Program on Technology Innovation: Heat Stress Monitoring and Sensors

Phase 1, State of Science of Wearable Physiological Monitors to Assess Occupational Heat Strain

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ABSTRACT

Workers in many industries are often required to perform arduous work in high heat stress conditions that may compromise body temperature regulation and may lead to heat-related illnesses or even death. Traditionally, efforts to protect workers from excessive heat strain has been directed to the assessment of heat stress (for example, wet-bulb globe temperature) rather than the associated physiological strain responses (for example, heart rate and skin and core temperatures). However, because a worker's physiological strain response to a given level of heat stress is modified independently by inter-individual factors (such as age, sex, and chronic disease) as well as intra-individual factors both within (for example, caffeine, alcohol and medication use, fitness, and acclimation and hydration state) and beyond the worker's control (for example, consecutive work shifts, shift duration, or illness), it becomes challenging to prevent heat-related illness in all workers without directly assessing those physiological responses. Recent technological advancements in wearable physiological measurement systems have made it possible to monitor one or more physiological indices of heat strain to protect workers on an individual basis from heat-related injury in the workplace. However, information on the utility of the wearable systems currently available for assessing heat strain and mitigating heat-related injury in an occupational setting is limited.

This project identified the physiological responses that may be monitored as indicators of heat strain in the workplace and evaluated the available wearable monitoring systems for monitoring those responses in harsh work conditions. Finally, this project was directed to identify challenges to the implementation of these devices as part of a greater heat injury management strategy in physically demanding occupations.

Keywords

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PRIMARY AUDIENCE: Health and safety directors, industrial hygienists, safety professionals

KEY RESEARCH QUESTION

Incorporating a heat strain monitoring program has been recommended as the best approach to mitigate heat-related illness in the workplace. However, do the wearable monitors available for assessing physiological heat strain provide the necessary information for safety professionals to develop a suitable strategy to mitigate heat illness in workers in power generation and delivery working environments?

RESEARCH OVERVIEW

In this project, researchers 1) reviewed the physiological responses that may be monitored at the workplace as precursors or indicators for heat-induced physiological strain (that is, heat syncope or heat exhaustion), 2) reviewed examples of the available personal heat strain monitoring systems with respect to equipment parameters (for example, cost, size, mode of data transmission, and accuracy) and the applicability of each system for use in occupational settings (for example, tolerance to environmental conditions, comfort, and wearability), and 3) identified potential challenges to implementing these devices in physically demanding occupations.

KEY FINDINGS

- Occupational heat strain may be quantified from measures of body core temperature, skin surface temperature, fluid loss, and cardiovascular strain—although some precautionary steps and augmented activities must be considered to ensure that these measures are representative of a worker's state of heat strain.
- Using wearable technology to monitor one or more indices of heat strain has the potential to provide individualized and real-time notification of excessive heat strain and may be particularly valuable during high-risk work/weather conditions and/or for workers who are more susceptible to heat-related injury because of the type and frequency of work performed as well as their age, fitness, health status, and so on.
- Despite the benefits of available wearable monitoring systems, they are costly and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy existing safety requirements (for example, flame and arc resistance). Further, most systems lack effective guidance in the interpretation of physiological data to identify signs and symptoms of excessive heat strain. It also remains unknown whether physiological monitoring may adversely affect worker behavior.
- Future product development should be directed at physiological monitoring solutions that are cost-effective, compliant with existing safety regulations, and well-tolerated by workers in order to be suitable for use as part of a companywide heat strain management strategy. Monitoring devices that satisfy these requirements may be an effective technology addition for protecting worker health.

WHY THIS MATTERS

These key findings highlight the utility of physiological monitoring (for example, body core and skin temperatures, heart rate, and sweat rate) to provide a real-time way to quantify each worker's level of heat strain and protect worker health in performing their normal duties, especially in high heat stress conditions.

However, these findings also indicate that the available wearable physiological monitors are costly and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy existing safety requirements (for example, flame and arc resistance). Indeed, there is a need for research and product development directed at physiological monitoring solutions that are cost-effective, compliant with existing safety regulations, and well-tolerated by workers in order to be suitable for use as part of a companywide heat strain management strategy.

HOW TO APPLY RESULTS

Four key suggestions are provided to health and safety directors, industrial hygienists, and other safety professionals:

1. Reliance solely on the workers themselves to modify their behavior (for example, reducing work output and increasing rest) to mitigate occupational heat injury is not advised. The evidence presented in this report indicates that self-monitoring provides only low-level protection to worker health.
2. Caution must be used when assessing the level of heat stress using traditional environmental parameters (for example, wet-bulb globe temperature) as a way to mitigate occupational heat injury. This approach cannot account for the inter-individual factors (for example, age, sex, and chronic disease) and intra-individual factors both within (for example, caffeine, alcohol and medication use, sleep quality, fitness, and acclimation and hydration state) and beyond the worker's control (for example, consecutive work shifts, shift duration, time of day work is performed, or illness) that can modify a worker's level of physiological strain to a given heat stress. As such, the assessment of heat stress using environmental parameters alone can compromise productivity in more heat-tolerant workers (false positive) while potentially reducing the safety of less heat-tolerant workers who may develop heat illness even in mild conditions (false negative).
3. Research to date suggests that one or more indices of physiological strain be monitored to provide more individualized protection from heat-related impairments in job performance as well as heat-related injuries, especially in high heat stress conditions. Although occupational heat strain may be quantified from measures of body core temperature, skin surface temperature, fluid loss, and cardiovascular strain, health and safety managers and personnel should consider intra-individual factors that can influence these responses (for example, sleep quality, level of fatigue, diet, and hydration) when relying on these indices to assess a worker's state of heat strain.
4. Although wearable devices reviewed in this research project purport to provide a non-invasive means of quantifying physiological strain, they are costly and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy existing safety requirements (for example, flame and arc resistance). Therefore, the research from this project suggests that future research be conducted to identify systems that are compliant with existing safety guidelines, offer acceptable precision in harsh industrial environments, and are well-tolerated by heat-vulnerable employees in high-risk conditions.

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GLOSSARY OF TERMS

Acclimatization: process of physiological adjustment to a change in environment (for example, temperature).

Ambient temperature: the temperature of the air surrounding a body; also called *air temperature* or *dry bulb temperature*.

Anhidrosis: absence of sweating.

Apparent temperature: perceived temperature in ºF derived from a combination of air temperature, wind speed, and humidity.

Asymptomatic: absence of symptoms.

Autonomic: self-governing or autonomous.

Blood volume: total volume of blood within the body.

Body core temperature: temperature of deep-body structures, including the brain, liver, and heart; also called *core temperature*.

Body fluid regulation: processes involved in the regulation of fluid within the body.

Body heat balance: steady-state equilibrium between body heat production and heat loss to the environment.

Body heat storage: The change in heat content of the body.

Breathing frequency: the number of breaths a person takes during one minute.

Buccal cavity: the cavity spanning from the entrance to the mouth to the esophagus.

Buddy system: system in which two people operate together to help and monitor one another.

Cardiac output: volume of blood pumped by the heart each minute.

Cardiovascular strain: compensatory cardiac and vascular responses to physiological strain (for example, increases in heart rate).

Cardiovascular system: delivers blood to the body's tissues via the heart and vascular network.

Central venous pressure: the blood pressure in the vena cava, near the right atrium of the heart.

Chemical dot thermometers: chemical dots attached to a plastic strip or adhesive patch that contain a chemical mixture that changes color at a specific temperature.

Cognitive function: mental processes that allow us to carry out any task, such as memory, orientation, gnosis, attention, or language.

Conduction: heat (energy) transfer by the movement of electrons or ions.

Convection: heat (energy) transfer due to movement of molecules within fluids such as blood.

Cutaneous vasodilatation: dilation of vessels in the skin.

Dry heat loss/gain: heat transfer to/from the body to the environment via convection, radiation, and conduction.

Electrolyte: ions such as sodium, potassium, magnesium, calcium, chloride, and bicarbonate that dissociate in biological fluids into ions capable of conducting electrical currents and constituting a major force in controlling fluid balance within the body.

Encapsulating clothing: personal protective clothing that encloses the wearer (for example, hazardous waste disposal).

Etiology: cause(s) of a disease or condition.

Euhydration: normal state of body water content; absence of dehydration.

Evaporation: the heat transfer from the body to the environment when sweat secreted onto the skin is transformed into water vapor (vaporized).

Fluid loss/depletion: body water loss from urine, sweat, or respiration.

Galvanic skin response: a measure of the electrical conductance of the skin as an index of emotional or physiological stress.

Homeostasis: stability or balance of the internal body environment.

Heart rate variability: variations in the time interval between heartbeats.

Heat-related illness/injury: health conditions and disorders related to heat exposure.

Heat cramps: involuntary muscle spasms during work in hot environments.

Heat edema: migration of body fluid into the hands or legs by gravity.

Heat rash: itchy, red bumps on the skin (miliaria rubra) due to heat exposure.

