importance of considering the body to be multi-compartmental, and should be expressed solely as a core-shell model. They specifically mentioned the addition of muscle as the third compartment, which has the ability to store a large amount of heat due to its specific heat capacity of 3.639 $kJ \cdot (kg \cdot °C)^{-1}$. During exercise, the increased metabolic heat production causes heat to be stored within the muscle, but is eventually dissipated to the rest of the body over time. This indicates that rectal temperature is not the best indicator of steady state, and using another index of whole-body steady state, such as time to reach a rate of steady-state heat loss, is more accurate.

The results of this study were similar to that by Tikuisis (64), who found that during cold exposure by water immersion, heat balance was attained before rectal temperature stabilized. His subjects, after several hours, keep a constant shivering rate even though core temperature continued to drop. This supports our results which showed that a core-shell representation of body heat content is inadequate. He further suggested that heat was being transferred to a 'third compartment' consisting of fat, connective tissue, muscle and bone, between the core and skin. This further supports the proposal that the body controls net heat flux between the skin and environment, and not just the temperature of the deep tissues of the body.

In conclusion, the results of this study support the theory that the control mechanism for human thermoregulation is heat flux with the body and the environment, as opposed to

temperature being controlled by tissue, specifically deep core temperature. Further investigation into body heat regulation should focus on temperatures of numerous tissues of the body, including active and inactive muscle, along with sites of higher fat content.

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TABLE LEGEND

Table 1. Mean (±SD) and individual data for T_{es}, T_{re} and T_{typ} for resting temperature, final exercise temperature, and time to steady state for each temperature and rate of heat loss.

FIGURE LEGEND

Figure 1. Rate of heat loss (A), and esophageal (B), rectal (C), tympanic (D) and skin temperature (E) at rest (t = 0 minutes) and during the 60 minutes of exercise.

Table 1: Mean (±SD) and individual data for T_{es}, T_{re} and T_{typ} for resting temperature, final exercise temperature, and time to steady state for each temperature and rate of heat loss.

Subject #	T_{es} (rest) (°C)	T_{re} (rest) (°C)	T_{typ} (rest) (°C)	T_{es} (exercise) (°C)	T_{re} (exercise) (°C)	T_{typ} (exercise) (°C)	Esophageal Steady State (min)	Rectal Steady State (min)	Tympanic Steady State (min)	Rate of Heat Loss Steady State (min)
1	37.10	37.14	37.00	37.69	37.85	37.00	24	48	19	46
2	36.87	37.24	36.91	37.33	37.74	36.79	25	56	21	45
3	n/a	37.44	36.78	n/a	37.97	37.22	n/a	49	26	45
4	36.98	37.13	36.34	37.53	37.72	36.17	33	45	17	29
5	36.78	36.89	36.63	37.53	37.84	36.77	26	51	26	34
6	36.95	37.09	37.00	37.53	37.87	37.44	19	55	24	44
7	36.90	36.99	35.80	38.28	38.47	37.30	29	56	33	27
8	37.18	37.38	37.06	38.91	39.00	38.85	none	none	none	47
9	36.60	36.89	36.53	36.77	37.25	36.60	29	32	16	24
10	36.96	37.34	36.88	37.30	37.93	36.86	11	28	11	22
11	36.81	37.32	36.90	37.14	37.76	36.95	15	47	13	39
12	36.75	37.03	36.79	37.45	37.88	37.37	31	none	34	none
13	36.79	37.05	36.83	37.19	37.33	37.02	26	54	30	43
14	36.83	36.85	36.72	37.53	37.55	37.33	22	None	34	none
15	37.00	37.14	36.99	37.42	37.56	37.19	15	42	16	31
16	36.94	37.13	36.71	37.35	37.41	36.77	17	26	19	21
Mean	36.90	37.13	36.74	37.53	37.82	37.10*	23.0*†	45.3†	22.6	35.5*
SD	0.15	0.18	0.31	0.50	0.43	0.57	6.7	10.5	7.7	9.7

n/a - subject was unable to swallow an esophageal probe; none – no steady state was reached by the end of exercise;
*, significantly different from rectal steady state time, $p < 0.01$; †, significantly different from heat loss steady state time, $p < 0.05$.

