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Assessment of Occupational Heat Strain

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by

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Dedication

This dissertation is dedicated to my dearest aunt, the late Ms. Bik-wan Tang - my "Auntie Bik." Her commitment to professionalism in her eminent acting career, her pursuit of excellence in every undertaking, and her philanthropic endeavors in promoting human welfare continue to inspire me and influence my daily life and work long after her passing.

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List of Abbreviations

%RH	relative humidity
ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	analysis of variance
AUC	area under curve
BMI	body mass index
BSA	body surface area
CI	confidence interval
CV	coefficient of variation
EKG	electrocardiogram
HR	heart rate
HR_{max}	maximum heart rate
HR_r	recovery heart rate
MTA	moving time average
MTA-5	moving time average at 5-minute intervals
MTA-10	moving time average at 10-minute intervals
MTA-20	moving time average at 20-minute intervals
MTA-30	moving time average at 30-minute intervals
MTA-45	moving time average at 45-minute intervals

NIOSH	National Institute for Occupational Safety and Health
OEL	occupational exposure limit
OSHA	Occupational Safety and Health Administration
PSI	physiological strain index
RER	respiratory exchange ratio
ROC	receiver operating characteristic
SD	standard deviation
T_d	disk temperature
T_{db}	dry bulb temperature
T_{ear}	ear canal temperature
T_{oral}	oral temperature
T_{qt}	QUESTemp° III temperature
T_{re}	rectal temperature
T_{skin}	skin temperature
TLV	Threshold Limit Value
V_{O_2}	oxygen consumption
WBGT	wet bulb globe temperature
WHO	World Health Organization

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ABSTRACT

Assessment of heat strain considers an individual's tolerance and indicates the risk and physiological cost of working in hot environments. This study evaluated the discrimination ability of metrics of heat strain. The null hypotheses were that (1) the metrics individually could not discriminate between acceptable and unacceptable heat strain, (2) there were no significant differences among these metrics, and (3) there were no significant differences in the applicability of the metrics due to clothing or heat stress level.

The experimental design was a case crossover. Clothing and heat stress level were potential confounders. Two clothing ensembles were work clothes and vapor-barrier coveralls with hood. Two heat stress levels for a moderate metabolic rate were 5°C-WBGT and 10°C-WBGT above the Threshold Limit Value adjusted for clothing. Eight male and four female acclimated individuals (age 18-36 years) participated. Four experimental trials were randomized in sequence. The transition point, when a participant's status changed from control (acceptable heat strain) to case (unacceptable), was the first occurrence of rectal temperature equal to or greater than 38.5°C, heart rate equal to or greater than 90% of maximum, or volitional fatigue. The metrics were rectal,

ear canal, oral, and disk temperatures, heart rate including moving time averages of 5, 10, 20, 30 and 45 minutes, recovery heart rate, and physiological strain index. The data at the transition point were the case data; the data 10 minutes prior to that point were the control data. Analyses used primarily receiver operating characteristic (ROC) curves, which indicated the ability to distinguish acceptable from unacceptable heat strain. Further analyses included factorial analysis of variance and exact conditional logistic regression.

Based on the ROC curve analyses, the physiological metrics can distinguish between acceptable and unacceptable heat strain with average area under the curves between 0.529 and 0.861. While there were no differences among the metrics based on the 95% confidence intervals of the areas under the curve, the results were compromised by low power. Based on ANOVA and logistic regression, clothing did not influence the metrics. There were insufficient data to evaluate the role of heat stress level.

Chapter One

Introduction

Workers are exposed to hot environments in many occupational settings. Examples include working outdoors in the summer, as in agriculture, or indoors in manufacturing operations, as in a foundry. In the United States in 2004, about 14 million workers were employed in manufacturing (Bureau of the Census, n.d.), the industry division with the highest number of heat-related injuries (Bureau of Labor Statistics, 2006a). In addition, when encapsulating clothing is worn to protect workers from hazardous substances, the suit microenvironment can be raised well above ambient conditions (Reneau & Bishop, 1996a), increasing the levels of heat exposure.

Heat Stress and Thermoregulation

Thermal Balance

Heat stress is the external heat load placed on the body due to the characteristics of the environment (Bishop, 1997), which includes climatic conditions, work demands, and clothing (Bernard, 2002; Brouha, 1960). This load must be balanced by a heat loss usually dominated by evaporative cooling. To maintain this balance in conditions of heat

stress, or to remain in what Lind (1963) called the prescriptive zone, the body's temperature is kept steady by adjustments of the thermoregulatory mechanism.

The body's thermoregulatory mechanism has two components: central and peripheral. The central component is the anterior hypothalamus (Astrand, Rodahl, Dahl, & Stromme, 2003; McArdle, Katch, & Katch, 2001). The hypothalamus may be activated in two ways. It is primarily stimulated by changes in the temperature of the blood perfusing the hypothalamus and it receives input from the thermal receptors in the skin. In either case, when the central control center is activated, it initiates responses to the heat stress. Heart rate and cardiac output increase while superficial arterial and venous blood vessels dilate (McArdle, Katch, & Katch, 2001). Vasoconstriction in the splanchnic and renal circulations allows blood to be diverted to the body shell. Increased cutaneous blood flow increases the thermal conductance of peripheral tissues. Depending on the air temperature and the average temperature of the solid surroundings relative to skin temperature, heat is gained or lost by convection and radiation. As the skin temperature increases, the peripheral component of the thermoregulatory mechanism is activated. Sweat glands are stimulated. The sweat rate increases so that the evaporation of sweat removes excess heat from the skin. The cooled peripheral blood flows back to the deeper tissues to absorb additional heat on its return to the heart.

In heat stress, the extra blood flow to the skin raises the skin temperature, heart rate, and cardiac output. Skin temperature may increase also due to a net heat gain from convection, radiation, or limited evaporative cooling, as when a person is wearing an encapsulating suit. As skin temperature increases and approaches core temperature, more blood must be delivered to the skin to achieve cooling.

For a given metabolic rate, the thermoregulatory mechanisms maintain a relatively constant core temperature for increasing levels of environmental heat until the upper limit of the prescriptive zone is reached (Lind, 1963). When the two defense mechanisms, heart rate and sweat rate, become inadequate, the core temperature rises steeply with increasing levels of environmental heat (Belding, 1976).

Compensable and Uncompensable Heat Stress

During compensable heat stress, the normal physiological responses result in enough heat dissipation to equal heat production. A new equilibrium in internal body temperature is obtained, which is within the physiological limits of the body and will not adversely affect the person's health or work performance. Once the heat stress is removed, the physiological parameters will gradually return to normal. On the other hand, during uncompensable heat stress, heat dissipation is less than heat production. The body continually stores heat. A rate of heat storage of about 40 W/m^2 is equivalent to an increase in mean body temperature of about 1°C per hour (Astrand, Rodahl, Dahl, & Stromme, 2003).

Occupational exposure limits (OELs), such as those recommended by the National Institute for Occupational Safety and Health (NIOSH, 1986) or the American Conference of Governmental Industrial Hygienists (ACGIH, 2006), are set at the boundary between compensable and uncompensable heat stress for the least heat tolerant people in the population. For exposures above the occupational limits, the population and individual risks increase. The increased risks are due to the loss of thermoregulatory balance and the excessive physiological strain that follows. The excessive strain leads to

heat disorders such as heat syncope, heat cramps, heat exhaustion, and heat stroke. Mental work capacity may also be reduced.

Occupational Exposure Limits (OELs) and Practice Guidelines

The Occupational Safety and Health Administration (OSHA) has not set a standard for heat stress requiring employers to control exposure in spite of the recommendations of the Standards Advisory Committee on Heat Stress more than 30 years ago (Ramsey, 1975; Wan, 2004). NIOSH and ACGIH have recommended practice guidelines. The NIOSH (1986) Recommended Exposure and Alert Limits are two graphical presentations, which depict the combined effects of environmental heat, represented by wet bulb globe temperature (WBGT), and metabolic heat for acclimated and unacclimated workers, respectively. The ACGIH (2006) threshold criteria for heat stress exposure are based on the WBGT index, with adjustments for work demands and clothing. ACGIH also recommends that exposure to heat stress should be stopped under certain conditions, for example, when the body core temperature of a healthy, acclimated worker is greater than 38.5°C.

The NIOSH and ACGIH guidelines are not upper tolerance limits for heat exposure for all workers, but rather levels at which hygiene practices and engineering and administrative controls should be implemented to reduce the risk of heat injuries. In many industrial settings where engineering controls are insufficient and administrative controls using pre-planned exposure times add considerably to labor costs and have complex scheduling and human resource problems, work above the OELs often occurs. For example, a study by Bird, MacIntosh, and Williams (2004) in coal-fueled power plants

found that 26% of the 1-hour time-weighted averages were exceeded for one or all of the recommended heat stress limits. In practice, the exposure is limited by self-determination; a person uses self-pacing or works until he or she cannot continue. This form of self-monitoring is unreliable. Workers frequently do not perceive the threat of overexposure until it is too late. A worker may be extremely motivated or may feel compelled to continue working despite symptoms of heat strain because he or she observes other workers continuing to work (Reneau & Bishop, 1996b). In private industry, exposure to environmental heat in 2004 has caused at least 18 fatalities (Bureau of Labor Statistics, 2006b) and 1,590 injuries (Bureau of Labor Statistics, 2006c). The actual incidence of heat-related disorders is likely to be higher because they may be mistakenly reported as heart attack or other illnesses. Even in the military, where mortality rates are generally lower than the civilian population, heat stress was found to be a primary or contributory cause in at least 33% of exercise-related deaths (Scoville, Gardner, Magill, Potter, & Kark, 2004).

The Rationale for Personal Monitoring

The assessment of heat stress is confined to workplace factors, such as environmental, work, and clothing effects. The only personal risk factor that is considered is acclimation state. The goal is to establish a threshold that will protect nearly all healthy workers from heat injury. Some workers may have heat intolerance problems even in mild conditions, where others may be much more heat tolerant. In the former case, monitoring the environmental conditions does not protect the worker. In the latter

case, early termination of work due to a threshold limit set to protect nearly all workers will reduce the productivity of the more heat-tolerant workers (Gun & Budd, 1995). Under-utilization of human resources is costly and in emergency response situations, it can have disastrous consequences. Brouha (1960) pointed out that workers similar in physical and acclimation condition and exposed to identical heat stress and work load could show a wide range of heat strain when their reactions were measured on the job, and that heat stress could vary during an 8-hour shift. Sometimes workers practice self-determination by adjusting their own work rate when they sense increased strain. This method of avoiding excessive strain is imprecise and insufficient to prevent heat-related disorders. Workers may not be proficient in sensing the status of their own heat storage (Ramsey, Bernard, & Dukes-Dobos, 1994). Excessive physiological strain often precedes overt symptoms (Bernard & Kenney, 1994). Personal monitoring makes objective information available to the worker and improves the reliability of decisions to terminate an exposure (Dukes-Dobos & Bernard, 1996). Protective and rehabilitative procedures can be instituted to reduce the heat strain when a particular worker's physiological responses reach a predetermined threshold. The decision to terminate work takes into account the actual physiological state of the individual.

Controlling exposure by the use of OELs decreases productivity due to repeated removal from the work environment for assessment or rest (Green, Clapp, Gu, & Bishop, 1999). Time lost due to this type of control may exceed productive work time. Because of the reduction in productivity, employers may not adhere to current recommendations. Continuous monitoring of individuals as they work would permit acceptable productivity while helping to ensure workers' safety. OSHA's Standards Advisory Committee on Heat

Stress recommended that actual physiological response to the job should be considered important in assessment of the individual's heat tolerance (Ramsey, 1975). The recommendations of ACGIH allow for physiological monitoring during heat stress exposures above the OELs to demonstrate effective management of the exposure. Personal monitoring, along with self-determination, allows more heat-tolerant workers to work longer than less heat-tolerant workers. It enhances both productivity and worker safety.