Heat strain: the sum of physiologic responses of the individual to heat stress.

Heat stress (thermal): the sum of the environmental and metabolic heat load imposed on the individual.

Heat stroke: severe heat illness characterized by a core temperature exceeding 40ºC, coupled with an absence of sweating and compromised central nervous system function.

Heat syncope: reduction in blood pressure due to heat exposure that briefly causes inadequate blood flow to the brain and loss of consciousness.

Humidity, relative: the ratio of the water vapor present in the ambient air to the water vapor present in saturated air at the same temperature and pressure.

Hydrostatic pressure: pressure exerted by the blood within the body.

Hypertension: persistent elevation of blood pressure within the arteries.

Hyperthermia: a condition in which the core temperature of an individual is higher than 37.2°C (99°F); hyperthermia can be classified as mild (37.2–38.5°C [99–101.3°F]), moderate (heat exhaustion) (38.5–39.5°C [101.3–103.1°F]), profound (>39.5°C [103.1°F]), or profound clinical hyperthermia (heat stroke) (>40.5°C [104.9°F]), and death can occur without treatment (>45°C [113°F]).

Hypoallergenic: product designed to minimize the possibility of allergic reaction.

Intra- and extracellular fluid: fluid within (intracellular) and outside (extracellular) of cells within the body.

Intra-individual variation: within-person variation.

Intravascular coagulation: development of small blood clots throughout the bloodstream that block small blood vessels.

Inter-individual factors: between-person variation.

Internal thermal energy: transformation of chemical energy into thermal internal energy within the body (that is, metabolism).

Isotope dilution: radiochemical method of analysis for measuring the mass and quantity of an element in a substance.

Measurement bias: systematic error due to a difference between the actual measurement and the measured value.

Metabolic rate: The internal body heat transfer associated with metabolic processes.

Metabolic heat production: The difference between metabolic rate and external work (positive or negative energy transfer).

Microclimate: ambient conditions within a clothing ensemble that differ from the external environment.

Minute ventilation: volume of gas inhaled per minute.

Multi-organ dysfunction: physiologic dysfunction in multiple organ systems.

Neurological function: function of the nervous system.

Non-invasive: procedure in which there is no contact with the mucosa, skin break, or internal body cavity beyond a natural body orifice.

Orthostatic intolerance: difficulty with the upright posture, particularly standing, which results in a range of conditions.

Orthostatic hypotension: decrease in blood pressure when standing.

Otoscope: medical device that is used to look into the ears.

Oxygen saturation: measure of the percentage of oxygen bound to hemoglobin in the blood.

Pathophysiology: the functional physiological changes associated with a disease or syndrome.

Periphery (body): boundary or outer part of the body.

Perceptual strain: perceived level of physiological and psychophysical strain.

Physiological strain: compensatory physiological responses to maintain homeostasis.

Pinna: helical outer portion of the ear (auricle).

Plasma hypertonicity: an increased concentration of solutes dissolved in blood plasma.

Plasma osmolality: the relative concentration of solutes dissolved in blood plasma.

Plasma volume: the total volume of blood plasma within the body (within the extracellular fluid compartment).

Preoptic anterior hypothalamus: central portion of the brain that regulates body core temperature.

Protein denaturation: structural breakdown of proteins within the body.

Psychophysical: relationships between physical stimuli and sensory response.

Radiation: the emission or transmission of thermal energy in the form of waves or particles through space or through a material.

Respiratory heat exchanges: heat exchange occurring during respiration.

Respiratory regulation: process of maintaining oxygen as well as carbon dioxide present in the blood.

Splanchnic regions: viscera or internal abdominal organs.

Stroke volume: volume of blood pumped from the left ventricle each heartbeat.

Sublingual: area underneath the tongue.

Sudomotor function: the sweating response.

Sweating: response of the sweat glands to thermal stimuli.

Systolic blood pressure: pressure exerted on the arterial walls when the heart contracts (beats).

Tachycardia: a heart rate that exceeds the normal resting rate.

Telemetry: process in which data are collected and transmitted to receiving equipment for monitoring.

Thermochromic thermometers: type of thermometer that contains heat-sensitive (thermochromic) liquid crystals in a plastic strip that change color to indicate different temperatures.

Thermoeffector mechanisms: the physiological responses that assist with body temperature regulation, including sweating, vasodilation, vasoconstriction, shivering, and non-shivering thermogenesis (brown fat heat production) as well as behavioral change.

Thermogenesis: metabolic process to produce heat.

Tidal volume: volume of inspired air during each breath.

Translocated blood volume: the volume of blood transported from one area to another within the body.

Universal Thermal Climate Index: index used to assess the outdoor thermal environment.

Urine specific gravity: index of hydration state derived from the ratio of the mass of urine compared to the mass of an equal volume of water.

Vasomotor function: processes of vasodilation (dilation) and vasoconstriction (narrowing) in blood vessels.

Venous pooling: accumulation of blood within the lower limbs resulting in smaller venous blood return to the heart that reduces stroke volume and cardiac output.

Vertigo: dizziness felt as a false sensation of movement.

Wet-bulb globe temperature: index of heat stress taking into account air temperature, humidity, wind speed, and solar radiation.

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INTRODUCTION

An estimated 2–5 million employees in the United States may be exposed to potentially unsafe levels of heat stress at the workplace [1]. Working in the heat represents a considerable challenge to body temperature regulation and integrated physiological processes of blood pressure and body fluid regulation [2–5]. That physiological strain is exacerbated by the physically demanding nature of many occupations [6–9] and the requirement for workers to don heavy and often impermeable protective clothing [10–13]. These conditions not only compromise productivity [7, 14], but also can cause dangerous rises in body temperature that can lead to heat-related illnesses and even death [15, 16]. Indeed, in the United States alone, over 350 deaths were ascribed to occupational heat exposure between 2000 and 2010 [17]. However, this mortality rate may be an under-estimation because several factors are well established:

- Surveillance of heat-related worker illnesses is not universally comprehensive [18–20].
- Heat stroke can be misdiagnosed as a result of similarities in its clinical presentation and pathophysiology to other illnesses [18, 21, 22].
- The criteria to define heat-related injuries and deaths often differ among physicians, medical examiners, coroners, and regions [23].

Given that the Occupational Safety and Health Administration (OSHA) has not issued a heat standard, it uses 5(a)(1) [24] citations in cases of heat illness or death—which limits the validity and relevance of these data for research purposes. Moreover, given the potential increases in the frequency and intensity of heat waves associated with warming trends, the incidence of work-related heat illness may rise and increasingly become an issue for workers operating in temperate climates [25]. Indeed, there is a growing body of literature supporting the findings of higher morbidity and mortality levels resulting from exposures to increased extreme temperatures and heat wave conditions [26, 27]. The dangers of occupational heat stress are particularly high for older (that is, ≥40 years) workers who display marked reductions in thermoregulatory function relative to young adults during work in the heat [28–31] and who form an increasing proportion of the work force [32].

To protect workers from heat-related illnesses, environmental parameters alone or environmental and clothing parameters along with the estimated rate of metabolic heat production are used to quantify the level of heat stress and determine engineering and administrative controls or hygiene practices to prevent dangerous levels of heat strain (for example, OSHA guidelines and American Conference of Governmental and Industrial Hygiene [ACGIH] Threshold Limit Values [TLV®]). Mathematical modeling of heat transfer in the body and between the body and surroundings using environmental parameters along with anatomical and thermal properties of the human body—as well as the heat transfer associated with changes in internal (metabolic) heat production and heat loss responses (sweating and skin blood flow)—are also used to predict heat strain [33–37]. However, although both approaches provide a convenient way to approximate the average level of physiological strain, the actual level of heat strain experienced by an individual in response to a given heat stress can vary markedly as a result of inter-individual factors (for example, age, sex, and chronic disease) and intra-individual factors both within (for example, caffeine, alcohol and medication use, fitness, and heat acclimation and hydration state) and beyond the worker's control (for example, consecutive work shifts, shift duration, time of day work is performed, or illness) [38]. This individual variability can compromise productivity in more heat-tolerant workers or reduce the safety of less heat-tolerant workers who may develop heat illness even in mild conditions.

Personal monitoring of physiological strain (for example, body core and skin temperatures, heart rate, and sweat rate) can provide a real-time way to quantify each worker's level of heat strain and has been suggested to provide individualized protection from heat-related illness [39, 40]. Recent technological advancements have led to both rapid growth in the development of wearable heat strain monitors and to subsequent research on the utility of these systems in occupational settings. However, although the use of wearable physiological monitors has been popularized for monitoring physical activity in the general population and as outlined by a recent series of reviews, it has also increasingly been used for identifying disease states, tracking rehabilitation, and optimizing performance [41–47]. An evaluation of the monitors available for assessing heat strain and the applicability of those systems for use as part of a heat illness mitigation strategy in an occupational setting is currently unavailable.