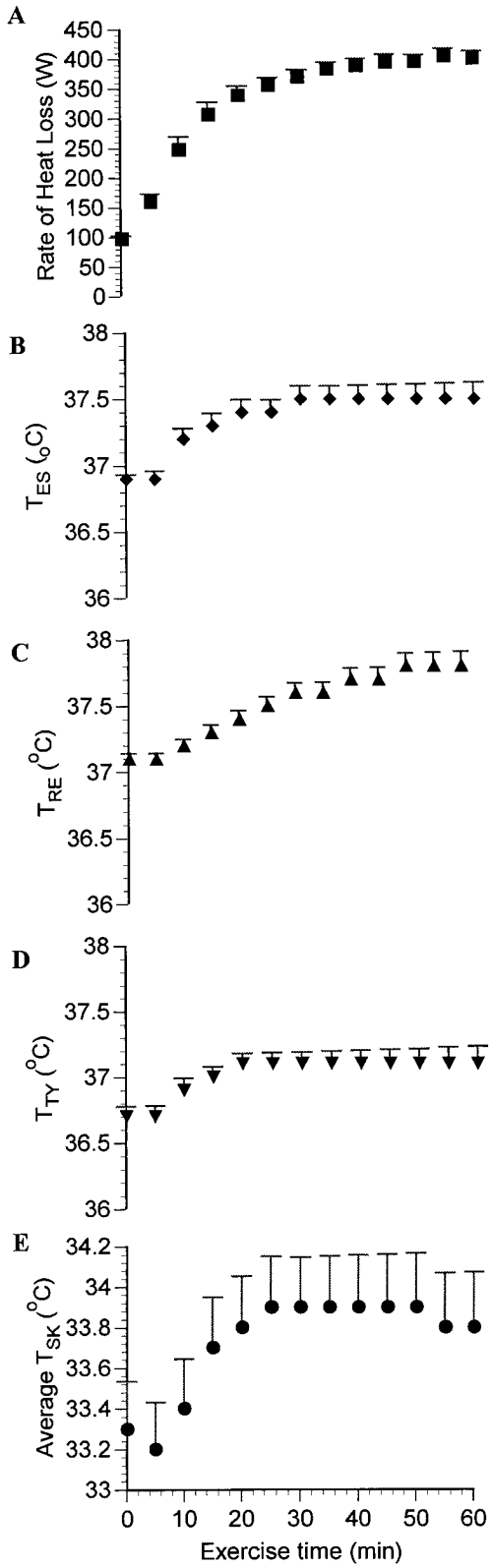

Figure 1: Rate of heat loss (A), and esophageal (B), rectal (C), tympanic (D) and skin temperature (E) at rest (t = 0 minutes) and during the 60 minutes of exercise.

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CHAPTER 5: DISCUSSION

For a given heat load on the body, there is a corresponding change in body heat content. Changes in body heat content can be measured directly using a calorimeter, or estimated by thermometric equations. Furthermore, the changes in body temperatures, such as core, skin and muscle, can be examined based on the change in heat content.

The first article compared the efficacy of conventional thermometry equations from Burton (9) to predict changes in body heat content and mean body temperature compared to measures by direct calorimetry. The results suggest that conventional thermometry significantly underestimated these changes. The use of a two-compartment model (skin and core temperature) was insufficient, and therefore a multi-compartment model was developed of core, skin and muscle. This allowed for more accurate estimation of changes in mean body temperature and body heat content.

The second study examined the thermometry "steady state" criteria during dynamic exercise. It is generally assumed that the body reaches a zero net heat balance once rectal temperature is stable. Based on our results, esophageal and tympanic temperature, plus rates of heat load and heat loss reached steady significantly earlier than rectal temperature, indicating that the body was in a whole-body state of thermal balance based on these measures. However, it is unknown what changes in temperature is occurring within active muscle, and it is possible that these may still be changing even though rectal temperature has reached steady state.

CHAPTER 6: CONCLUSIONS

The overall conclusion of this work was that when considering human thermoregulatory responses, one must consider changes in mean body temperature using a multi-compartmental model of core, skin and muscle as opposed to just core and skin.

The first study focused on the efficacy of thermometry to predict changes in body heat content. It was found that, when compared to measurement by direct calorimetry, changes in mean body temperature and body heat content was estimated to be significantly lower using thermometry. To improve the accuracy of thermometry, a new model to predict changes in body heat content was developed.