When exposure assessments are made, the measurement is an index of exposure that is related to the dose through empirical evidence or rational models. It provides no information about the safety of the exposure or the extent to which a person can adjust to the thermal load, which is largely explained by personal risk factors (ACGIH, 2001). On the contrary, personal monitoring assesses directly the heat strain, that is, the body's responses to heat stress. This method of assessment considers an individual’s tolerance and provides a clearer picture of the risk and physiological cost of working in hot environments.

Researchers have recommended objective measurement and monitoring of physiological parameters (Bernard & Kenney, 1994; Brouha, 1960; Fuller & Smith, 1981). Personal monitors have been developed to gather data on heat strain from surrogates of core temperature and heart rate. They can provide alert thresholds and averages in real-time. The alert thresholds give useful information to the worker and ensure that safety limits are not exceeded. The records of peak demands and overall trends are available for further evaluation. These methods allow feedback to the worker, individualized protection from heat stress, and optimization of safe work time. Their

effectiveness in heat stress management must be evaluated. The sensitivity and specificity should be examined. One of the most common techniques for examining sensitivity and specificity is the receiver operating characteristic (ROC) curve, along with the area under the curve (AUC) statistic.

Chapter Two

Literature Review

Recognizing that heat stress exposure assessment is protective and that many exposures occur above the OELs, the assessment of heat strain is recommended as an alternative method of evaluation.

Metrics of Heat Strain

Core Temperature and Surrogates

Internal body temperature is the best single gauge of heat strain (Bishop, 1997). It is indicative of the total heat content of the body. It provides a reproducible index to estimate the percentage of a population that will incur exhaustion from heat strain during uncompensable heat stress (Sawka et al., 2001). The World Health Organization (WHO, 1969) considered it inadvisable for the deep body temperature to exceed 38°C for prolonged daily exposure while transient core temperatures above 39.0°C are acceptable. In its criteria document, NIOSH (1986) also stated that deep body temperatures above 38°C were undesirable for an average industrial workforce. Its review of scientific data and industry experiences showed that the risk of heat-exhaustion collapse was about 25% at a deep body temperature of 39.2°C associated with a skin temperature of 38°C. A

value of 38.5°C for body core temperature is suggested by ACGIH (2006) for the evaluation of heat strain.

During exposure to heat, the increase or decline in the estimated temperature in the hypothalamus and rectal temperature (T_{re}) is of the same magnitude; therefore, T_{re} mirrors the core temperature and reflects body heat gain or loss (Astrand, Rodahl, Dahl, & Stromme, 2003). Because of its longer history as a laboratory measure, T_{re} is used as the standard and all other measures of core temperature are judged by how well they predict T_{re} (Bernard & Kenney, 1994). Since the measurement of T_{re} is invasive and unsuitable for use in the field, surrogates of core temperature are used. They include oral, ear canal, and disk temperatures.

Oral temperature (T_{oral}). Studying the T_{re} and T_{oral} of 16 men and 38 women, Horvath, Menduke, and Piersol (1950), noted a possible correlation between the absolute value of T_{re} and the difference between T_{re} and T_{oral}, although they did not fully analyze the precise nature of this relation. They also found that in any specific person there was no single constant rectal-oral temperature difference. T_{oral} may be affected by thermal exchange occurring between arteries and veins in the cervical and cephalic regions (McCaffrey, McCook, & Wurster, 1975). Strydom et al. (1965) observed a difference of 0.65°C between T_{re} and T_{oral}. Mairiaux, Sagot, and Candas (1983) found a difference of 0.33°C. The current consensus is that T_{oral} is a good indicator of the cumulative effects of heat stress (Logan & Bernard, 1999; Moran & Mendal, 2002; Stephenson, Colwell, & Dinman, 1974) and a common practice is to treat T_{oral} as about 0.5°C lower than core temperature. Since OELs are set at a T_{re} of 38.5°C, a T_{oral} below 38.0°C is acceptable in a closely monitored situation with acclimated workers (ACGIH, 2001; NIOSH, 1986).

Electronic and disposable thermometers that measure T_{oral} have sufficient accuracy and reliability. To obtain an accurate reading, a person cannot smoke or have anything hot or cold to eat or drink for 15 minutes prior to the measurement and must keep the mouth closed during the measurement to prevent evaporative cooling inside the mouth (Beaird, Bauman, & Leeper, 1996; Moran & Mendal, 2002; Terndrup, Allegra, & Kealy, 1989). The thermometer must be correctly placed under the tongue.

Ear canal temperature (T_{ear}). The literature has reported the validity of mean T_{ear} as a stable measure of mean core temperature (Ishii et al., 1993). A correct reading of the T_{ear} may actually reflect brain temperature and may be more important than T_{re} (Knochel, 1996). Belding and Kamon (1973) found that T_{ear} was consistently read at a level 0.5°C to 0.6°C below T_{re}. The environmental effects on the head may play a role in the ability of T_{ear} to map against T_{re}. Morgans, Nunneley, and Stribley (1981) observed environmental influences on T_{ear} that were high unless there was appropriate insulation. Muir, Bishop, Lomax, and Green (2001) used a well-insulated ear thermistor and achieved reasonable accuracy in predicting T_{re} from T_{ear}.

To measure T_{ear} accurately, a thermistor or other type of temperature sensor is placed near the eardrum and packed with a foam earplug or a similar device that can serve as insulation from the influence of environmental conditions. Vapor-barrier coveralls with hood create a microenvironment that is largely isolated from the ambient environment, reducing the error in predicting core temperature from T_{ear} (Muir, Bishop, Lomax, & Green, 2001).

Disk temperature (T_d). To overcome the influence of environmental conditions on the surface of the skin, Bernard and Kenney (1994) proposed an insulated skin

temperature (T_{skin}), called disk temperature (T_d). The device consisted of a thermally conducting disk 2.5 cm in diameter, covered by an insulator 4.2 cm in diameter and 0.8 cm thick. This method does not directly measure core temperature at the skin. Rather, it is a substitute measure to predict excessive T_{re}. For an individual, the T_d increases without a change in T_{re} in the first 10 to 15 minutes, and then there is a linear relationship. The authors found that the relationship of T_{re} to T_d over a range of participants was not the same for different clothing ensembles. The relationship is expressed in the two equations below:

$$\text{Single-layer clothing} \quad T_{re} = 20.2 + 0.47\ T_d \tag{1}$$

$$\text{Vapor-barrier clothing} \quad T_{re} = 13.2 + 0.65\ T_d \tag{2}$$

Skin Temperature (T_{skin})

T_{skin} is monitored using small sensors attached to the skin at various places. To assess average T_{skin}, a weighting across several sites is applied (Parsons, 1993). Investigators have used different methods and formulas for measuring average T_{skin}. Ramanathan (1964) used the following equation, where T is the temperature and the subscripts refer to the sites of measurement:

$$T_{skin} = 0.3\ T_{chest} + 0.3\ T_{arm} + 0.2\ T_{thigh} + 0.2\ T_{calf} \tag{3}$$

According to Shoenfeld, Udassin, Shapiro, Ohri, and Sohar (1978), 75% of T_{skin} change occurs during the first 10 minutes of heat exposure and 75% to 100% during the first 20 minutes. Although T_{skin} is more uniform in hot environments, it is largely influenced by environmental conditions and clothing. It is a direct response to changes in microenvironment temperature when impermeable protective clothing is worn, as the

microenvironment is the only environment to which the body can react (Muir, Bishop, and Kozusko, 2001).

Heart Rate (HR)

HR reflects the demands of the circulatory system and is an immediate effector of the vasomotor response to environmental and metabolic conditions (Moran, Shitzer, & Pandolf, 1998). The cardiovascular response to work and heat stress is marked by a redistribution of blood to the working muscles and to the skin in proportion to the need. Cardiac output will increase to meet the metabolic demands of the working muscles.

HR is an accessible and reliable index of cardiac output for a healthy person doing work under conditions of heat stress. In stable conditions of work and heat, changes in HR closely reflect changes in T_{re}, making HR a useful index of physiological strain (Bishop, 1997; WHO, 1969). The elevation in HR due to heat stress reflects the chronotropic compensation for decreasing venous return and has an underlying physiological validity as a safety feature (Bernard & Kenney, 1994). HR will respond to heat stress with a lag time of seconds only (Fuller & Smith, 1981). Smith, Bishop, Beaird, Ray, and Smith (1994) measured a wide range of personal and job variables associated with heat stress, including maximum voluntary ventilation, T_{re}, HR, and oxygen consumption (VO_2). HR was the only variable that significantly increased with increased heat exposure. Boisvert, Nakamura, Shimai, Candas, and Tanaka (1993) observed that the HR drift during exercise was closely related to the rise in body temperature and, particularly in humid conditions, the greater HR probably paralleled the increase in cardiac output necessary to supply increased skin circulation. On the other hand, HR

depends on the type of work, physical fitness, and disease state of the individual, and can be confounded by medications (Bernard & Kenney, 1994).

HR monitors are commercially available. They can measure and record HR and be programmed for a high threshold alert. With industrial work, there may be transient increases in HR associated with temporary peaks above the threshold, for instance, while walking up stairs or lifting a heavy object. These temporary peaks above the threshold are not physiologically significant and represent a false positive alarm. Conversely, setting a static high threshold may miss sustained HRs just below the threshold that may represent significant physiological strain if maintained for a sufficiently long time. Some HR monitors have a data-logging function. With this feature, the average HR over the course of a workday can be used as an indicator of overall demand. Minard, Goldsmith, Farrier, and Lambiotte (1971) reported a residual loss of aerobic capacity at the end of a shift for workers who had an average HR greater than 120 bpm. This level represents the average HR of someone who would work at one-third of his or her aerobic capacity, which is the generally accepted metabolic limit for work (Kenney et al., 1988; Rodgers, 1976). HR moving time average (MTA) thresholds avoid the problems of a static threshold (Bernard & Kenney, 1994).

Another indicator of physiological strain is recovery heart rate (HR_r). It looks to a pattern of HR immediately after a bout of work. Brouha (1960) first pointed out the value of examining HRs at the end of work and for the following three minutes at 1-minute intervals. Fuller and Smith (1981) refined this method by using 30-second pulse counts multiplied by two. NIOSH (1985) suggested an application of a 1-minute HR_r for hazardous waste sites. Logan and Bernard (1999) used the HR_r at one minute to make

judgments about heat strain in aluminum smelters. A value less than 110 bpm indicated low heat strain; a value greater than 120 bpm pointed to actual or impending excessive heat strain (Bernard, Dukes-Dobos, & Ramsey, 1994).

Physiological Strain Index (PSI)

Moran, Shitzer, and Pandolf (1998) proposed a PSI to incorporate T_{re} and HR to depict the combined strain of the thermoregulatory and cardiovascular systems. The PSI is represented by the following equation:

$$PSI = 5(T_{re} - 36.5) / (39.5 - 36.5) + 5(HR - 60) / (180 - 60), \quad (4)$$

where T_{re} and HR are measurements made at any time, 36.5°C and 60 bpm are baseline reference values for T_{re} and HR, respectively, and 39.5°C and 180 bpm represent the maximum rise of T_{re} and HR, respectively. The T_{re} of 39.5°C is a value consistent with military exposures, which is the background of the investigators. The rise in HR is derived from the threshold of 180 bpm for safe exposure in research (Moran, Kenney, Pierzga, & Pandolf, 2002). The index has a nominal range of 0 to 10, with 0 being representative of no strain and 10 indicative of very high strain. The mean age of the participants in the original study was 20 years. The index has been validated for men and women of various ages under several conditions (Moran, Kenney, Pierzga, & Pandolf, 2002; Moran, Montain, & Pandolf, 1998; Moran, Shapiro, Laor, Izraeli, & Pandolf, 1999).