As such, the purpose of this research project and this report has been threefold:

- To review the physiological responses that may be monitored at the workplace as precursors or indicators for heat-induced physiological strain (that is, heat syncope or heat exhaustion).
- To review available personal heat strain monitoring systems with respect to equipment parameters (for example, cost, size, mode of data transmission, and accuracy) and the applicability of each system for use in an occupational setting (for example, tolerance to environmental conditions, comfort, and wearability).
- To identify potential challenges to implementing these devices in physically demanding occupations.

2

PHYSIOLOGICAL STRAIN DURING WORK IN HOT CONDITIONS

In most industries, occupational heat stress originates from harsh environmental conditions (for example, high air temperature and humidity, radiant heat sources, and low air flow), the requirement to wear insulated and/or impermeable protective clothing, and the high metabolic heat load from performing physically demanding tasks—especially when wearing heavy equipment [48]. Accordingly, performing arduous work in high heat stress conditions is associated with progressive rises in body core temperature, cardiovascular strain, and fluid depletion, which can lead to heat stroke or death. Excessive heat stress may also cause psychophysical strain (for example, discomfort and fatigue) and may lead to labor losses by compromising worker productivity and safety [7]. These physiological and psychophysical effects of heat stress on the worker and their performance characterize the heat strain response. Moreover, previous research suggests that heat strain is not only prevalent in high-humidity/high-temperature environments, but also may also occur in workers operating in cold weather environments with substantial thermal protective clothing along with requisite personal protective equipment (PPE) in Continental temperate climatic zones. The sources of occupational heat stress and the resulting heat strain responses are summarized in Figure 2-1 and detailed in the following subsections.

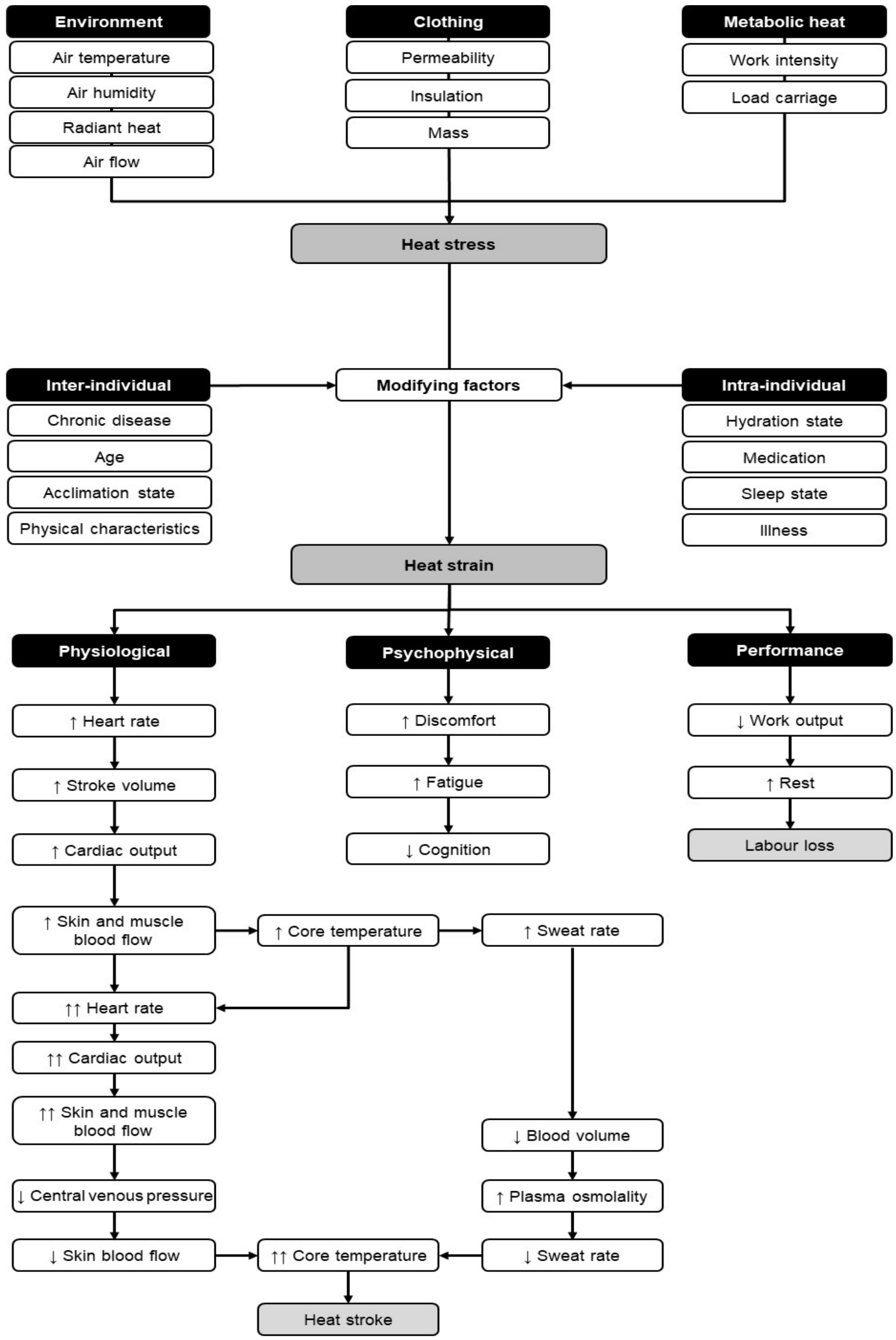

Figure 2-1
Summary of the sources of occupational heat stress

Body Temperature Regulation

To maintain homeostasis, humans strive to regulate body core temperature within a narrow range. This requires a balance between metabolic heat production—which represents the difference between heat produced from metabolic processes and external work—and the dry (convection, radiation, conduction), evaporative, and respiratory heat exchanges occurring between the body and surroundings [38, 49]. These heat exchanges occur passively and are actively driven by behavioral (for example, addition or removal of clothing [50]) and autonomic effector mechanisms (as defined by changes in skin blood flow and sweating as well as changes in metabolic rate [51]), which are activated by temperature changes in peripheral (skin, muscle) and deep-body structures (core). A rate of metabolic heat production that exceeds the rate of heat loss will cause heat to be stored within the body as well as a subsequent rise in body core temperature—which in turn causes cutaneous vasodilatation and sweating to restore heat balance, leading to a stable albeit elevated core temperature [51, 52]. Cutaneous vasodilation increases skin blood flow to promote convective heat delivery to the skin surface, which facilitates dry heat loss when the skin temperature exceeds the ambient temperature and buffers dry heat gain in hotter environments [53]. Sweat secreted onto the skin provides evaporative cooling; sweat dripping off the skin provides no cooling benefit.

Heat stress in the workplace represents the combined heat load from the environment and clothing along with heat generated from metabolic processes (metabolic heat); the resulting physiological and psychophysical effects of that heat stress on the worker and work performance characterize the heat strain response (see Figure 2-1). Excessive heat stress can result in labor loss and multiple physiological adjustments that can progress to heat stroke if left unchecked [54].

During light work in temperate, dry conditions (that is, compensable thermal conditions), heat storage will return to zero and body core temperature will stabilize following ~30–60 min of continuous work [38]. However, workers more commonly operate in hot, humid indoor and outdoor environments with substantial radiant heat load (for example, hot machinery/ equipment and sunlight), which causes dry heat gain and restricts sweat evaporation. Under such conditions, the rate of evaporative heat loss required to maintain heat balance—which is equal to the sum of the rate of dry heat gain, respiratory heat loss, and metabolic heat production—will often exceed the maximum rate of evaporation possible in the surrounding environment [55]. In these uncompensable thermal conditions, continued work will cause progressive rises in body core temperature that compromise worker safety.

The thermoregulatory challenge of working in hot indoor and outdoor environments is often exacerbated by the physically demanding nature of many occupations (for example, bush firefighting, open pit mining, and electric utilities). Because humans are relatively inefficient when performing various types of physical activity (such as walking, running, digging, and climbing), less than ~20% of the energy from metabolic processes is used to perform external work [56]; the remaining internal thermal energy is stored in the body. For instance, moderate to high-intensity work tasks (such as manual handling or digging) may cause a three- to fourfold elevation in heat production [57]. As such, continuous, arduous work will greatly increase the rate of heat loss required to restore heat balance, causing accelerated rises in body core temperature in uncompensable environments [11, 58, 59].

To protect workers from radiant heat sources (for example, boilers, furnaces, fire, and high surface temperatures) and noxious gases or materials when performing arduous work in the heat, many occupations necessitate the use of protective clothing systems (such as firefighting or hazardous materials disposal). Such garments can restrict movement and require the wearer to carry the additional mass of the clothing and protective equipment (for example, breathing apparatus), which can exceed ~20 kg in some industries [60]. As such, wearing protective clothing or equipment, particularly on the hands or feet [60, 61], will increase the metabolic heat produced during manual work by ~20–30% [57, 60, 62]. In some occupations, this clothing is also heavily insulated and sometimes impermeable to water vapor (encapsulating). This encapsulation creates a hot, humid microclimate around the worker that increases dry heat gain and impedes sweat evaporation [11, 63], further exacerbating heat strain [12, 64].