The second study showed that rectal temperature was the last indices to reach steady state compared to esophageal and tympanic temperature, and rate of heat loss and heat gain. Therefore, based on the data, whole-body thermal steady state is reached once rectal temperature has reached steady state.

CHAPTER 7: REFERENCES AND APPENDICES

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Appendix A – Trial Preparation Checklist

Calorimeter Trials Pre-Trial Checklist

Name:	Date:	Chamber Temperature:
Ergometer Setting:	Chamber Barometric Pressure:	Chamber Humidity:

Trial Set-up (minimum 8 hours before start of trial)

Task	*Initials when completed*
Ergometer console properly set up (terminal mode)	
Double check all wire and tubing connections: • Turbine • Sampling Line • Core body wires • MOXUS connections • Data acquisition system • camera and microphone • Wire hole through calorimeter wall is plugged and taped • Muscle implant wires and connections	
Check computer system to ensure temperature and fan speed is correct. Adjust as needed.	
Inside chamber: (try to keep clutter closer to the floor of the chamber) • Two or three pairs of nose-clips • One box of kleenex • One to two rolls of tape • Syringe for turbine calibration • Magazines, guest book, puzzle books	
Prepare the Trial Cart • heat flux discs untangled, organized and protected with double-stick discs • DRDC discs (3) and Paul Webb's insulating disks (2) connecting wires untangled and organized • muscle implant connection wires untangled and organized • Have headpiece / mouthpiece clean and ready for subject Trial cart should also contain (see checklist): • Head phones • cotton balls, • alcohol swabs (1 box), • skin preps (1 box), tape (>2 rolls), • razor, • double-stick discs (1 package), • non-latex gloves, • tensor bandages (2), • esophageal probes (2), • tympanic probe with Q-tip (1)	

2 Hours Before Start of Trial

Task	*Initials when completed*
• **Turn on Power Regulator and Mass flow measurement system** • **Turn on RH 1 / RH 2 Sampling Control Box and Computer Instrument** • **Turn on "Heater", "Pump" and "Dew/Front Control" on RH 1 / RH 2 Computer Instrument** • **Open data collection file on Mass flow and T/H station** • **Turn on electric blanket for MOXUS sampling line**	
Ensure time clocks on two monitoring computers are showing the same time	

While Subject is Having Muscle Probes Implanted

Task	*Initials when completed*
Calibration of MOXUS (gas), and **Calibration port turned OFF after calibration**	
Enter environmental information into MOXUS computer	
Open data collection file for skin and core temperature and ergometer readings	
Prepare for insertion of esophageal probe with thermos of warm water, and cup of cool water for participant	

Instrumentation

Task	*Initials when completed*
• **Turn off Power Regulator and Mass flow measurement system (record time)**	
Attach all instruments to subject: • Rectal, tympanic, esophageal sensors • 12 skin temperature/heat flux discs • DRDC discs nearby to muscle implantation sites • Paul Webb's Discs contralateral to muscle implantation sites	
Test core body (3) and muscle (3) temperature probes to ensure they work	
Attach HR monitor with watch (record start time)	
With subject, bring the following into the calorimeter: • Headpiece and mouth piece, moxus tubing, turbine, • Head phones • All temperature and heat flux wires • Reading material	
Have subject select 4 CD's or pick a radio station	
Adjust seat height according to subject	
Feed all wires (DRDC, Paul Webb's, and Skin discs) through hole, and cover hole	
Attach muscle implant connector wires and instruct subject how to check connections during the trial	
Clip in esophageal, rectal and tympanic probe wires	
Ensure that all data is being collected in lab view, check for faulty connections	
Calibrate turbine, using syringe	
Fit mask and head piece to subject and place head phones over top of head piece	

Calorimeter Trials Post-Trial Checklist

With Subject

Task	*Initials when completed*
Remove esophageal probe, mask and head piece as soon as possible	
Remove tympanic probe	
All surface instruments removed from subject	
Subject weighed, and skin folds taken	
Subject removes rectal probe	
All implanted muscle probes removed, procedure requires: • Non- latex gloves • Isopropryl (rubbing) alcohol • 4" x 4" gauze • 2" x 2" gauze • polysporin • surgical tape • Sharps container and biohazards discard container	

If not already scheduled, schedule participant's DEXA scan	
Fill out participant form for honorarium	

Don't forget to ask them if they would come back!