Instrumentation

Instruments and personal monitors to measure the above metrics are available. Some of them are designed to provide an alert when a pre-set threshold is reached. Their sensitivity and specificity have not been adequately described in the literature. Laboratory evaluations of two devices have shown that they may not be as predictive of excessive physiological strain as designed. Reneau and Bishop (1996b) tested the validity of the Metrosonics hs-3800 personal heat strain monitor in predicting T_{re}. They found that the sensitivity and specificity were low. Green, Clapp, Gu, and Bishop (1999) evaluated the QUESTemp II Personal Heat Stress Monitor, which used an insulated T_{ear}, and concluded that the design of the earplug and probe of the instrument did not eliminate effectively ambient influence on T_{ear} measures. They attributed the poor correlations between QUESTemp II and T_{re} to errors resulting from ambient influence. In that study, sensitivity and specificity analyses were not possible due to an insufficient number of T_{re} observations showing significant physiological strain. Further evaluation of these metrics is needed to elucidate their usefulness in real-time self-determination, in surveillance, and in epidemiological studies.

Objectives of the Study

Personal monitoring provides information on heat strain to help individual workers in self-determination and self-pacing when working under conditions of heat stress. The metrics designed for this purpose have not been evaluated with respect to their

ability to discriminate between acceptable and unacceptable heat strain. The specific aim of this study was to evaluate the discrimination ability of metrics for the assessment of heat strain, using ROC curves and their related AUC statistics. Evaluation conditions were two levels of heat stress in two clothing ensembles at a moderate rate of work.

Hypotheses

The null hypotheses were as follows:

1. The metrics individually could not discriminate between acceptable and unacceptable heat strain.
2. There were no significant differences among these metrics.
3. There were no significant differences in the applicability of the metrics due to clothing or heat stress level.

Chapter Three

Methods

Experimental Design

This study was a matched case control study, specifically a case crossover design. The status of a participant within a trial changed from control to case when the heat strain went from acceptable to unacceptable. The data analyses used this control/case status as the dependent, or outcome, variable. Since clothing and heat stress levels might affect the outcome, they were treated as confounders controlled for in the experimental design. The clothing ensembles were cotton work clothes and vapor-barrier coveralls with hood. Both clothing configurations represented those commonly worn in various types of work. Two heat stress levels were set at 5°C-WBGT and 10°C-WBGT, respectively, above the Threshold Limit Value (TLV) recommended by ACGIH (2006), so that transition from acceptable to unacceptable heat strain was expected. Combinations of the two heat stress levels and two clothing configurations resulted in four experimental conditions. Each participant completed the four trials in a balanced design.

Participants

Eight male and four female healthy participants were recruited through an advertisement disseminated in the local community (Appendix A). Informed consent was obtained in accordance with the approval by the Institutional Review Board of the University of South Florida (Appendix B).

Before taking part in this study, a potential participant was examined by a physician. The physician obtained the person's medical history and assessed his or her current state of health before deciding if the person should participate according to the inclusion and exclusion criteria. Potential participants were excluded if they reported one of these diagnosed conditions: hypertension, cardiovascular disease, renal pathology, diabetes, muscular or skeletal injuries, or previous incidence of heat injury. These pathological conditions were known to affect a person's thermoregulatory and cardiovascular responses to heat stress. In addition, the physician might exclude a potential participant based on history and physical examination, if the physician believed that an undiagnosed disease was present and that it would interfere with the person's ability to tolerate heat stress.

Under the supervision of the examining physician, the investigators took a resting electrocardiogram (EKG) of the participant and conducted a graded exercise stress test to exhaustion to determine the person's maximum V_{O_2} and maximum heart rate (HR_{max}) using the Bruce protocol (Bruce, 1971; Bruce, Blackmon, Jones, & Strait, 1963; Bruce & McDonough, 1969). The HR_{max} was used to compute the HR at the transition point and end point (see the sections Transition Points and End Points). A valid maximum V_{O_2} was

accepted when at least two of the following criteria were met: (a) a plateau in V_{O_2} with increasing work rate, (b) HR within 10 bpm of age-predicted maximum, that is, 220 minus age, and (c) a respiratory exchange ratio (RER) at maximum exercise of more than 1.10.

When the potential participant was a woman, she was asked to perform a home pregnancy test and to report the results to the principal investigator. A woman who was pregnant or attempting to become pregnant would be excluded.

All potential participants tested qualified. Each was given written instructions (Appendix C). Briefly, he or she was asked to report to the laboratory well rested and hydrated at every subsequent session, to refrain from strenuous exercise or drinking caffeinated or alcoholic beverages within 12 hours prior to a session, and to wear adequate athletic shoes, shorts, tee-shirt or, for a woman, a sports bra or halter top. The instructions also described the proper insertion and cleaning of the T_{re} probe and insertion of the sensor for measuring T_{ear}. Each participant was paid a stipend of $35 per session, including the session of physical examination.

Equipment

The experiments were conducted in a Model 7010 climatic chamber designed by Forma Scientific, Inc., Marietta, Ohio. The internal dimensions were 2.7 m wide, 3.0 m deep, and 2.2 m high. The air speed was 0.5 m/s. The environmental conditions inside the chamber were measured with a QUESTemp° 34 Thermal Environment Monitor (Quest Technologies, Oconomowoc, Wisconsin). A ClubTrack (StairMaster, Kirkland,

Washington) or a PaceMaster Pro-Plus (Aerobics Inc., West Caldwell, New Jersey) motorized treadmill was used for the exercises. Metabolic rate was controlled through settings of speed and slope.

Design and Procedures

For each participant, the sessions were carried out on consecutive days as far as possible. In no case were more than two days skipped between two consecutive sessions. The instruments were calibrated and used following the laboratory's standard procedures or according to the manufacturers' instructions. After each use, the instruments were cleaned with alcohol pads or bleach solution as appropriate. Appendices D and E are the standardized procedures used for acclimation and experimental trials, respectively.

Acclimation

The first five sessions comprised the acclimation period, to allow the participant to adapt to working in hot environments. The environmental conditions were set at dry bulb temperature (T_{db}) of 40°C and relative humidity (%RH) of 30%.

At the beginning of each session, a participant was asked to insert a T_{re} probe (model 401AC, YSI Precision Temperature Group, Dayton, Ohio) 10 cm beyond the anal sphincter. The wire of the rectal probe was taped to the participant's buttock to prevent the probe from being pulled out during the session. The participant's pre-trial semi-nude weight was taken, with the participant wearing athletic shoes, shorts, and a tee-shirt or sports bra or halter top. Then the participant was dressed with work clothes, which

consisted of a cotton long-sleeve shirt (4 oz/yd^2) and a pair of khaki pants (8 oz/yd^2). The transmitter of an HR monitor (Polar USA, Lake Success, New York) was secured with a chest strap. The participant's pre-trial clothed weight was taken.

The participant underwent two 50-minute work bouts of treadmill walking at about 300 W, separated by 10 minutes of rest. The metabolic rate was established from assessment of VO_2. An automatic metabolic assessment system (model 17670, Vacu-Med, Ventura, California) or a Douglas bag was used. To improve accuracy, three samples were taken at approximately 30, 65, and 90 minutes to compute the average metabolic rate. T_{re}, HR, T_{db}, and %RH were recorded every five minutes except at 55 minutes, which was in the middle of the rest period. The participant was provided with cool water or Gatorade according to preference and encouraged to drink as often and as much as comfortable. The amount of fluid intake during each hour was recorded.

The session was stopped before the lapse of a total of 110 minutes if one of the safety criteria was reached:

- T_{re} equals to or greater than 39.0°C.
- HR equals to or greater than 95% of HR_{max}.
- Volitional fatigue (an expressed, unsolicited desire of the participant to stop the trial).

Immediately after the session, the participant's post-trial clothed weight was obtained. The work clothes and HR transmitter were removed. The participant's post-trial semi-nude weight was obtained. The work clothes were laundered after each use.

Experimental Trials

After the acclimation sessions, four experimental trials were carried out for each participant wearing two types of clothing ensembles in two environmental conditions. The metabolic demand was set at a moderate level normalized to body surface area (BSA) of 150 W/m^2. BSA was calculated using the Du Bois and Du Bois equation (1916):

$$\text{BSA in } m^2 = W^{0.425} \times H^{0.725} \times 0.007184, \quad (5)$$

where W is the body weight in kg and H is the height in cm.

Clothing ensembles. The clothing ensembles were cotton work clothes and Tychem QC 35127 vapor-barrier coveralls (E. I. du Pont de Nemours and Company, Wilmington, Delaware). The cotton work clothes were the same as worn during acclimation. The coveralls were made of polyethylene-coated Tyvek and had an attached hood, a front zipper closure, elastic wrists, elastic ankles, and sewn seams. They were disposable for one-time use only.

Environmental conditions. Two heat stress levels characterized by environments and adjusted for clothing were set, with a fixed %RH of 50%, at 5°C-WBGT and 10°C-WBGT, respectively, above the TLV recommended by ACGIH (2006). Since the participants were acclimated and worked 100% of the time at a moderate metabolic rate during the experimental trials, the applicable TLV was 27.5°C-WBGT.

WBGT clothing adjustments. Paull and Rosenthal (1987) suggested a clothing adjustment of 10°C-WBGT for vapor-barrier ensemble. This adjustment factor may be high for lighter or thinner fabrics (Bernard, Dukes-Dobos, & Ramsey, 1994) or ambient temperatures above 18°C-WBGT (Muir, Bishop, & Kozusko, 2001). Bernard, Luecke,

Schwartz, Kirkland, and Ashley (2005) determined that the clothing adjustment at %RH of 50% for Tychem QC coveralls without a hood was 7.8°C-WBGT. Making allowance for a configuration with a hood, in the current study a clothing adjustment of 8.5°C-WBGT was used for the Tychem QC ensemble. In other words, the target for the cotton work clothes were 32.5°C-WBGT and 37.5°C-WBGT and the target for the vapor-barrier coveralls were 24.0°C-WBGT and 29.0°C-WBGT.

Procedures. Each participant completed all combinations of clothing ensembles and environmental conditions. One exception was the last participant, who completed one combination of clothing ensemble and environmental condition. A Latin Square randomization sequence was used to balance the combinations of clothing ensembles and environmental conditions.

The same instrumentation was fitted on the participant as for acclimation. In addition, the following instruments were used:

1. The sensor of a QUESTemp° II Personal Heat Stress Monitor (Quest Technologies, Oconomowoc, Wisconsin) was inserted into the left ear and the related monitor was attached to a web belt worn by the participant at the waist.
2. A QUESTemp° III Personal Heat Stress Monitor sensor belt assembly (Quest Technologies, Oconomowoc, Wisconsin) was attached to the participant's chest and the monitor was attached to the web belt.
3. A Mio Ultimate HR monitor (Physi-Cal Enterprises Inc., Blaine, Washington) was worn by the participant on the left wrist to measure HR_r.

Before walking on the treadmill, the participant sat on a chair for 15 minutes in the climatic chamber at the environmental conditions for the trial. This waiting period allowed the instruments to reach equilibrium for accurate reading. At the end of 15 minutes, baseline measurements were recorded and the exercise began. The treadmill grade was set at 0% and the speed was computed to achieve a moderate metabolic rate normalized to BSA (150 W/m^2). Every 15 minutes, the exercise was paused for two minutes to record T_{oral} and HR_r at one minute. The participant was encouraged to drink cool water or Gatorade during every pause, after the T_{oral} was taken.

Measured Variables

The following data were measured at 5-minute intervals and at the transition point (see below):

- T_{re}.
- HR.
- T_{ear}.
- Disk temperature, converted by the QUESTemp° III to "core temperature" (T_{qt}).

The participant's T_{oral} and HR_r at one minute were recorded every 15 minutes. T_{oral} was taken using a Tempa-DOT™ disposable thermometer (3M, St. Paul, Minnesota).