Integrated Physiological Processes

Occupational heat stress represents a challenge not only to thermoregulation, but also to blood pressure, body fluid regulation, and, to a lesser extent, respiratory regulation. Indeed, in such work conditions, cardiac output (volume of blood pumped by the heart each minute) increases above what is required to provide oxygen to the working musculature to support thermoregulatory increases in skin blood flow [65] (see Figure 2-1). This causes reductions in blood pressure that may be particularly problematic when working in upright postures—elevations in hydrostatic pressure promote blood pooling in the lower limbs and contribute to orthostatic intolerance, which can lead to fainting (syncope) [52, 66]. To maintain blood pressure in such instances, a coordinated response from the cardiovascular system must occur. This involves compensatory elevations in heart rate (Figure 2-1) as well as the redistribution of blood volume from inactive skeletal muscle and visceral structures (for example, liver and splanchnic regions). During heavy work, however, this translocated blood volume is often inadequate, and skin blood flow (to support thermoregulation) is compromised to maintain blood pressure [65, 67].

Cardiovascular strain is commonly experienced by workers during prolonged work, especially in the heat [68, 69], and is exacerbated when sweat losses cannot be matched by fluid intake. Sweat losses can range between 1 and 1.5 L/hr^{-1} in many industries [70, 71] and originate from intra- and extracellular fluid compartments within the body that freely exchange fluid between one another [72, 73]. Although intracellular fluid volume generally remains constant as fluid is lost [74], these fluid losses cause progressive reductions in extracellular fluid through decreases in blood (plasma) volume, which in turn increases the concentration of salts (ions) within the blood (plasma hypertonicity). The resulting reductions in plasma volume reduce blood pressure and cause further compensatory elevations in heart rate to maintain blood pressure [75] (see Figure 2-1). At the same time, plasma hypertonicity stimulates osmoreceptors (receptors sensitive to changes in salt concentration in the blood) to release anti-diuretic hormone to stimulate thirst and reduce urinary water loss [72]. However, even when drinking water is provided ad libitum (as desired), sweat losses generally exceed fluid intake [76, 77], resulting in "voluntary dehydration" [78, 79]. Progressive dehydration has been shown to attenuate sweat secretion during work in the heat [73, 80] and cause a subsequent 0.2–0.4°C increase in body core temperature for every 1% of body mass lost from fluid (see Figure 2-1) [58, 81, 82]. Dehydration, therefore, is a key factor that predisposes workers to heat-related illness [16, 83, 84].

Heat-Related Illness in the Workplace

The physiological challenges of performing arduous work in hot conditions create the environment for workers to develop heat-related illnesses [4, 18, 85, 86]. Those illnesses are described as either *classical* or *exertional*; the former occurs in individuals with compromised thermoregulatory or cardiovascular function, and the latter develops among otherwise healthy individuals during prolonged, heavy work [15, 16]. Milder heat illnesses are associated with elevations in body core temperature of up to 40°C and normal central nervous system function [16, 84]. These illnesses can include heat edema (interstitial fluid pooling) in the limbs from prolonged periods of cutaneous vasodilatation as well as heat rash in areas of profuse sweating from the obstruction of sweat ducts [83]. Heat cramps may also develop from excessive sweating, particularly when fluid and electrolyte intake are inadequate, although the associated etiology remains unclear [87]. In some instances, venous pooling in the lower limbs from peripheral vasodilatation can cause orthostatic hypotension (reduced blood pressure), followed by dizziness and fainting [65]. Mild heat illnesses may also cause aftereffects (for example, cellular and organ damage) that can progress to chronic heat illnesses (such as vertigo, tachycardia, and hypertension) or death with long-term heat exposure [66, 88]. If rises in body core temperature continue, more severe symptoms of heat exhaustion can develop (for example, fatigue, vomiting, and profuse sweating). Symptoms left untreated can progress to heat stroke (see Figure 2-1), which is clinically defined as a core temperature exceeding 40°C, coupled with an absence of sweating (anhidrosis) and compromised central nervous system function (for example, delirium or shock) [16, 84]. Unless immediate medical assistance is provided in such instances, body core temperature will continue to rise—resulting in intravascular coagulation, protein denaturation, multi-organ dysfunction, and eventually death [16, 88].

Work Performance and Psychophysical Strain

It is well established that heat stress is also associated with a profound reduction in worker productivity [7, 14, 89]; the magnitude of this labor loss is expected to increase with warming trends [90, 91]. These effects were perhaps first observed in Bantu laborers employed in the underground mines of South Africa [14] who performed only 21, 44, and 59% of the work completed in temperate conditions (wet-bulb temperature [WBT] of 27.7ºC with a wind speed of ~0.5 m/s-1) at a WBT of 30.5ºC with a wind speed of ~0.5, 2, and 4 m/s-1 over a 5-hr work shift. Much more recently, time motion analysis of arduous grape-picking work on four separate days during a 77-day harvest revealed that workers spent ~12% of the total work shift on breaks; that time increased by 0.8% for every 1ºC increase in air or wet-bulb globe temperature [7]. Although similar studies have not, to our knowledge, been conducted in the electric utilities industry, these outcomes demonstrate that heat stress has degrading effects on work output that would likely translate into substantial costs to company earnings—particularly during extreme heat events or in the performance of arduous work activities.

Cognitive processes may be equally affected by both heat strain and dehydration [92–96]. Cognition involves mental processes such as perception, learning, language, and executive functioning [97] and is fundamental for working safely and effectively [98, 99]. Several investigators have demonstrated heat- and dehydration-induced impairments in cognitive task performance [100–103]. These impairments may have profound effects on the performance of complex job tasks and may compromise safety in high-risk occupations (see Figure 2-1), particularly among workers who are required to operate for extended periods, whose circadian rhythms are disrupted by night- or shift-work [104, 105], and/or who are exposed to hot environments [106].

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HEAT STRAIN MONITORING TO MITIGATE OCCUPATIONAL HEAT INJURY

Over the past few decades, significant progress has been made in our understanding of human physiology during heat stress. However, despite extensive implementation of procedures to mitigate the development of heat stress symptoms by industry, heat exposure still causes high rates of morbidity and mortality [18, 27, 48, 107]. As recent work showed, even in relatively cool and temperate environments, the high physical demands combined with restrictions to heat loss and elevated body core temperatures caused by the protective work uniforms caused some workers to experience levels of physiological strain that severely compromised their performance [68, 69, 108]. Moreover, it has been reported that injurious increases in body core temperature—which can result in serious heat-related injuries or death—can go undetected over the course of a work shift [108]. This risk can be exacerbated in workers who must perform consecutive days of prolonged work in hot environments and who experience a significant state of dehydration [108]. Further, workers face additional risk factors for injuries associated with stress and overexertion during work in the heat, including the following:

- Elevated and sustained central nervous system activation caused by performing high-risk and physically demanding activities
- Rapid transitions from low to high levels of physical exertion
- Carrying, lifting, and wearing heavy protective gear and equipment
- Prolonged exposure to high temperatures

For these reasons, a monitoring program to identify signs that may be related to physical fatigue and/or heat-related illness can be part of an effective management strategy.

A simple approach for mitigating occupational heat illness is to rely on the workers themselves to modify their behavior (reducing work output, increasing rest, and so on) when heat strain is perceived to be excessive or when symptoms of heat illness are experienced. Although self-monitoring has been shown to be effective in preventing excessive heat strain in some industries [109, 110], it can be compromised when work is time-pressured or compensation-driven [111]. Moreover, as noted previously, dangerous increases in body core temperature during work in the heat can still go undetected with potentially deadly consequences [108]. To better prevent excessive heat strain, the level of heat stress may be assessed using either environmental parameters alone (for example, Universal Thermal Climate Index or wet-bulb globe temperature [WBGT]) or environmental and clothing parameters as well as the estimated rate of metabolic heat production to identify to acceptable work limits (for example, ACGIH TLV®) or to approximate the level of heat strain that may be experienced by a worker (that is, mathematical modeling). However, although these approaches provide additional protection beyond self-monitoring, it becomes challenging to protect all workers in the electric utility environments because the individual variation in heat strain in response to a given level of heat stress is extensive [68, 69]. Previous research suggests that it is necessary both to provide further and individualized protection from excessive heat strain and to directly monitor the physiological adjustments (for example, increases in heart rate and body core temperature) to that heat stress. As such, these strategies may be classified into four levels according to the level of protection to worker health provided (see Figure 3-1): self-monitoring (Level IV) provides low-level protection; heat stress monitoring using environmental parameters alone (Level III) or measures of the environment, clothing, and metabolic rate (Level II) both provide moderate protection; heat strain monitoring (Level I) forms the highest level of protection. The effectiveness of these strategies as a way to mitigate heat-related illness is detailed in the following subsections.