Once Subject has left:

Task	*Initials when completed*
All instruments returned to their proper location	
Chamber cleaned of garbage, apparatus cleaned with disinfectant	
Heat flux discs, DRDC discs, and Paul Webb's discs cleaned and untangled and placed back on cart for next trial	
Probes cleaned with alcohol swabs, placed in sterile-peel envelopes and sealed with indicator tape, number and muscle site indicated on envelope	
Packaged probes placed in autoclave for cleaning and sterilization (ensure water level is appropriate)	
All data files stored in proper computer files, backed up on data key	
HR monitor data downloaded and saved	
Clean turbine, see instructions	
Run macro on computer files	

Trial Cart Checklist

Equipment Required on Cart for Trial	*Initials when completed*
All heat flux discs untangled, organized and protected with double-stick discs • Lower back • Upper back • Chest • Forehead • Bicep • Hand • Forearm • Hamstring • Back calf • Front calf • Quadriceps • Abdomen	
All DRDC disc connection wires untangled and organized, with 2 DRDC discs (green) • Quadriceps • Triceps	
Paul Webb's insulating disks untangled and organized, with 3 tensor bandages and clips • Quadriceps • Triceps • trapezius	
All muscle implant connection wires untangled and organized • Quadriceps • Triceps • trapezius	
Esophageal probes (2) and tympanic probe (1) with Q-tip	
Cotton balls (1 bag)	
alcohol swabs (1 box)	

skin preps (1 box)	
Surgical tape (>2 rolls)	
Razor	
double-stick discs (1 package)	
non-latex gloves	
tensor bandages (3) with clips	
non-latex gloves (1 box)	
Have headpiece / mouthpiece ready for subject	
Have head phones ready for subject	

Equipment for Muscle Implantation Checklist

Equipment Required For Muscle Implantation Procedure	*Initials*
Portable Omega microprocessor thermometer	
Skin Preps (1 box)	
Razor (1)	
Surgical Tape (1 roll)	
Alcohol swabs	
PROBE PACK: •3 sterile muscle probes: Quadriceps, Trapezius, Triceps •Tegaderm (6 sheets minimum) •25 G x 1 1/2" needles (3) •25 G x 1 ¾" catheter (3)	
SPARE PROBE PACK: • spare sterile muscle probe • spare tegaderm (2 sheets minimum) • spare 18 G x 1 1/2" needles (2) • spare 18 G x 1 ¾" catheter (2)	

Calorimeter Preparation

Part #1

- Check computer system to ensure temperature and fan speed is correct. Adjust as needed.

Part #2

- Turn on Power Regulator and Massflow measurement system
- Turn on RH 1 / RH 2 Sampling Control Box and Computer Instrument
- Turn on "Heater", "Pump" and "Dew/Front Control" on RH 1 / RH 2 Computer Instrument
- Open data collection file on Massflow and T/H station
- Turn on electric blanket for MOXUS sampling line

Part #3

- Turn off Power Regulator and Massflow measurement system (record time)
- Open data collection file for skin and core temperature and ergometer readings

Appendix B – Ethics Approval

Insert ethics application here

Appendix C – Calibration Results

Appendix A: Non-Human Calibration Trials

The modified Snellen calorimeter located in the Laboratory of Human Bioenergetics and Exercise Physiology was calibrated through two systems.

1. Dry heat loss was calibrated by the use of a simple electrically heated dummy, which was constructed from flat heated wire that has a uniform temperature throughout its entire length. The wire was wrapped around plastic-coated chicken wire, and shaped to represent the size and dimensions of an average human. The dummy was supplied with constant levels of power that was measured with a wattmeter (+/- 0.1 % of reading), with an operating range from 0 – 650 W. The standard procedure was to operate the dummy throughout the range expected from a human being at rest and during intense exercise at different environmental temperatures (30 to 350 W). The dummy was designed such that the wire length proportions approximate the surface areas of each body segment, but altered slightly to represent rate of heat loss in each area, i.e.: there was a lower heat loss for the torso while higher for the head.

	Dubois area	Length of heater wire
Head and neck	7.0 %	13.0 %
Torso	35.0 %	26.7 %
Arms	19.0 %	20.0 %
Legs	39.0 %	40.0 %

The dummy was connected in series to a voltage transformer and a precision wattmeter.