Transition Points

Within a trial, the transition point marked the change in physiological state from acceptable to high. A participant's status changed from being a control to being a case at the first occurrence of any one of the following conditions:

- T_{re} equals to or greater than 38.5°C.
- HR equals to or greater than 90% of HR_{max}.
- Volitional fatigue.

These criteria were selected because they would allow a participant or a worker in the field to safely exit from the hot environment. The time it took a participant during each trial to reach a transition point was recorded.

End Points

After the transition point, body temperature and HR were allowed to rise until one of the safety criteria was reached, at which time the trial would be stopped:

- T_{re} equals to or greater than 39.0°C.
- HR equals to or greater than 95% of HR_{max}.
- Volitional fatigue.

An upper limit of 120 minutes was set as the maximum time for a trial.

Data Analyses

It was found that regardless of the type of clothing, few of the trials at the lower heat stress level (32.5°C-WBGT for work clothes or 24.0°C-WBGT for vapor-barrier coveralls) reached a transition point. In other words, the participants did not appear to experience unacceptable heat strain. For this reason, the analyses used only data from the higher heat stress level (37.5°C-WBGT for work clothes or 29.0°C-WBGT for vapor-barrier coveralls).

A window of 10 minutes was taken for each trial. The transition point marked the end of the window. Ten minutes before that was the pre-transition point.

Data at the pre-transition point and transition point were tabulated. The following derived variables were calculated:

1. The PSI was computed according to Equation (4) (Moran, Shitzer, & Pandolf, 1998).
2. MTAs of HR were calculated for 5-, 10-, 20-, 30-, and 45-minute intervals.

The data were analyzed using statistical analysis software SAS version 9.1 (SAS Institute Inc., Cary, North Carolina), S-PLUS 7 (Insightful Corporation, Seattle, Washington), and Microsoft Excel 2000 (Microsoft Corporation, Redmond, Washington). For all hypothesis testing, the significance level was set at 0.05 ($\alpha = 0.05$).

Univariate analyses were conducted to obtain descriptive statistics for participant characteristics and measured and derived variables. A factorial analysis of variance (ANOVA) with repeated measures was used to determine if significant difference existed

between the values of each variable at the pre-transition and transition points, and to examine if the type of clothing had any significant effect.

An exact conditional logistic regression was carried out, conditioning on the variable subject. The dependent variable was the presence or absence of a high physiological strain state. The independent variables were clothing and each measured and derived variable.

A statistical procedure was used to plot ROC curves for each measured and derived variable and to compute the AUC and the 95% confidence interval (CI) (Y. Wu, personal communication, June 30, 2006). In constructing an ROC curve for each metric using the control and case data, cutpoints for predicting control or case status were varied from very low to very high. At each cutpoint, the sensitivity and specificity were calculated by comparing the "positives" and "negatives" with the established standard, which was one of the three transition criteria. "Positives" were classified as true positives if they would have been classified as positives using the established standard, otherwise they would be false positives. "Negatives" were classified into true negatives and false negatives in a similar manner. Consequently, the sensitivity would be low and specificity would be high at a very low cutpoint, and vice versa at a very high cutpoint. Sensitivity was plotted on the y-axis and (1 - specificity) was plotted on the x-axis to obtain the ROC curve. The area under the ROC curve was calculated. The 95% CI was obtained using the jackknife procedure, a statistical method for estimating standard errors and CIs by systematically dropping out subsets of data one at a time and assessing the resulting variation.

Chapter Four

Results

Participant characteristics are presented in Table 1 as mean and standard deviation. The individual values are provided in Appendix F.

Table 1

Participant Characteristics as Mean and Standard Deviation (SD)

Category	n	Statistic	Age (yrs)	Weight (kg)	Height (cm)	BSA (m^2)	BMI[a] (kg/m^2)	Maximum VO_2 (L/min)	Maximum VO_2 (ml/kg/min)	HR_{max} (bpm)
Men	8	Mean	26.0	73.6	176.3	1.9	23.5	2.7	37.0	190
		SD	6.5	18.4	5.3	0.2	4.7	0.6	4.2	9
Women	4	Mean	25.5	64.0	157.2	1.6	25.6	2.1	31.6	189
		SD	5.8	13.1	13.2	0.2	1.4	0.8	6.4	6
All	12	Mean	25.8	70.4	169.9	1.8	24.2	2.5	35.2	189
		SD	6.0	16.9	12.4	0.3	3.9	0.7	5.4	8

[a]BMI = body mass index = W / H^2, where W is the weight in kg and H is the height in m (Quetelet, 1842/1968).

The transition point was identified as the time when one of three criteria for excessive heat strain was met. It represented the point at which the participant changed status from control to case. Table 2 is the distribution of reasons for the transition by clothing ensemble.

Table 2

Distribution of Reasons for the Transition by Clothing Ensemble

Clothing	$T_{re} \geq 38.5°C$	$HR \geq 90\%\ HR_{max}$	Volitional Fatigue
Work Clothes	6	2	3
Vapor-barrier	8	1	3

More than 60% of the transitions were due to T_{re} reaching 38.5°C and another 13% were due to HR reaching 90% of HR_{max}. Volitional fatigue accounted for 26%. If self-determination were based on subjective judgment, about 74% of the time a person might be continuing to work while experiencing unacceptable heat strain.

The pre-transition point was defined as the physiological state 10 minutes prior to the transition point. Univariate analyses were carried out for each of the measured and derived variables. Table 3 presents the mean, standard deviation, and coefficients of variation (CV) of these variables at the pre-transition and transition points. The CVs were about 1% for the temperatures and about 10-15% for the other metrics. Appendix G has the pre-transition values for individual participants and Appendix H has the transition values.

Table 3

Measured and Derived Variables as Mean and Standard Deviation (SD) with Coefficient of Variation (CV) Expressed as a Percentage at Pre-transition (Pre) and Transition (Trans) Points for Each Clothing Ensemble

Metric		Statistic	Work Clothes		Vapor-barrier		Both	
			Pre	Trans	Pre	Trans	Pre	Trans
T_{re}	(°C)	Mean	38.2	38.3	38.3	38.4	38.2	38.4
		SD	0.2	0.4	0.1	0.1	0.2	0.3
		CV	0.5	1.0	0.3	0.3	0.5	0.8
T_{ear}	(°C)	Mean	37.7	38.0	37.8	38.0	37.7	38.0
		SD	0.2	0.3	0.2	0.3	0.2	0.3
		CV	0.5	0.8	0.5	0.8	0.5	0.8
T_{oral}	(°C)	Mean	37.9	38.1	37.7	37.8	37.8	38.0
		SD	0.2	0.3	0.3	0.5	0.3	0.5
		CV	0.5	0.8	0.8	1.3	0.8	1.3
T_{qt}	(°C)	Mean	37.5	37.6	37.5	37.7	37.5	37.7
		SD	0.7	0.7	0.3	0.3	0.5	0.5
		CV	1.9	1.9	0.8	0.8	1.3	1.3
HR	(bpm)	Mean	141	148	138	144	139	146
		SD	17	18	21	21	19	19
		CV	12.1	12.2	15.2	14.6	13.7	13.0
HR MTA-5	(bpm)	Mean	137	145	132	141	135	143
		SD	15	16	21	17	18	17
		CV	10.9	11.0	15.9	12.1	13.3	11.9
HR MTA-10	(bpm)	Mean	135	141	132	136	134	138
		SD	14	15	20	18	17	16
		CV	10.4	10.6	15.2	13.2	12.7	11.6
HR MTA-20	(bpm)	Mean	130	138	128	134	129	136
		SD	13	14	19	19	16	17
		CV	10.0	10.1	14.8	14.2	12.4	12.5
HR MTA-30	(bpm)	Mean	126	134	125	131	125	132
		SD	12	13	18	18	15	16
		CV	9.5	9.7	14.4	13.7	12.0	12.1
HR MTA-45	(bpm)	Mean	118	127	120	126	119	126
		SD	12	11	17	18	15	15
		CV	10.2	8.7	14.2	14.3	12.6	11.9
HR_r	(bpm)	Mean	121	126	116	120	119	123
		SD	16	16	19	22	18	19
		CV	13.2	12.7	16.4	18.3	15.1	15.4
PSI		Mean	6.1	6.7	6.2	6.7	6.1	6.7
		SD	0.8	0.6	1.0	1.0	0.9	0.8
		CV	13.1	9.0	16.1	14.9	14.8	11.9

The values in Table 3 for work clothes and vapor-barrier coveralls are shown graphically in Figures 1, 2, and 3 for the temperatures, heart rates, and PSI, respectively. For all metrics and both clothing ensembles, there was an increase in the mean value from control (pre-transition) to case (transition point). There were also large overlaps in the individual data based on the standard deviations. Some differences in the mean values for the controls and the cases between the clothing ensembles were observed.

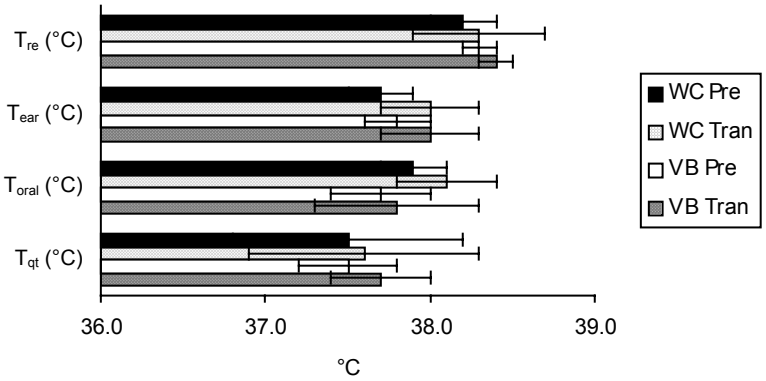

Figure 1. Temperatures (± 1 SD) at pre-transition and transition by clothing.

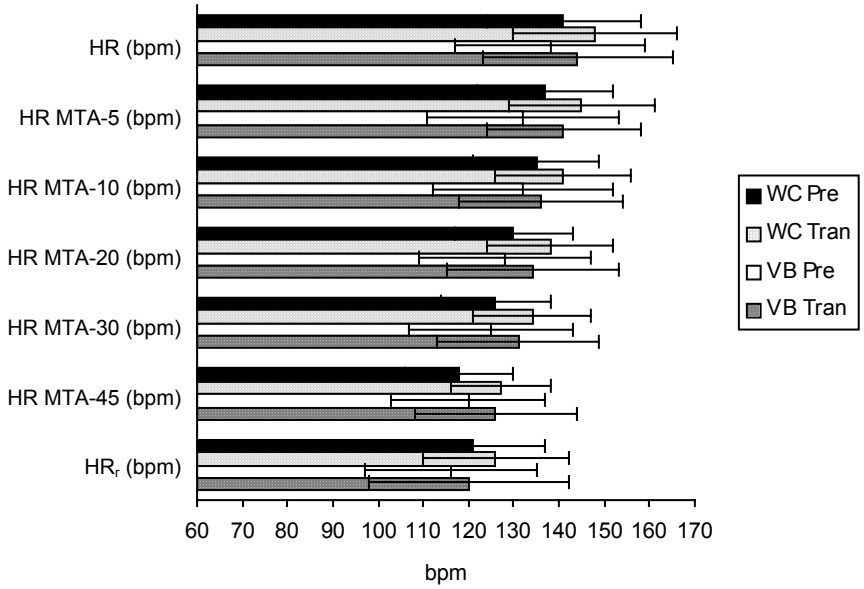

Figure 2. Heart rates (± 1 SD) at pre-transition and transition by clothing.