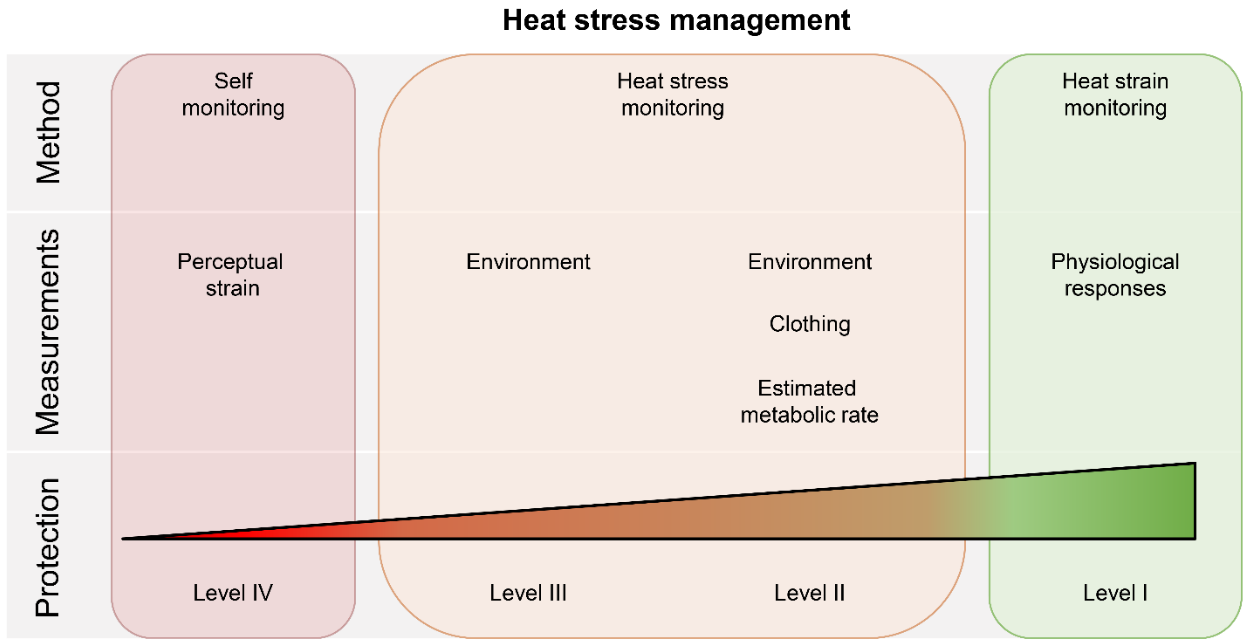

Figure 3-1
Methods to prevent heat illness during work in the heat

An illustration of the methods available to prevent heat-related illness during work in hot environments and the associated level of protection offered by each: low (Level IV), moderate (Levels III and II), and high (Level I), including self-monitoring of the strain perceived; heat stress monitoring using either environmental parameters alone or a combination of environmental, clothing, and metabolic data; and the monitoring of physiological data using wearable technologies.

Self-Monitoring

Typically, experienced workers monitor their own physiological and perceptual strain during work in high heat stress conditions and subsequently modify their behavior when excessive heat strain or symptoms of heat illness are detected [110]. These behavioral modifications primarily involve self-pacing strategies to reduce internal heat production by lowering work rate and taking more frequent and longer rest breaks [7, 111, 112]. Workers also tend to avoid high heat sources and attempt to facilitate cooling by removing clothing where possible (for example, rolling up sleeves or removing jacket during breaks) [113]. Self-monitoring has been shown to successfully mitigate heat-related illness in experienced workers in various high heat stress occupations such as mining [114], ceramics [110], and construction [109]. However, it has been suggested that this approach is inappropriate when a worker is offered productivity incentives [111] because highly motivated or heat-tolerant workers may continue working even with excessive heat strain to maximize their earnings (that is, performance-based pay). Further, there is evidence that some workers may suffer excessive heat strain and heat stroke even when self-pacing is permitted [111, 115]. This may be because some workers are either unwilling or unable to sufficiently modify their work rate to prevent excessive heat strain because of time or peer pressure [116], despite symptoms of heat-related illness [117]. In previous research in the electric utility work environment, observations indicate that reliance on self-monitoring was marginally useful and on occasion presented danger to the worker's well-being due to lack of self-awareness—physiologically driven and not willful or elective—putting the worker at risk.

Heat Stress Assessment

Traditional strategies to mitigate occupational heat illness have involved the assessment of environmental parameters alone (for example, ambient temperature and humidity or WBGT) or both environmental and clothing parameters (such as insulation or vapor permeability) as well as the estimated internal heat production from metabolic processes during work (metabolic heat production). These data are then used to prescribe engineering (for example, ventilation or shade) and administrative controls (scheduled recovery, work-to-rest allocations, and so on) as well as hygiene practices (for example, clothing, personal cooling devices, and fluid consumption schedule) to prevent dangerous levels of heat strain. For instance, the ACGIH guidelines known as the *Threshold Limit Values* (TLV®) for heat stress consist of work-to-rest allocations that consider environmental conditions, expressed as WBGT, as well as clothing and estimated work intensity (metabolic rate) [118]. These guidelines are designed to ensure that body core temperature will not exceed the predefined threshold of 38.0ºC for extended periods that may place an individual at risk of heat-related injury, as recommended by the World Health Organization [119]. Similarly, OSHA provides guidelines to assist employers in safeguarding workers exposed to heat stress using the United States National Oceanographic and Atmospheric Administration (NOAA) heat index system, which combines outdoor air temperature and relative humidity into a single measure of apparent temperature (ºF). These heat index values are divided into four bands that classify the risk of heat-related illness at the work site as low (<91ºF), moderate (91–103ºF), high (103–115ºF), and very-high-to-extreme (>115ºF). Each band is associated with respective protective measures involving basic heat safety and planning (ensuring adequate drinking water, worker acclimatization, and so on), implementing precautions and heightened awareness (for example, worker training, work-rest schedules, and the "buddy" system), taking additional precautions to protect workers (for example, cooling techniques or actively encouraging fluid consumption), and implementing more aggressive protective measures (such as physiological monitoring or a fluid consumption schedule).

Mathematical modeling of thermoregulatory function has also been used to safeguard workers from high heat stress conditions for some time [36]. Such models simulate heat transfer occurring within the body and between the body and the surrounding environment using an array of environmental parameters (for example, wind speed, air temperature, humidity, and solar load) as well as the average anatomical and thermal properties of the human body (that is, passive heat exchange) [120]. Such models also consider the heat transfer associated with changes in metabolic heat production as well as heat losses through the respiratory system, sweating, and changes in peripheral blood flow—which are obtained from experimental data (that is, the active system) [36]. More recent models account for various clothing parameters (for example, insulation or vapor permeability) [34] and differences in physical characteristics (height, body mass, surface area, and so on) [33, 37]. These data are then computed and used to predict the typical or average physiological strain—body core temperature—that a worker is likely to experience during specific work conditions.

Heat Strain Monitoring

The use of either heat stress exposure guidelines or mathematical models provides a convenient way to approximate heat strain in multiple workers without the use of expensive equipment. However, because physiological strain may be modified by both inter-individual factors (age, sex, chronic disease) and intra-individual factors both within (for example, caffeine, alcohol and medication use, fitness, or acclimation and hydration state) and beyond the worker's control (for example, consecutive work shifts, shift duration, time of day work is performed, or illness; see Figure 2-1), the individual variability in heat strain in response to a given level of heat stress is extensive. For example, workers as young as 40 years of age demonstrate marked reductions in whole-body heat loss that exacerbate heat strain during work in the heat relative to young adults [29, 30, 121, 122] while young adults of higher aerobic fitness display enhanced whole-body heat loss and therefore reduced heat strain during work in the heat compared to individuals with similar physical characteristics but lower aerobic fitness [123, 124]. As such, heat stress exposure guidelines and mathematical models can lead to the early termination of work and a reduction in productivity in more heat-tolerant workers (false positive), while the latter would compromise the safety of less heat-tolerant workers who may develop heat-related illness even in mild conditions (false negative). For instance, a recent evaluation of the effectiveness of the ACGIH TLV®, which recommends specific work-to-rest allocations to prevent excessive rises in core temperature (≥38.0ºC) during work in the heat, suggests that this threshold would likely be surpassed during work shifts ≥4 hours in some young [125] and in all older workers assessed [126] even when moderate intensity work is performed within these limits.

To provide individualized protection from occupational heat stress, it has been recommended that one or more physiological indices of heat strain should be monitored [39]. Physiological monitoring provides a way to directly quantify the level of heat strain experienced by an individual in real time while considering both the intra- and inter-individual factors that may independently modify heat strain (see Figure 3-1). Applications of this approach would work to ensure that productivity is maximized in more heat-tolerant employees working in high heat stress conditions and that heat-related illness is prevented in less heat-tolerant employees working in temperate conditions. Further, these physiological data can be used to provide alert thresholds to management to ensure that safety limits are not exceeded and to the worker to assist with self-pacing. However, although heat strain monitoring forms a requirement of current heat exposure guidelines when the level of heat stress exceeds a specific threshold (for example, ACGIH TLV®), additional information and guidance are needed on the individual specific physiological responses that provide the best indices of heat strain in the workplace—as well as the most appropriate wearable physiological monitoring systems to measure those responses.