In order to perform a calibration, the dummy was set up in the chamber, resting against the chair frame to represent the similar position of a human seated inside. The dummy was set at the desired wattage output, and the change in output temperature was measured and computed into a rate of dry heat loss (in watts) by the dummy. This computed value was compared to the output by the voltage transformer (displayed on the precision wattmeter). Since the dummy only emits dry heat, it was not necessary to measure evaporative heat loss.

In the following calibration, values from ~ 10 to 220 W were used to represent the rate of dry heat loss of a human at 30°C. Calibration results were based on the difference in results from that between the dummy output and calorimeter measurements. Results showed these values to match within reasonable limits when measured at 30°C at outputs of 30 to 100 W, which was within the values measured for humans during these trials.

2. Combined dry and evaporative heat loss was calibrated against each other by the use of a water-tray evaporation method, in which trays of identical surface area (~ 0.126 m^2) were covered with water, and the change in humidity and temperature were compared to each other. The development of this system was based on the first Law of Thermodynamics, which states that the total energy of the system plus the surroundings is constant, i.e.: energy can neither be created nor destroyed. In simplified terms, the Law states that the energy gained by the system to evaporate the water is equal to the energy loss by change in

temperature, and therefore the values for rate of dry heat loss and rate of evaporative heat gain should be equal to each other.

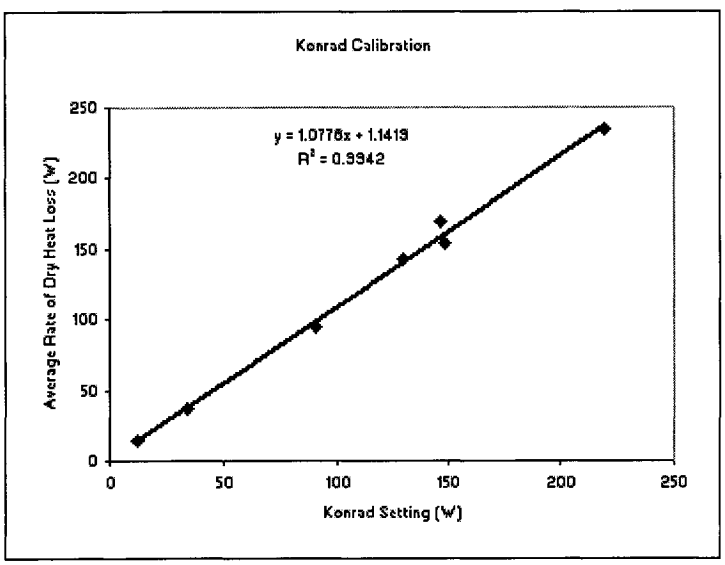
To perform a calibration, a parallel stack of ten trays was set inside the chamber in the same location as the subject would be seated. A set number of trays was covered in water, and the change in output temperature and humidity is computed as a rate of dry heat loss and evaporative heat gain.

In the following calibration, a set number of trays was covered with water. The rate of dry heat loss and evaporative heat gain for each number of trays is listed, showing the difference between dry heat loss and evaporative heat gain is $\pm$ 0.01 W.

Konrad Results

Date:	18-May-05
Chamber Temperature:	24.0
Chamber Relative Humidity:	32.0

Trial #	Konrad Setting (W)	Average Rate of Dry Heat Loss (W)	Standard Deviation of Rate of Dry Heat Loss (W)	Total Collection Time (min)
1	12.0	14.6	0.4	0:10:00
2	34.0	37.3	0.5	0:09:00
3	91.0	94.4	0.6	0:06:00
4	148.0	154.1	0.6	0:08:00
5	219.0	234.6	1.1	0:05:00
6	129.4	143.3	2.4	0:05:00
7	145.7	169.4	2.5	0:06:00



Water Trays Results - July 7 to July 21

Chamber Temperature:	30.0
Chamber Relative Humidity:	32.0

Number of Trays	Rate of Dry Heat Loss (W)	Rate of Latent Heat Gain (W)	Differential Rate (Dry + Latent)
1	-0.014	0.011	-0.003
2	-0.021	0.021	0.000
3	-0.032	0.032	0.000
5	-0.051	0.046	-0.005
7	-0.066	0.059	-0.007
10	-0.098	0.087	-0.011