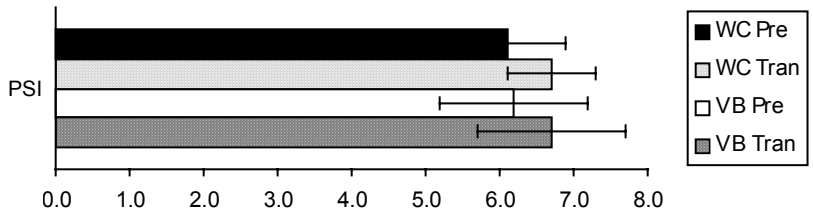

Figure 3. PSI (± 1 SD) at pre-transition and transition by clothing.

Since the pre-transition and transition measurements were taken from the same participants and since two types of clothing ensembles were worn, a two-way factorial ANOVA with repeated measures was used to examine the main effects of status (control versus case) and clothing and their interaction. For all measured and derived variables, significant differences were found between the values for control and case. The clothing effect and the interaction between status and clothing were not significant. Because this was a case crossover design, exact conditional logistic regression was used. It produced similar results of insignificance of the clothing effect. The *p*-values of the ANOVA and logistic regression are shown in Table 4.

Table 4

p-*Values of Status and Clothing Effects from Analysis of Variance (ANOVA) with Repeated Measures and Exact Conditional Logistic Regression*

Metric		ANOVA				Logistic Regression	
		n_1[a]	Status	Clothing	Status*Clothing	n_2[b]	Clothing
T_{re}	(°C)	23	0.0258	0.0950	0.6332	46	0.4970
T_{ear}	(°C)	22	< 0.0001	0.5552	0.3841	44	0.2233
T_{oral}	(°C)	22	0.0019	0.0865	0.6525	45	0.2002
T_{qt}	(°C)	23	0.0001	0.8445	0.5343	46	0.8900
HR	(bpm)	23	0.0007	0.6372	0.5908	46	0.8484
HR MTA-5	(bpm)	23	0.0004	0.5297	0.9880	46	0.6690
HR MTA-10	(bpm)	23	0.0024	0.5547	0.5105	46	0.8259
HR MTA-20	(bpm)	23	< 0.0001	0.6576	0.0805	46	0.8485
HR MTA-30	(bpm)	23	< 0.0001	0.7723	0.0660	46	0.9712
HR MTA-45	(bpm)	23	< 0.0001	0.9644	0.0575	46	0.5397
HR_r	(bpm)	21	0.0001	0.4970	0.3868	42	0.6621
PSI		23	< 0.0001	0.9044	0.9266	46	0.5981

n_1[a] = number of participants
n_2[b] = number of observations

Table 5 presents the areas under the ROC curves with 95% CIs for the measured and derived variables by clothing ensemble. All of the AUCs had values above 0.5 for both types of clothing. The lower confidence limit was above 0.5 for all the metrics in both clothing ensembles except for T_{oral}, HR MTA-10, and HR_r in the vapor-barrier coveralls. The confidence intervals were wide for all metrics.

Table 5

Area Under Curve (AUC) for Measured and Derived Variables by Clothing Ensemble

Metric		Work Clothes			Vapor-barrier		
		AUC	95% CI		AUC	95% CI	
			Lower	Upper		Lower	Upper
T_{re}	(°C)	0.785	0.550	1.000	0.861	0.703	1.000
T_{ear}	(°C)	0.711	0.564	0.857	0.711	0.528	0.894
T_{oral}	(°C)	0.678	0.581	0.775	0.546	0.474	0.617
T_{qt}	(°C)	0.603	0.507	0.700	0.632	0.524	0.740
HR	(bpm)	0.603	0.522	0.684	0.569	0.514	0.625
HR MTA-5	(bpm)	0.645	0.545	0.744	0.618	0.538	0.699
HR MTA-10	(bpm)	0.612	0.522	0.701	0.556	0.496	0.616
HR MTA-20	(bpm)	0.661	0.572	0.750	0.604	0.544	0.664
HR MTA-30	(bpm)	0.669	0.594	0.745	0.611	0.556	0.666
HR MTA-45	(bpm)	0.736	0.607	0.865	0.625	0.540	0.710
HR_r	(bpm)	0.600	0.508	0.692	0.529	0.483	0.575
PSI		0.711	0.522	0.900	0.667	0.579	0.754

Chapter Five

Discussion and Conclusion

Characteristics of Participants

The physical characteristics of the participants are provided in Table 1 in the Results section. This table gives an opportunity to compare the participant population to the working population. The mean age of the participants in this study was 25.8 years. This group was younger than the average working population. In 2006, more than 65% of the labor force was at the age of 35 years or older (Bureau of Labor Statistics, 2006d), implying that the average age is well above this participant population.

Body size is a characteristic that may influence a person's heat exchange. The mean body weights of the men and women in this study were 73.6 kg and 64.0 kg, respectively. The mean height of the men was 176 cm and that of the women was 157 cm. These values were within one standard deviation of the medians of anthropometric data gathered from military and civilian working populations in the United States (Eastman Kodak Company, 2004). Since BSA is derived from weight and height, it is reasonable to assume that the BSA of the study population was also representative of the working population. The mean BMI of the participants was 24.2 kg/m^2, similar to the median BMI of adults in the United States, which is 25 kg/m^2 (Astrand, Rodahl, Dahl, &

Stromme, 2003). Based on physical size, this population was representative of adults in the United States.

Aerobic capacity, being an indicator of physical fitness, is another factor that may affect heat tolerance. The aerobic capacities of the participants were mean maximum V_{O_2} of 37.0 ml/kg/min for men and 31.6 ml/kg/min for women. These values were comparable to the mean aerobic capacities reported for industrial men and women, which range between 35-39 ml/kg/min for men and 25-34 ml/kg/min for women (Eastman Kodak Company, 2004). Since aerobic capacity generally decreases with age (McArdle, Katch, & Katch, 2001) and the participants were younger, the comparable aerobic capacities showed that the state of physical fitness of the participants might be lower than the working population. For the age group of the study population, HR_{max} should be about 195 ± 10 bpm (Astrand, Rodahl, Dahl, & Stromme, 2003). The current study group's mean was 189 bpm and was within the range. Since it was a younger group than the working population, the average HR_{max} of the working population would be lower.

The above observations lead to the conclusion that although the participants were younger, they displayed similar characteristics as the working population.

Discrimination Ability

The ROC curve for a metric is a plot of the sensitivity versus (1 - specificity) at various cutpoints. An effective metric is one that has both high sensitivity and high specificity. The area under the ROC curve indicates the probability that if a case and a control are selected at random, the value of the metric will be higher for the case than for

the control. The closer the AUC is to 1.0, the better the metric is in predicting the outcome variable. A metric that is not related to physiological state will result in an AUC of 0.5 since it will produce equal numbers of correct and incorrect predictions.

The AUCs for the metrics were computed for each clothing ensemble. The computational method provided the mean and 95% CI. These are reported in Table 5 in the Results section. Figures 1 and 2 are graphical representations of the values of the AUCs and their respective CIs for the two types of clothing.

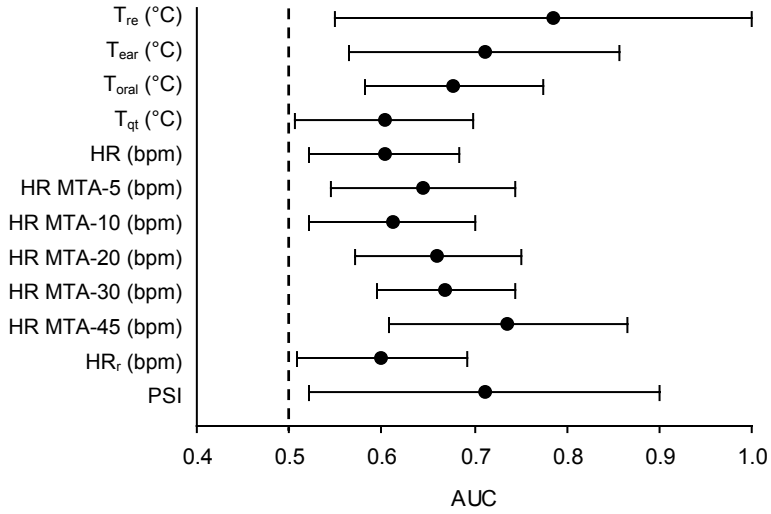

Figure 4. Area under Curve (AUC) and 95% CI of metrics for work clothes.

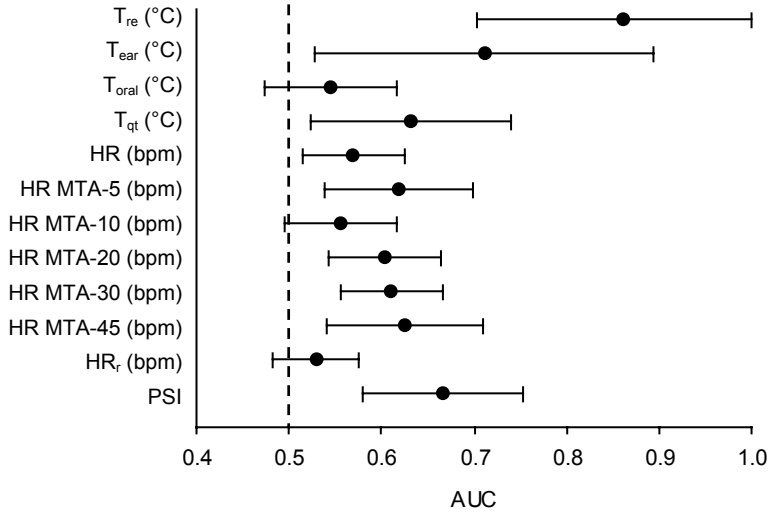

Figure 5. Area under Curve (AUC) and 95% CI of metrics for vapor-barrier coveralls.

For work clothes, all the metrics had AUCs of more than 0.5. The smallest value of the lower confidence limit was 0.507, in the case of T_{qt}. The first null hypothesis, that the metrics individually could not discriminate between acceptable and unacceptable heat strain, is rejected for work clothes. For vapor-barrier coveralls, all the metrics also had lower confidence limits on the AUCs greater than 0.5, except for T_{oral}, HR MTA-10, and HR_r. The first null hypothesis is rejected only with regard to the other metrics. All of the metrics showed potential to discriminate between controls and cases.

For both types of clothing ensembles, T_{re} had the highest AUC (0.785 for work clothes, 0.861 for vapor-barrier coveralls). Since 6 out of 11 transitions during the trials for work clothes and 8 out of 12 transitions during the trials for vapor-barrier coveralls were marked by the T_{re} criterion, a high AUC for this metric would be expected. One reason that the AUC was not 1.0 is because other criteria also contributed to the transition. Another feature of T_{re} that is not true for the other metrics is that it is not an acceptable method for field applications. This means that a surrogate measure must be used and it will have a lower AUC value due to the added uncertainty of the measure. That is, T_{re} is the benchmark for surrogate measures. In the current study, T_{ear}, T_{oral}, and T_{qt} were candidate surrogates, and all of these had lower AUCs as expected. As a socially acceptable metric to predict unacceptable heat strain based on temperature, T_{ear} (AUC = 0.711 for both clothing ensembles) appeared to be the best candidate. T_{oral} (AUC = 0.678 for work clothes and AUC = 0.546 for vapor-barrier coveralls) and T_{qt} (AUC = 0.603 for work clothes and AUC = 0.632 for vapor-barrier coveralls) were less discriminate. All the AUC statistics displayed wide CIs and there were largely no significant differences

among these metrics, as seen in the overlapping CIs. The exception was that for vapor-barrier coveralls, the T_{oral} was different from the T_{re}.

HR as a metric to discriminate acceptable and unacceptable heat strain did not perform as well as expected. The AUCs for work clothes and vapor-barrier coveralls were 0.603 and 0.569, respectively. Even though HR continually increased during uncompensable heat stress like the conditions in the current study, the individual variation was high. Further, the criterion was a fraction of the individual's HR_{max}. This means that the criterion level was a different absolute value for each person. For these reasons, it is difficult to fix an absolute value of HR as a marker. This difficulty is reflected in low discrimination.