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INDICES OF OCCUPATIONAL HEAT STRAIN

Occupational heat stress is associated with a cascade of physiological adjustments to regulate body temperature, blood pressure, and fluid volume (see Figure 2-1). However, although these responses may represent indices of heat strain, quantifying them in an occupational setting can be challenging and often impossible—even with recent technological advancements. This section identifies the physiological responses that may be measured in an occupational setting to quantify excessive heat strain and potentially safeguard the health and safety of workers in hot environments. Emphasis is directed to the methods available to non-invasively measure body core temperature or indirectly estimate body core temperature using skin surface temperature as well as measures of fluid loss and cardiovascular strain.

Body Core Temperature

The inability to regulate body core temperature during work in the heat is perhaps the most direct index of heat strain [127]. Excessive rises in body core temperature (≥40ºC) can rapidly lead to organ failure and death if medical care is unavailable [16, 84]. As such, the WHO recommends that core temperature should not exceed 38ºC for prolonged durations of work in the heat; work should cease if core temperature reaches 39ºC [119]. Similarly, the ACGIH recommends that body core temperature should not exceed 38ºC and 38.5ºC for extended periods for unacclimatized and acclimatized workers, respectively, and provides specific work/rest ratios depending on the WBGT and the work intensity to achieve this [118]. Nonetheless, the most clinically relevant measurements of body core temperature—for example, rectum, gastrointestinal tract, and esophagus (that is, at the level of pulmonary artery)—can be difficult to obtain in an occupational setting. For some, the invasive nature of the measurement technique can be distracting and may cause physical discomfort, especially when used for prolonged durations. Moreover, many of these measurement systems are non-reusable and may be costly. Although the measurement of body core temperature can provide a valuable measure of a worker's state of hyperthermia, caution must be employed when assessing body core temperature.

Studies show that body core temperature can underestimate body heat storage by as much as 40% during steady-state work in the heat [38]. This is because much of the heat produced by the working muscles remains in the active and inactive musculature, blunting the increase in body core temperature. The following subsections describe the methods available to approximate body core temperature in the workplace. These methods are discussed in detail elsewhere [128, 129] and are summarized next with emphasis on their utility for use in an occupational setting.

Gastrointestinal Temperature

To approximate body core temperature without the complications associated with other internal body temperature measurements (rectum, esophagus, or pulmonary artery), gastrointestinal temperature may be measured using an ingestible, telemetric pill. This relatively new technology uses a miniaturized crystal quartz oscillator enclosed in a small, disposable silicon-coated pill, which oscillates at different frequencies in response to changes in temperature [129]. Those oscillations then transmit a low-frequency radio wave in real time to a portable logger to provide measures of occupational heat strain from ingestion to passing (5–83 hours) [130]. Telemetric pill temperatures have been reported to share acceptable agreement with more invasive measures of body core temperature (such as esophagus or rectum) during work in the heat [131, 132]. However, there are important factors to consider when employing this technique. For example, measurements of body core temperature using the telemetric pill often lag behind more invasive measures (esophagus or rectum) at the onset of work or during intermittent activities [133]. Further, recent reports indicate that ~12% of telemetric pills display systematic bias, and calibration against a certified reference thermometer should be performed prior to use to correct for this issue [134]. Other considerations include food and fluid consumption, which can also introduce measurement bias. This is typically greatest within ~30 min of ingestion and may last up to 11.5 hours following ingestion [135], although this artefact can be minimized by delaying data collection by 2–6 hours following ingestion [132, 136]. As such, measures of gastrointestinal temperature from telemetric pills, when appropriately calibrated and monitored 2–6 hours following food or fluid consumption, provide a portable way to accurately assess heat strain in an occupational setting.

Oral Temperature

Core temperature estimated from the oral cavity (sublingual area) by placing a thermometer underneath the tongue has long been used to quantify occupational heat strain in conjunction with heart rate during recovery [137]. The bilateral lingual arteries (located underneath the tongue) branch directly from the external carotid artery and therefore provide a temperature that is reflective of brain temperature [128]. Oral temperature is known to track rectal temperature during work in the heat, albeit at a 0.3–0.6ºC lower temperature [138–140]. This method is non-invasive and can be easily measured using a digital or disposable thermometer (for example, chemical dot thermometers). However, some precautionary steps must be considered when employing this technique to ensure that the body core temperature is representative of the worker's state of hyperthermia. First, oral temperature can be independently influenced by evaporative cooling in the buccal cavity during breathing [140]. Therefore, it is important to avoid mouth breathing for several minutes while the thermometer is placed underneath the tongue to ensure equilibration with body temperature. Second, the consumption of hot or cold food or fluids prior to measurements may also transiently modify body core temperature [141]. This effect can be minimized by restricting fluid consumption prior to measurement [142, 143]. Taking these simple steps can help track occupational heat strain more accurately using oral temperature.

Tympanic and Aural Temperature

Surrounded by the pinna and located near the brain, the auditory (aural) canal represents a small tube running from the outer ear to middle ear and ending with the tympanic membrane [144]. The tympanic membrane receives blood from the anterior tympanic and caroticotympanic arteries, which arise from the external and internal carotid arteries, while the aural canal receives blood from the superficial temporal artery adjoined to the external carotid artery [144]. As such, both temperatures are representative of brain temperature—the tympanic membrane, because of its more direct brain blood supply and deeper position within the aural canal, provides the more precise index of body core temperature [145, 146]. However, because measuring a true tympanic membrane temperature requires a sensor that is in constant contact with that membrane, as verified using an otoscope to avoid perforation [147, 148], it is unsuitable for use in an occupational setting. Fortunately, commercially available handheld infrared thermometers can detect radiation emitted from the tympanic membrane and therefore provide a non-invasive, cost-effective way to measure true tympanic membrane temperature. Given that the presence of ear wax can prevent direct sight of the tympanic membrane, the ear canal should be cleaned prior to measurement. However, it is important to note that in some individuals, the temperature recorded is typically that of the aural canal because of its curvature [149]. Regardless, this measurement site can provide an effective measurement of a worker's level of thermal strain.

In addition to infrared thermometers, aural canal temperature may be measured using an insulated, ear-molded plug thermometer. Insulated aural canal temperature has been shown to closely track both esophageal and rectal temperature during work in the heat under controlled laboratory conditions [150–152]. However, because aural canal temperature can be influenced by external air and surface temperatures (both heat and cold), which modify temperature in the highly vascular structures of the pinna and face that supply blood to the aural canal [151, 153, 154], it is important to minimize this bias to use this method to better approximate occupational heat strain. This can be achieved by wearing non-permeable, hooded clothing, which creates a hot, humid microclimate surrounding the face to minimize extraneous heat transfer with the external environment [155]. A zero-gradient approach may also be used to actively remove the influence of cooler air temperatures on aural canal temperature [156]. This involves the placement of a heating device on the pinna to track and replicate aural canal temperature and therefore nullify heat transfer between the aural canal and external environment.

Body Surface Temperature

The body surface (skin) represents the medium between the body core and the external environment. As such, skin temperature is influenced not only by environmental (for example, high ambient and surface temperatures) and clothing parameters (clothing insulation and permeability), but also by metabolic heat production as well as behavioral and autonomic heat loss responses (skin blood flow and sweating). In cooler conditions, where cutaneous vasoconstriction minimizes the thermal gradient for dry heat exchange, regional differences in skin temperature are extensive [157–159]. However, during work in hotter environments or when wearing whole-body protective clothing—where increases in cutaneous vasodilatation facilitate blood-borne heat transfer to the skin surface [65]—skin temperature increases and becomes more uniform [157–159]. Indeed, during high-intensity work when wearing encapsulating protective clothing, skin temperature in some regions may eventually approach that of the core [13, 160]. In such instances, heat flow between the core and skin is reduced to zero, and measures of skin temperature alone may be used to estimate core temperature and, ultimately, occupational heat strain [161, 162].

Mercury-in-Glass or Electric Thermometers

Core temperature is often approximated from skin temperature measurements obtained using mercury-in-glass (that is, expansion thermometers) or electric thermometers from the axilla (armpit) region in home or clinical settings [129]. By placing the thermometer on the skin surface between the upper arm and trunk for several minutes, the thermometer is naturally insulated from the external environment, and axilla temperature may be used to estimate body core temperature. Although this approach represents a cost-effective method, it is important to take into consideration that axilla temperature can be modified by variations in air temperature, skin temperature, and continued sweating in the axillary region [131, 132]. Finally, obtaining measures of axilla temperature in an occupational setting may require workers to cease work and remove their protective clothing. In instances in which the work activity cannot be interrupted and/or the work environment does not permit the measurement of axilla temperature, axilla temperature can be quickly obtained when a rest period is possible.

Insulated and Zero-Gradient Skin Temperature

In a laboratory setting, skin temperature is continuously measured from multiple regions across the body surface using small, wired thermocouples or thermistors. Recent technological advancements have also led to the development of wireless sensors, including button-sized thermosensors (for example, iButton or Thermocron sensor), thermochromic thermometers (that is, liquid crystal strips), and infrared thermography that provide a more practical way to estimate body core temperature than mercury-in-glass or electric thermometers. However, because the temperature recorded may be influenced by external heat sources (for example, surfaces) [163], which can often exceed 50ºC [164], it is important to adequately insulate sensors placed on the skin surface. Indeed, several investigators have shown that placing insulating material (for example, foam or rubber) over a thermistor or thermocouple on the skin surface attenuates heat transfer between the covered area and surrounding heat sources, allowing skin temperature to more closely track variations in rectal [39, 162], esophageal [163], and muscle temperature [165, 166] during work in hot environments (that is, exceeding skin temperature). Others have employed a zero-gradient method to actively minimize the influence of extraneous heat sources on skin temperature [154, 161, 167]. This method uses a skin probe consisting of two insulating layers with thermistors positioned in the center of each layer. The lower layer is attached to the skin surface, while a heater covers the upper insulating layer (exposed to the external environment), which detects the temperature difference between the upper and lower thermistors and heats the upper insulating layer to remove any thermal gradient between the two layers [129]. With this design, heat transfer between the skin and external environment is nullified so that skin temperature may more closely track core temperature during work in hot environments [154].

Fluid Loss

If a sufficient change in the thermal status of peripheral (skin, muscle, and so on) and core temperature occurs during work in the heat, the 3–4 million eccrine sweat glands distributed across the body surface are activated by the preoptic anterior hypothalamus to secrete sweat and facilitate evaporative cooling [51, 52]. As such, monitoring whole-body sweat losses or the resulting changes in hydration state represents a potential way to quantify occupational heat strain.

Whole-Body Sweat Losses

In the laboratory, whole-body sweat losses are typically measured from gross mass changes (corrected for fluid and food intake, urine production, and respiratory mass losses) at specific time points or continuously (for example, ergometer mounted on a weighing scale) [168]. At the workplace, however, whole-body mass measurements are likely possible only prior to and at the end of the work shift—and correcting for fluid and food intake and urine production would require strict cooperation from the individuals under investigation. Furthermore, because sweat losses are influenced by various extraneous factors (for example, clothing and relative humidity), as well as intra- (for example, hydration state) and inter-individual factors (body morphology, aging) [169–171], predicting sweat losses is challenging. For these reasons, previous attempts to use sweat rate to quantify occupational heat strain have, to the authors' knowledge, been unsuccessful [172]. However, the monitoring of fluid loss—and therefore hydration status—can provide valuable insights regarding a worker's state of cardiovascular and thermal strain.

Hydration State

Whole-body sweat losses without adequate fluid replacement will cause progressive reductions in plasma volume (that is, total body water) as well as plasma hypertonicity (increased salt [ions] concentration in blood plasma), which in turn stimulate thirst and reduce urinary water loss [72, 173]. As such, acute measures of hydration state may provide an indirect index of heat strain in the workplace. However, although multiple techniques are available to assess hydration state—including isotope dilution, whole-body mass change, urinary and hematological markers, and sensory measures (that is, thirst sensation)—consensus has yet to be reached on the most precise measure of changes in hydration state. This is largely because fluid turnover is a complex and dynamic regulatory process, and the precision associated with each approach is situational [173]. Further, many of the more sensitive measurement techniques available are not suitable for field site use and require expensive equipment and extensive technical expertise to be conducted.

More simple and convenient markers such as thirst sensation, urine color, urine specific gravity, and body mass change may be used to assess heat strain in a field setting, albeit with some limitations. Thirst sensation is perhaps the most inexpensive and convenient index of fluid loss for occupational use. However, thirst is thought by some to not be perceived until fluid losses exceed 1–2% of body mass loss [79] and has shown poor agreement with criterion techniques during progressive dehydration [174]. Moreover, it is known that thirst perception is lower in older adults during fluid losses induced by exercise in the heat [175, 176]. Thirst sensation may therefore be unsuitable for monitoring occupational heat strain in some instances, particularly in older workers.

Urinary color and specific gravity (density) are also relatively inexpensive, easily obtainable markers of hydration state [174], although both measures require that workers cease work intermittently (such as during a break or rest period) to provide urine samples for analysis—a process that may take only a few minutes. Urine appearing as pale yellow corresponds to a state of euhydration [177], while darker colors indicate increasing fluid losses and therefore heat strain. Similarly, urine specific gravity can be measured with a handheld refractometer; greater fluid losses and therefore heat strain are indicated by higher urine specific gravity values. However, although both urine color and specific gravity can track gross changes in fluid loss [173], these urinary markers may be influenced by the consumption of a large volume of fluid (for example, consuming a bottle of water prior to measurement) [177]. Changes in euhydrated nude body mass forms another method to assess hydration state [178]. However, although this can easily be obtained prior to a work shift, this approach would likely be unsuitable during a work shift because workers would be required to periodically cease work to remove their clothing to measure nude body mass. With proper planning, measurements could easily be performed prior to leaving the work station for a job site, followed by measurements performed prior to the lunch break and again at the end of the work shift to quantify heat strain.

Heart Rate

In addition to supporting blood pressure regulation and maintaining oxygen delivery to the working musculature, increases in heart rate facilitate compensatory cardiovascular adjustments (cutaneous blood flow and cardiac output) to maintain heat balance (and therefore a stable body core temperature) during work in the heat [179]. These increases in heart rate occur in proportion to elevations in both metabolic demand and core temperature [127] and therefore provide an effective way to assess occupational heat strain. Because heart rate can be conveniently measured using low-cost, portable, and lightweight monitors equipped with a wireless transmitting device, several investigators have attempted to assess occupational heat strain by monitoring heart rate [137, 180]. More modern heart rate monitors can also incorporate predetermined thresholds, which provide a way to alert the worker or management that excessive strain may be present or will occur if the present work pace/exposure is continued. However, although monitoring either the average or recovery heart rate during work in the heat represents a convenient way to assess occupational heat strain, several factors (for example, intra- and inter-individual factors or nature of the work activity) must be carefully considered when attempting to set safe upper limits for heart rate that do not under-protect or provide overly conservative protection to each worker. The following subsections detail the use of average or recovery heart rate and the prediction of core temperature using heart rate to assess occupational heat strain.

Average Heart Rate During Work

In many occupations, workers may perform sporadic periods of high-intensity work, which may cause heart rate to briefly exceed a static upper limit in the absence of excessive heat strain (that is, false positive). Similarly, prolonged work eliciting a heart rate just below an upper threshold may represent a period of excessive heat strain that goes undetected (false negative). As such, it has been recommended that a moving average heart rate is used to define upper limits for safe work during activity [39]. ACGIH guidelines stipulate that a peak heart rate (assessed over several minutes) above ≥180 beats/min minus age should not be exceeded during a workday [118], while Minard et al. [181] suggest that a daily average heart rate of ≥120 beats/min would be indicative of excessive heat strain. Because most commercially available heart rate monitoring devices possess the capacity to average heart rate data collected over a given time, this approach provides a convenient and non-invasive way to prevent excessive heat strain.

Recovery Heart Rate

Because an increase in heat strain is also paralleled by a slower decline in heart rate following activity [137], others proposed the use of recovery heart rate (measured either by pulse palpation or portable monitor) to assess heat strain [180]. This approach is advantageous in that 1) it does not require a heart rate monitor with the capability to record and average data and 2) it typically involves the measurement of heart rate over the final 30 seconds of a 3-minute period as well as oral temperature during seated rest following a period of work. The value obtained during the last 30 seconds of each minute is then doubled to obtain recovery heart rates for the first, second, and third minutes. A heart rate ≥90 beats/min in the first minute or a ≤10 beats/min difference between the first and third minute coupled with an oral temperature ≥37.5ºC is considered indicative of excessive heat strain that may be present or will occur if work is continued.

Heart Rate Predictions of Core Temperature

More recently, a Kalman filter [182]—a mathematical algorithm often used in engineering and econometrics to track and predict data trends—has been used to estimate body core temperature from time-dependent changes in heart rate with acceptable precision (±0.63ºC) in both laboratory and field experiments involving work in the heat [183]. Given that heart rate can be conveniently measured, a commercially available heart rate monitor incorporating this model may provide a valid, practical, and economically viable way to obtain real-time estimates of body core temperature to prevent excessive occupational heat strain.