For work clothes, the HR MTA for 45 minutes (HR MTA-45) had the highest AUC of 0.736 among the alternative HR methods. Generally the AUCs of the MTAs increased as the intervals of averaging increased. The exception was HR MTA-10, which had an AUC less than that of HR MTA-5. All of the MTAs appeared to be better metrics than HR. This result is not surprising. Bernard and Kenney (1994) argued that MTAs would be better monitors of heat strain than HR due to variations in work demand. They pointed out that shorter averaging periods would provide protection from short-term, high demands and longer averaging periods would provide protection from long-term, moderate demands. The present study resembled the latter condition as participants exercised at a moderate rate at a steady pace for durations of up to two hours. For vapor-barrier coveralls, a similar trend among the AUCs of the MTAs was observed. The HR MTA-45 also had the highest AUC among the MTAs (AUC = 0.625). The HR MTA-10 had a lower AUC than HR. All the MTAs had lower AUCs than their respective values

for work clothes and varied from 0.556 for HR MTA-10 to 0.618 for HR MTA-5. These variations were an indication of the lack of power in a small sample.

Another alternative to HR is HR_r. This method has been used in the assessment of occupational heat strain for a long time. As early as 1960, Brouha stated that the cardiac cost of recovery seemed to be a more sensitive indicator than the cardiac cost of work and might be the more significant criterion of physiological strain produced by muscular work and the environment. In the present study, the AUCs for HR_r had low values of 0.600 for work clothes and 0.529 for vapor-barrier coveralls. This outcome may be due to the difficulty of some participants in obtaining readings from the Mio Ultimate HR monitor. When that happened, the reading was taken more than one minute after pausing from exercise and the HR might be lower than it would have been had a timely reading been taken.

The PSI is computed from T_{re} and HR, therefore the AUC for PSI is expected to be high because it uses information from two metrics. The AUC for PSI obtained in this study was 0.711 for work clothes and 0.667 for vapor-barrier coveralls. Although these values were higher than the corresponding AUCs for HR, they fell below the AUCs for T_{re}. The reason for the fact that the AUCs for PSI were not the highest among these three metrics may be due to the way T_{re} and HR were incorporated into the relationship. A different approach may have offered a better index by which to discriminate.

Taken together, the AUC statistics showed that the second null hypothesis, that there were no significant differences among these metrics, is supported. Given the wide confidence intervals, there was likely insufficient power to conclude that they were the same in their ability to discriminate.

Effects of Clothing

The ANOVA and the exact conditional logistic regression found that clothing was not a significant factor; that is, clothing did not contribute to any population differences in any of the metrics between the pre-transition point (controls) and transition point (cases). These results suggest that there were no significant differences in the applicability of the metrics between different clothing ensembles used in this study. The statistical procedure employed in the AUC analyses could not be used to examine directly the data for both types of clothing ensemble simultaneously; therefore, the procedure was unable to discover any confounding effect of clothing. However, when the resulting confidence intervals of the AUCs are compared, no difference between clothing is observed but this observation is compromised by the low power. The different ways of examining any clothing effect seem collectively to suggest that such an effect is marginal. The third null hypothesis, that there were no significant differences in the applicability of the metrics due to clothing, is supported.

Limitations

Eleven participants completed two experimental trials under the low WBGT conditions. Four of them exhibited a transition from control to case while wearing work clothes. Because of the small number that reached transition, these data were not used in the analyses and that portion of the third null hypothesis was not tested. This situation suggests that the lower heat stress level targeted at 5°C-WBGT above the TLV might be

too low. At that level, most participants were exercising in compensable heat stress. Future studies should consider testing under WBGT conditions that are more than 5°C-WBGT above the TLV.

The likelihood and severity of heat strain experienced by a person for a given level of heat stress depends on the physiological capacity of that individual to respond to the stress. Various personal factors may increase or decrease a person's heat-tolerance. These factors include physical fitness, age, and gender. Due to the small sample size and the narrow age range of 18-36 years among the participants, the data in this study were not analyzed for possible effects of these personal factors. At the same time, it would be extremely difficult and impracticable when assessing heat strain in the workplace to consider individual characteristics of each worker. It is recommended that future studies should use larger sample sizes recruited from the working population of a wider community so that the study population would mimic a representative workforce. By examining the metrics in that way, it would be possible to arrive at methods that are useful for most of the working population in spite of individual variations. A larger sample size would reduce the wide CIs of the AUCs, reduce the possibility of Type II error, and increase the power of the analyses.

Conclusion

Various metrics were evaluated for their ability to discriminate between acceptable and unacceptable heat strain with a view to identifying suitable metrics for use in the workplace. As shown by the AUC statistics, the metrics evaluated in this study

could distinguish between acceptable and unacceptable heat strain. The ability of the various metrics to distinguish case status was not different but the small sample size and consequently the lower statistical power probably inferred no differences where difference may exist. The types of clothing ensemble appeared to have no influence on the metrics.

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Appendices

Appendix A: Advertisement

PARTICIPANTS NEEDED FOR RESEARCH STUDY

ON

ASSESSMENT OF OCCUPATIONAL HEAT STRAIN

You must be healthy and between 18 and 64 years old. You must not have any one of these conditions: hypertension, cardiovascular disease or family history of cardiovascular disease, renal pathology, diabetes, pregnancy or attempting to become pregnant, muscular or skeletal injuries, and previous incidence of heat injury. You must pass a physical examination by a physician, which we will provide at no cost to you, before participation in this study.

If you qualify and participate, you will receive a stipend of $35 per session. Up to 12 sessions are planned. Each session will last three hours. The study will be conducted at the University of South Florida, Tampa.

To find out if you qualify, please call **(727) 643-9389.**

Appendix B: Informed Consent for an Adult

Informed Consent for an Adult

University of South Florida
Information for People Being Asked to Take Part in Research Studies
IRB Study # 103094a

Researchers at University of South Florida (USF) study how workers respond to the stress of occupational demands. To do this, we need the help of people who agree to take part in a research study.

Title of Research Study: Assessment of Occupational Heat Strain

Person in Charge of Study: Margaret Wan, M.S.P.H.

Faculty Advisor: Thomas E. Bernard, Ph.D.

Where the study will be done: University of South Florida

Who is paying for the study: National Institute for Occupational Safety and Health

Should you take part in this study?

This form tells you about this research study. You can decide if you want to take part in it. You do not have to take part. Reading this form should help you decide if you want to take part in the study. If, at any time, you have any questions, feel free to ask the person explaining this study to you.

Before you decide:

- Read this form.
- Talk about this study with the principal investigator. You can have a friend or family member with you when you talk about the study.
- Find out what the study is about.

This form explains:

- The purpose of this research study.
- What will happen during this study and what you will need to do.
- The potential benefits of being in this study, if any.
- The risks of having problems because you are in this study.
- The answers to any questions you might have.

You can ask questions:

- You may have questions this form does not answer. If you do, ask the people doing the study as you go along.
- You don't have to guess at things you don't understand. Ask the people doing the study to explain things in a way you can understand.

After you read this form, you can:

- Take your time to think about the information that has been provided to you.
- Have a friend or family member read the form.
- Talk it over with your personal doctor.

It's up to you. If you choose to be in the study, then you can sign the form. If you **do not** want to take part in this study, you **do not** sign the form.

Why is this research being done?

The purpose of this study is to find out:

- If personal monitors and methods for assessing heat strain are valid for a range of environmental factors and types of clothing;
- If there is difference between younger and older age groups in their physiological responses to heat stress work conditions.

Why are you being asked to take part?

We are asking you to take part in this study because you are in the age group representative of a large portion of the working population.

How long will you be asked to stay in the study?

You will be asked to spend about three weeks in this study. The minimum number of days is 10. Twelve is a more likely number. If we need to repeat sessions, it could be up to 15 days.

How often will you need to come for study sessions and what will you do?

You will come for 10 to 15 study sessions. Most study sessions will take three hours or less.

Before participating in this study, you will be examined by a physician. A resting electrocardiogram (EKG) will be taken. The physician will obtain your medical history and assess your current state of health and will decide if you should participate in this study. If you are a woman, you will be asked to perform a home pregnancy test at home and to report the results.

If you do participate in this study, you will be asked to visit the College of Public Health, where this study will be performed. You should report to the laboratory well-rested and hydrated every time. You will be expected to provide adequate walking shoes (e.g., gym, tennis or running shoes), gym shorts and tee or, for women, a halter top.

The first session is a graded exercise stress test that follows the Bruce protocol, which is a commonly used treadmill protocol to measure maximum oxygen consumption and heart rate during physical exertion. It consists of progressive increments in effort by changing the grade and speed of the treadmill every three minutes until the person tested cannot continue.

Since body core temperature is an important measure of heat stress, you will be asked to insert a special temperature sensor rectally. The procedure will be explained to you. You will then place the sensor in the privacy of a dressing room. You will begin each session by having small EKG sensors taped to the chest, and four temperature sensors will be taped to the skin. An ear canal temperature sensor will be inserted into each ear. If you are a woman, you may elect to attach the sensors yourself or be assisted by another woman. The sessions will take place in an environmental chamber where the temperature and humidity will be controlled. You will walk on a treadmill, just as if you were doing exercise by walking on a treadmill at home or at the gym. The speed and slope of the treadmill will be set to a moderate work demand. During this time, we will monitor your core body temperature and heart rate. Each session will last about three hours, including the time to prepare, dress, and shower.

The first five to eight days of your participation in the project will be used to allow you to adapt to working in hot environments. This is called acclimation. You will wear cotton work clothes during these sessions. Each acclimation session will consist of two 50-minute periods of treadmill walking at a moderate rate of work, separated by 10 minutes of rest. The environmental conditions will be 40°C (104°F) at 30% relative humidity. We will collect the air that you breathe out for three minutes, at least once and up to four times in one session. This will allow us to estimate the work demands. The expired air will be collected by asking you to breathe through a mask that covers your mouth and nose or your face.

We will provide you with cotton work clothes or coveralls to wear for the experimental trials. The coveralls are typical of protective clothing worn in some workplaces. A private dressing area is available.

For the other sessions after acclimation, the air temperature and humidity, along with treadmill speed and slope, will be set in such a way that you will walk at a moderate metabolic rate. We will measure your physiological responses with the instruments mentioned above. We will collect the air that you breathe out for three minutes, up to four times in one session. This will allow us to verify the work demands.

As you keep walking, your core body temperature is expected to rise steadily. The person supervising any session will stop it once your body core temperature reaches 39°C (102.2°F) or you have a sustained heart rate greater than 95% of your maximum heart rate. Such temperature and heart rate are considered safe during controlled experiments. You may experience fatigue, light-headedness, nausea, dizziness, faintness, or muscle cramps. If any of these symptoms appear, or if you feel unable to continue for any other reason, you must inform the person supervising the session so that he or she can stop the exposure. There is no advantage to the study for you to continue when you begin to feel unable to continue.

You will be provided cool water or a commercially available drink suitable for working in hot environments. You will be encouraged to drink often and as much as you are comfortable with.

All of the measures that will be taken are traditional measures of physiological response to heat stress.

How many other people will take part?

Thirty people will take part in this study.

Will the medical treatment you get from your personal doctor change if you take part in this study?

This study does not involve medical treatment and does not affect any routine health care you may be getting from your personal doctor.

What other choices do you have if you decide not to take part in this study?

Since you are not being treated as a patient, there are no alternative treatments or procedures. Your only alternative is to not participate in this study.

How do you get started?

If you decide to take part in this study, you will need to sign this consent form. Then you can take the physical examination.

What will happen during this study?

During every study session, your physiological responses to heat stress conditions will be measured. The session will stop if your body core temperature or your heart rate exceeds a safety threshold or if you feel unable to continue for any reason.

Will you be paid for taking part in this study?

We will pay you for the time you volunteer while being in this study. We will pay you $35 for each session started. It makes no difference how it ends, whether we stop the trial or whether you ask us to stop. The fewest number of sessions will be 10 and the maximum will be 15. We will pay you for each session started. For example, if you start 10 sessions, we will pay you a total of $350.

What will it cost you to take part in this study?

It will not cost you anything to take part in this study, other than the time.

What are the potential benefits if you take part in this study?

As an individual, you will not benefit. By taking part in this research study, you may increase our overall knowledge of how heat stress affects workers and how to better protect them.

What are the risks if you take part in this study?

If you experience any of the side effects described below, call Margaret Wan at (727) 643-9389.

You may have difficulty completing a full session on the first few days of the acclimation period. This is normal, but the work will become progressively easier to perform. During experimental sessions, you will likely reach the safe tolerance limits between 30 minutes and two hours. There is a possibility that you will experience fatigue, heat exhaustion, or sore muscles for several hours afterwards. You may experience some discomfort while wearing the face mask for measuring aerobic capacity.

While very unlikely, cardiac arrest is a risk.

Is there any risk to your unborn children if you take part in this study?

It is possible that heat stress and elevated body temperatures for long periods of time may cause side effects on unborn children. If you are a woman, before starting, we will provide you with a home pregnancy test. You will be asked to report the results to the physician responsible for qualifying you. If you become pregnant while taking part in this research study, tell one of the study personnel supervising the study immediately.

If we learn of any new side effects, we will promptly inform you.

What if you get sick or hurt while you are in the study?

If you need emergency care:

- **Go to your nearest hospital or emergency room right away. Call 911 for help.** It is important that you tell the doctors at the hospital or emergency room that you are participating in a heat stress research study. If possible, take a copy of this consent form with you when you go. You should know that the USF does not provide emergency care.
- Call the principal investigator as soon as you can. She will need to know that you are hurt or ill. Call Margaret Wan at (727) 643-9389.

If it is NOT an emergency, and you get hurt or sick while you are taking part in this study:

- Go to your personal doctor. It is important that you tell your personal doctor that you are participating in a heat stress research study. If possible, take a copy of this consent form with you when you go.
- The USF Medical Clinics may not be able to give the kind of help you need. You may need to get help somewhere else.

If you are harmed while taking part in the study:

The state of Florida enjoys what is called "sovereign immunity." This means that you usually cannot sue the state of Florida. However, the state has waived sovereign immunity (agreed to be sued) in certain situations. One of those situations is if a state employee, such as a USF employee, is negligent in doing his or her job in a way that harms you during the study. The money that you might recover from the state of Florida is limited in amount.

You can also call the USF Self Insurance Programs (SIP) at (813) 974-8008 if you think:

- You were harmed because you took part in this study.
- Someone from the study did something wrong that caused you harm, or didn't do something he or she should have done.
- Ask the SIP to look into what happened.

What will we do to keep your study records private?

Federal law says that we must keep your study records private. We will keep the records of this study private by ensuring that only the investigators will have access to records where your identification may be revealed.

However, certain people may need to see your study records. By law, anyone who looks at your records must keep them completely confidential. The only people who will be allowed to see these records are:

- The people doing this study.
- Certain government and university people who need to know more about the study. For example, individuals who provide oversight on this study may need to look at your records. These include the USF Institutional Review Board (IRB) and the staff that work for the IRB. Some people who work for USF that provide other kinds of oversight may also need to look at your records. Other individuals who may look at your records include people from the Florida Department of Health, the United States Food and Drug Administration (FDA), and the National Institute for Occupational Safety and Health. This is done to make sure that we are doing the study in the right way. They also need to make sure that we are protecting your rights and your safety.

We may publish what we find out from this study. If we do, we will not let anyone know your name. We will not publish anything else that would let people know who you are.

What happens if you decide not to take part in this study?

You should only take part in this study if you want to take part. If you decide not to take part**,** you will not be in trouble or lose any rights you normally have.

What if you join the study and decide you want to stop later on?

You can decide, after signing this informed consent document, that you no longer want to take part in this study. If you decide you want to stop taking part in the study, tell the study staff as soon as you can.

Are there reasons we might take you out of the study later on?

Even if you want to stay in the study, there may be reasons we will need to take you out of it. You may be taken out of this study if:

- We find out it is not safe for you to stay in the study. For example, your health may change. Then you may be taken out of the study.
- You do not follow our instructions for the experiment or do not show up at the appointed time.

You can get the answers to your questions.

If you have any questions about this study, call Margaret Wan at (727) 643-9389.

If you have questions about your rights as a person who is taking part in a study, call the Division of Research Compliance of the University of South Florida at (813) 974-9343.

Signatures for Consent to Take Part in this Research Study

It is up to you to decide whether you want to take part in this study. If you want to take part, please read the statements below and sign the form if the statements are true.

I freely give my consent to take part in this study. I understand that I am agreeing to take part in research. I have received a copy of this consent form to take with me.

_____ _____

Signature of Person Taking Part in Study Date

_____

Printed Name of Person Taking Part in Study

Statement of Person Obtaining Informed Consent

I have carefully explained to the person taking part in the study what he or she can expect.

I hereby certify that when this person signs this form, to the best of my knowledge, he or she understands what the study is about, what needs to be done, what the potential benefits might be, and what the known risks might be.

I also certify that he or she does not have any problems that could make it hard to understand what it means to take part in this study. This person speaks the language that was used to explain this study.

This person reads well enough to understand this form or, if not, this person is able to hear and understand when the form is read to him or her.

This person does not have a medical problem that makes it hard to understand what is being explained and can, therefore, give informed consent.

This person is not taking drugs that make it hard to understand what is being explained and can, therefore, give informed consent.

_____ _____

Signature of Person Obtaining Informed Consent Date

Margaret Wan

Printed Name of Person Obtaining Informed Consent

Appendix C: Instructions to Participants

Reporting to the Lab

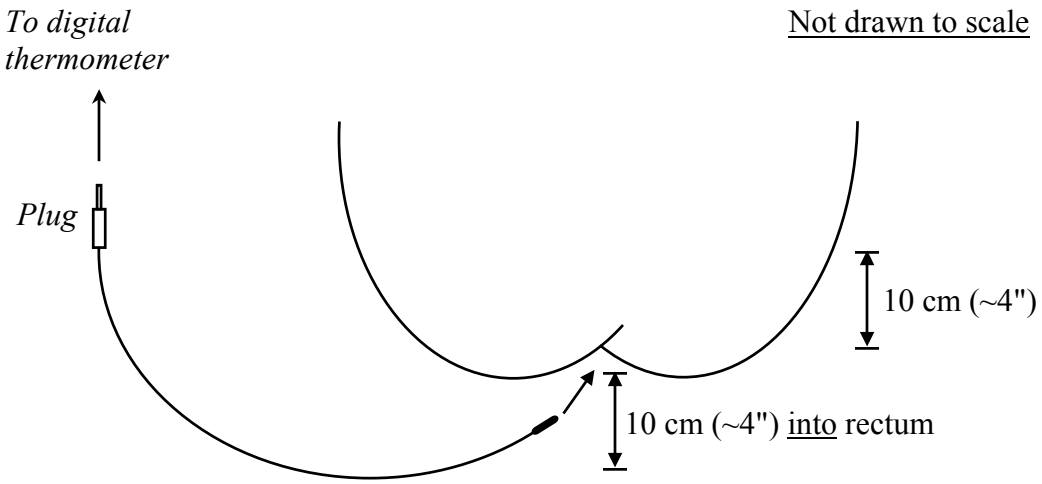
1. You should be well rested and hydrated. Please avoid strenuous exercise or caffeinated or alcoholic beverages within 12 hours prior to your scheduled session.

2. During the treadmill exercise, you should wear walking shoes (for example, gym, tennis, or running shoes), shorts, tee-shirt or, for a woman, a sports bra or halter top. If desired, you may bring a change of clothes. Shower facility is available.

3. Please arrive at the lab punctually at your scheduled time. If you are unable to attend a session, please call Margaret Wan as soon as possible (cell phone 727-643-9389). Also let her know if you are sick or become pregnant during the period of your participation.

Using the Rectal Temperature Probe

1. Insertion - The end of the probe should be inserted about 10 cm (about 4 in) beyond the rectal sphincter. A tape is positioned on the probe at about 6 in for reference. Please refer to the figure below. Lubricant is available in the preparation room if you desire to use it. After you have inserted the probe properly, tape the wire to your buttock so that the probe will be secure during the exercise session.



2. Cleaning - The same probe is reserved for your use for all sessions. After each session, please clean the probe with alcohol and iodine. Alcohol and iodine pads are available in the preparation room. When wiping clean, start at the sensing tip and wipe the probe and lead wire toward the plug. Avoid excessive pressure or

flexing of the cable jacket and lead wires. After cleaning, put the probe back into the plastic bag marked with your name, close the bag, and bring it back to the lab before you leave.

Measuring Oxygen Consumption

We shall measure your oxygen consumption to verify your metabolic rate several times during each session. The measurement will take approximately three minutes. You will be given a nose clip and a mouthpiece assembly. Place the nose clip on your nose so that you will not breathe through your nose. You will breathe through your mouth only. Put the blue tube of the assembly in your mouth and bite on the square pieces with your back teeth. Place your entire mouth around the tube so that no air escapes. It may be easier to hold the black part of the assembly while you are doing the test so that all the air from your breath goes into the tube.

Inserting the Ear Sensor

1. Roll the disposable yellow E.A.R.® foam earplug, containing a black protruding tube, back and forth with the fingers until it forms a small crease-free cylinder. See Steps 1 and 2.

2. Using only light pressure to keep the E.A.R.® plug rolled tight, gently slide it over the sensor of the earmold assembly. The black tube should slide into the earmold leaving only the yellow foam plug visible. The sensor should fill the black tube of the E.A.R.® plug with the tip lying flush with, or just inside of, the outer end of the tube.

3. With the E.A.R.® plug still rolled tight, hold on to the blue earmold and quickly insert the rolled up plug into the ear canal and hold it in place until it expands. The yellow portion of the earplug should be completely contained within the ear canal without any danger of hurting the inner ear. Fitting is easier if the outer ear is pulled outward and upwards during insertion as shown in Step 3. Once the plug has expanded, pushing or twisting will not improve its fit; therefore, if the initial fit is inadequate, remove the plug and repeat the process.

4. Maneuver the ear hanger over the ear.

Step 1 Step 2 Step 3

Appendix D: Standardized Procedures for Acclimation

Acclimation (40°C WBGT, 30% RH)

1. When the participant arrives, give him/her the calibrated rectal probe. Remind him/her to insert the probe properly and to tape the wire to the buttock. The participant goes to the preparation room to insert the probe, then returns to the lab.

2. Obtain the participant's pre-trial semi-nude weight.

3. Attach the Polar heart rate monitor transmitter.

4. Dress the participant with the work clothes (white shirt and khaki pants).

5. Obtain the participant's pre-trial clothed weight.

6. Position the participant on the treadmill. Connect the temperature probe to the YSI thermometer and turn on the Polar heart rate monitor receiver.

7. Start the treadmill exercise at the speed computed for the participant and record measurements on the data sheet at time = 0 and every 5 min thereafter.

8. In addition, record VO_2 (for 3 min) at time = 30, 65, and 90. Also record the fluid intake for the first and second hour, respectively. (Note: The participant can drink any time during the session.)

9. At time = 50, have the participant sit in a chair in the climatic chamber and rest for 10 min. Resume the exercise at the end of 10 min (time = 60).

10. Continue until one of the safe exposure limits is reached, or the participant wants to stop, or at time = 110, whichever occurs first. Record the time and final measurements immediately before stopping.

11. Obtain the participant's post-trial clothed weight.

12. Remove the work clothes and the Polar heart rate monitor transmitter. Obtain the participant's post-trial semi-nude weight.

13. The participant can now return to the preparation room, remove and clean the rectal probe, and shower.

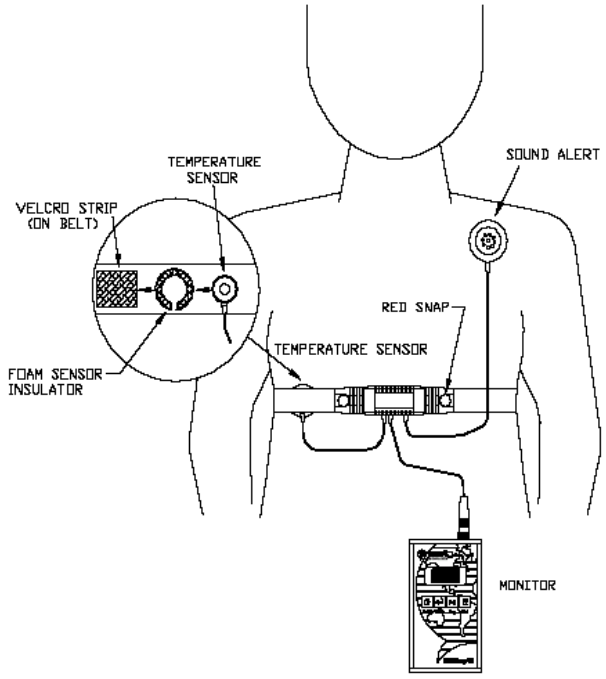
Appendix E: Standardized Procedures for Experimental Trials

Experimental Trials - 50% RH, 2 WBGTs x 2 clothing ensembles

1. When the participant arrives, give him/her the calibrated rectal probe. The participant goes to the preparation room to insert the probe, then returns to the lab.

2. Obtain the participant's pre-trial semi-nude weight.

3. Attach the Mio heart rate monitor (wear as a wrist watch), 4 skin temperature probes (left chest, right arm, right thigh, and left calf), and the QuesTemp° III sensor assembly. See the figure below for correct placement of the QuesTemp° III sensor assembly.



4. Dress the participant with the appropriate clothing (work clothes or coveralls).

5. Ask the participant to insert the QuesTemp° II ear sensor.

6. Attach the logging units of the instruments to the belt we provide.

7. Obtain the participant's pre-trial clothed weight.

8. Have the participant sit in a chair in the climatic chamber set to 50% RH and the WBGT in which he/she will be exercising. Connect the temperature probes to the

YSI thermometer. Start the logging function on the QuesTemp° II and QuesTemp° III.

9. Let the participant sit for 15 min. This waiting period allows the instruments to reach equilibrium for accurate reading.

10. At the end of 15 min, record baseline measurements on the data sheet.

11. Start the treadmill exercise at the speed computed for the participant and record measurements in the first eight and last two columns of the data sheet at time = 0 and every 5 min thereafter and at the transition point. (The transition point is based on one of two criteria, whichever occurs first.) Record oral temperature at time = 0 and VO_2 (for 3 min) at time = 25, 55, and 85. Also record the fluid intake for the first and second hour, respectively. (Note: The participant can drink only immediately after the oral temperature is taken - see 12. below.)

12. In addition, at time = 15, 30, 45, 60, 75, 90, 105, and 120, have the participant step off the treadmill and sit in the chair in the chamber. Set the timer for 2 min. Take oral temperature with a Tempa-DOT™ disposable thermometer. At the end of 1 min, record oral temperature and recovery HR. Provide the participant with Gatorade or water and encourage him/her to drink. (Note: He/she cannot drink again until another 15 min have passed.) At the end of 2 min, have the participant return to the treadmill and continue walking. Set the timer for 3 min (this is the remainder of the 5-min interval).

13. Unless the participant wants to stop earlier, continue the trial beyond the transition point, until one of the safe exposure limits is reached or at time = 120, whichever occurs first. Record the time and final measurements immediately before stopping.

14. Obtain the participant's post-trial clothed weight.

15. Remove the clothing ensemble and all instruments except the rectal probe. Obtain the participant's post-trial semi-nude weight.

16. The participant can now return to the preparation room, remove and clean the rectal probe, and shower.

Appendix F: Participant Characteristics -- Individual Data

Participant	Gender	Age (yrs)	Weight (kg)	Height (cm)	BSA (m^2)	BMI[a] (kg/m^2)	Maximum V_{O2} (L/min)	Maximum V_{O2} (ml/kg/min)	HR_{max} (bpm)
2	M	23	85.0	182.88	2.07	25.41	3.19	37.53	186
3	M	20	51.4	167.64	1.57	18.29	2.06	40.08	199
4	M	36	65.5	175.26	1.80	21.32	2.58	39.39	183
5	M	18	57.3	171.45	1.67	19.49	2.47	43.05	192
6	M	32	108.2	181.10	2.28	32.99	3.89	35.95	171
7	M	24	66.8	173.99	1.80	22.07	2.52	37.72	194
8	M	23	68.6	176.53	1.84	22.01	2.25	32.80	193
9	W	34	50.5	140.46	1.37	25.60	1.30	25.74	189
10	M	32	85.9	181.61	2.07	26.04	2.56	29.80	198
11	W	23	80.0	171.45	1.93	27.22	3.16	39.53	191
12	W	24	56.8	154.43	1.54	23.82	1.55	27.22	196
13	W	21	68.6	162.56	1.74	25.96	2.33	34.02	181

[a]BMI = body mass index = W / H^2, where W is the weight in kg and H is the height in m (Quetelet, 1842/1968).

Appendix G: Measured and Derived Variables at Pre-transition Point

Participant	Gender[a]	Clothing[b]	T_{re} (°C)	T_{ear} (°C)	T_{oral} (°C)	T_{qt} (°C)	HR (bpm)	HR MTA-5 (bpm)	HR MTA-10 (bpm)	HR MTA-20 (bpm)	HR MTA-30 (bpm)	HR MTA-45 (bpm)	HR_r (bpm)	PSI
2	M	WC	38.2	37.5	38.2	37.7	150	128	128	125	122	117	133	6.6
2	M	VB	38.3	37.8	37.5	37.8	164	163	161	154	151	146	107	7.3
3	M	VB	38.2	.	37.7	37.7	152	149	145	139	134	130	.	6.7
3	M	WC	38.4	37.6	37.8	38.1	167	158	158	151	147	144	.	7.6
4	M	WC	38.0	37.5	37.6	37.8	112	109	110	107	107	104	95	4.7
4	M	VB	37.9	37.4	37.1	37.3	111	108	103	100	100	98	93	4.5
5	M	WC	38.1	37.9	37.9	37.9	139	142	140	133	128	115	113	6.0
5	M	VB	38.4	37.8	38.4	37.6	120	125	128	126	125	120	120	5.6
6	M	VB	38.2	37.9	37.6	37.0	111	104	110	108	106	106	100	4.9
6	M	WC	38.4	37.9	38.0	37.9	126	132	126	120	115	109	114	5.9
7	M	VB	38.2	38.0	37.9	37.7	137	130	129	125	122	113	114	6.1
7	M	WC	38.1	38.0	38.2	38.0	134	131	127	120	115	104	117	5.7
8	M	VB	38.3	37.9	37.8	37.8	163	147	146	140	137	131	140	7.3
8	M	WC	38.2	37.8	38.3	38.0	148	146	143	139	131	117	136	6.4
9	W	WC	38.3	37.8	37.7	37.9	144	144	142	138	134	128	134	6.5
9	W	VB	38.2	38.0	37.7	37.8	146	140	142	140	138	131	136	6.5
10	M	VB	38.3	37.8	37.7	37.7	159	154	154	149	143	135	148	7.1
10	M	WC	37.8	37.3	37.6	36.2	167	162	157	148	140	126	148	6.6
11	W	WC	38.3	37.9	37.9	36.8	136	131	128	123	119	115	110	6.1
11	W	VB	38.4	37.8	37.1	37.3	123	125	127	122	120	119	95	5.7
12	W	VB	38.3	37.9	37.7	37.4	157	147	142	140	133	127	127	7.0
12	W	WC	38.0	37.4	37.7	36.2	128	124	130	127	125	122	111	5.3
13	W	VB	38.3	37.4	37.6	37.2	114	97	97	94	91	84	99	5.2

[a]Gender M = man, W = woman.
[b]Clothing WC = work clothes, VB = vapor-barrier.

Appendix H: Measured and Derived Variables at Transition Point

Participant	Gender[a]	Clothing[b]	T_{re} (°C)	T_{ear} (°C)	T_{oral} (°C)	T_{qt} (°C)	HR (bpm)	HR MTA-5 (bpm)	HR MTA-10 (bpm)	HR MTA-20 (bpm)	HR MTA-30 (bpm)	HR MTA-45 (bpm)	HR_r (bpm)	PSI
2	M	WC	38.5	37.7	38.2	37.8	148	136	131	130	127	123	134	7.0
2	M	VB	38.5	38.0	37.7	38.0	167	161	155	158	155	151	102	7.8
3	M	VB	38.5	.	.	38.0	152	145	140	143	139	133	.	7.2
3	M	WC	37.2	38.3	38.1	38.2	179	169	160	159	154	149	.	6.2
4	M	WC	38.3	37.7	37.7	37.9	130	125	120	115	112	111	101	5.9
4	M	VB	38.2	37.8	37.1	37.5	109	107	106	104	102	101	93	4.8
5	M	WC	38.5	38.3	38.5	38.1	148	147	140	140	136	126	117	7.0
5	M	VB	38.5	38.0	39.2	37.8	148	141	139	134	130	126	126	7.0
6	M	VB	38.3	38.1	37.6	37.1	119	117	117	113	111	108	108	5.4
6	M	WC	38.5	38.0	38.1	38.0	124	122	124	125	121	116	117	6.0
7	M	VB	38.5	38.2	37.7	38.0	139	134	130	129	126	121	116	6.6
7	M	WC	38.5	38.4	38.5	38.2	129	146	141	134	127	118	125	6.2
8	M	VB	38.5	38.1	38.2	37.8	162	152	150	148	143	138	146	7.6
8	M	WC	38.4	37.7	38.6	38.0	159	152	151	147	143	130	141	7.3
9	W	WC	38.5	38.2	37.7	38.1	154	154	148	145	141	136	135	7.3
9	W	VB	38.5	38.3	37.7	38.0	154	152	150	146	143	138	145	7.3
10	M	VB	38.5	38.2	37.7	37.9	170	165	161	157	153	145	155	7.9
10	M	WC	38.1	37.7	37.8	36.4	178	172	166	161	154	141	158	7.5
11	W	WC	38.5	38.1	38.0	36.5	140	137	132	130	126	121	120	6.7
11	W	VB	38.5	37.8	37.5	37.4	127	128	120	123	122	120	99	6.1
12	W	VB	38.5	38.0	37.7	37.6	159	152	145	144	141	135	127	7.5
12	W	WC	38.2	37.4	37.9	36.7	143	138	133	131	129	126	112	6.3
13	W	VB	38.3	37.3	37.7	37.2	118	135	113	105	101	94	99	5.5

[a]Gender M = man, W = woman.
[b]Clothing WC = work clothes, VB = vapor-barrier.

About the Author

Margaret Wan received a Bachelor of Laws degree in 1985 from the University of London, U.K. She is also a Fellow of the Institute of Chartered Secretaries and Administrators, U.K., specializing in business management and corporate law.

While working in Florida for a health care organization as Director of Program Development, Ms. Wan enrolled in the Master of Science degree program in Health Services Administration at Nova Southeastern University and graduated in 1998. She received her Master of Science in Public Health degree, with concentration in industrial hygiene, from the University of South Florida in 2004. She continued her education in the Ph.D. program.

Ms. Wan presented papers on aging workers at national and international conferences. She was President of the USF student chapter of the Human Factors and Ergonomics Society. She serves on the Ergonomics Committee and Communication and Training Methods Committee of the American Industrial Hygiene Association.