Physiological and Perceptual Strain Indices

Until this point, emphasis has been directed at the use of a single physiological variable to assess occupational heat strain. However, because work in the heat represents a challenge to body core temperature as well as integrated physiological processes of blood pressure, body fluid, and respiratory regulation, the validity of this approach has been questioned [47, 184–186]. Indeed, even though body core temperature is often considered the best indicator of heat strain, it is known that healthy, asymptomatic individuals often display body core temperatures that are the same as or higher than those who have collapsed from heat-related illnesses during sporting [187] or military [188] activity in the heat. For this reason, several investigators have attempted to combine multiple physiological or perceptual measures into a single heat strain index; the most well-recognized are the Normalized Physiological Strain Index [189], Modified Craig Index [190], Cumulative Heat Strain Index (CHSI) [191], Physiological Strain Index (PSI) [186], and Perceptual Strain Index (PeSI) [192]. These are briefly discussed in the following subsections.

The Normalized Physiological Strain Index

The Normalized Physiological Strain Index was perhaps the first index developed to quantify the physiological effort associated with work in various environmental conditions [189]. Physiological effort (E_p) is quantified as the combined (sum) effects of such work conditions on heart rate (E_h; Equation 4-1), skin temperature (E_s; Equation 4-2), rectal temperature (E_r; Equation 4-3), and sweat rate (E_w; Equation 4-4):

$$E_h = \frac{100}{H_2 - H_1}(H_3 - H_1) \quad \textbf{Eq. 4-1}$$

$$E_s = \frac{100}{S_2 - S_1}(S_3 - S_1) \quad \textbf{Eq. 4-2}$$

$$E_r = \frac{100}{R_2 - R_1}(R_3 - R_1) \quad \textbf{Eq. 4-3}$$

$$E_w = \frac{100}{W_2 - W_1}(W_3 - W_1) \quad \textbf{Eq. 4-4}$$

Where H_1, S_1, R_1, and W_1 are baseline values for heart rate, skin and rectal temperatures, and sweat rate determined when resting in a cool environment; H_2, S_2, R_2, and W_2 are the maximal heart rate, skin and rectal temperatures, and sweat rate (assessed by whole-body mass change) during severe heat stress; and H_3, S_3, R_3, and W_3 are the observed heart rate, skin and rectal temperatures, and sweat rate during the work conditions being evaluated. However, this index has obvious limitations when applied in a field setting because much of those physiological data may be challenging to obtain while workers are performing their regular duties (for example, sweat rate [192]). In addition, the arbitrary summation of each measure implies that all variables are of equal importance to quantifying physiological strain [193], which may lead to an under- or overestimation of a worker's state of physiological strain.

The Modified Craig Index of Physiological Strain

Measurements of heart rate as well as changes in rectal temperature and sweat rate have also been combined to yield the Modified Craig Index of Physiological Strain [194] (I_s; Equation 4-5):

$$I_s = (HR/100) + \Delta T_r + \Delta W_n \quad \textbf{Eq. 4-5}$$

Where HR is the observed heart rate, ΔT_r is the rise in rectal temperature from baseline (ºC/h), and ΔW_n is the rise in sweat rate (assessed by whole-body mass change) from baseline (kg/h). This index has been used to quantify heat strain in laboratory-based comparisons of cooling strategies [195, 196] and different clothing ensembles during heat exposure [197]. However, like the Normalized Physiological Strain Index, the use of this index in an occupational setting is limited by the requirement to obtain measurements of sweat rate, which can be challenging in the workplace [172].

The Cumulative Heat Strain Index

The Cumulative Heat Strain Index (CHSI) represents the integrated cardiovascular and thermoregulatory costs of maintaining heat balance and has been used to assess individual differences in heat tolerance [198] and to quantify the effects of clothing insulation and heat acclimation on heat strain [185]. The CHSI is calculated as the product of heart rate and the change in rectal temperature over time (Equation 4-6):

$$CHSI = [\textstyle\sum_0^t hb - HR_0 \cdot t] \cdot 10^{-3} \cdot \left[\int_0^t T_{re} \cdot dt - T_{re0} \cdot t\right] \; (units) \quad \textbf{Eq. 4-6}$$

Where $\sum hb$ is the accumulation of heartbeats over the measurement period (t), HR_0 is the baseline resting heart rate (beats/min), T_{re} is the measured rectal temperature, and T_{re0} is the baseline resting rectal temperature. Unlike the Normalized Physiological Index and the Modified Craig Index, which consider the heart rate and core temperature response to work to be additive, the CHSI takes both variables as complementary. With this approach, it is possible to detect excessive heat strain in individuals who may display a low heart rate but a high core temperature (or vice versa). Moreover, expressing heart rate and body core temperature as a change from baseline resting levels reduces the individual variability associated with those data. Two possible shortcomings of this index are that it has been shown to lack sensitivity in the early stages of work (<60 min) and during recovery, and it relies on work being performed for the same duration to draw comparisons between workers [186]. Perhaps for these reasons, few investigators have employed the CHSI to assess occupational heat strain [181, 199, 200].

The Physiological Strain Index

The Physiological Strain Index (PSI) incorporates both heart rate and rectal temperature to quantify the combined strain of the thermoregulatory and cardiovascular systems [186]. The strain placed on each system is scored out of five, then summed to represent physiological strain on a zero to ten scale (0 = no strain; 10 = very high strain). The index is suitable for evaluating physiological strain in instances in which rectal temperature ranges from 36.5ºC to 39.5ºC and heart rate is between 60 and 180 beats/min. The PSI can be derived using Equation 4-7:

$$\mathrm{PSI} = 5(T_{ct} - T_{c0}) \cdot (39.5 - T_{c0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \qquad \textbf{Eq. 4-7}$$

Where T_{ct} and HR_t are the observed rectal temperature and heart rate, respectively, and T_{c0} and HR_0 are the baseline resting values for rectal temperature and heart rate, respectively. The PSI has been validated as a suitable way to detect differences in physiological strain during work in the heat with differences in hydration state [186] and in both men and women [201]. Further, even though the PSI assumes a fixed maximal heart rate (180 beats/min; note: maximal heart rate is the greatest in young adults and declines with age), the PSI has been shown to accurately evaluate heat strain in older men and women (including women undergoing hormone replacement therapy) during exercise–heat stress, heat acclimation, and after aerobic training [202]. Because of its robustness and simplicity, the PSI has also been used to evaluate heat strain in various arduous occupations, including electrical utilities [68, 69, 203] and firefighting [204, 205].

However, because it is known that healthy individuals often display body core temperatures that are similar to or even greater than patients with heat illness [188], the utility of this index to detect unsafe levels of heat strain has been questioned [47]. To improve precision in such instances, Buller and colleagues [47] proposed a modification to the upper (critical) temperature limit (39.5ºC) in the PSI calculation to consider narrowing the thermal gradient between the core and skin associated with increasing heat strain. This modification is described in Equation 4-8:

$$T_{c(critical)} = 39.5\,\frac{(T_c - T_{sk}) - 4}{4} \qquad \textbf{Eq. 4-8}$$

Where $T_{c(critical)}$ is the modified upper limit specified in the PSI and T_{sk} is the mean skin temperature. Although this adaptive Physiological Strain Index (aPSI) has been used to effectively account for variations in clothing during work in the heat [47], obtaining accurate measures of skin temperature in some occupational settings can be challenging as noted previously.

Perceptual Strain Indices

Given the challenges of measuring physiological data in the workplace, others have relied on perceptual strain indices [192, 205–207]. These indices typically incorporate subjective scales of thermal sensation and rating of perceived exertion as surrogate indices of physiological strain; the most well-known is the Perceptual Strain Index (PeSI) [193]. Although such indices often show good agreement with physiological strain indices such as the PSI when evaluated in a laboratory setting [192, 207], there is recent evidence that a mismatch between perceptual and physiological strain occurs in the workplace [208, 209]. This disparity may be explained by cultural factors (for example, peer pressure) that encourage workers to report lower perceived strain even when heat strain is excessive [116, 117]. Further, it is known that individuals who routinely experience high levels of physiological strain will consistently underestimate it [192]. As such, perceptual strain indices do not appear to provide the precision required to be a suitable alternative to physiological data to prevent occupational heat illness in all workers. Therefore, the results obtained from the use of this index in the assessment of heat strain in workers must be used with caution.

5

TECHNOLOGIES FOR MONITORING OCCUPATIONAL HEAT STRAIN

Although physiological responses are easily measured using non-portable and non-reusable equipment in a laboratory setting, quantifying physiological strain in the field has additional barriers that must be considered. However, recent technological advancements have led to increases in the development of wearable monitors that purport to provide a non-invasive and portable way to quantify physiological strain. This section examines the utility of these monitoring systems with respect to equipment parameters (for example, cost, mode of data transmission, accuracy, portability, and tolerance to environmental conditions) and the applicability of each system as a strategy to provide early detection and to guide mitigation of work-related heat strain. Although other promising physiological monitoring systems are under development (for example, Vivonics MICROS and Bodytrak), the focus is on the commercially available systems at the time of this report's writing.

Commercially Available Heat Strain Monitoring Systems

Of the numerous portable systems available for monitoring physiological strain, six of the most commonly used and commercially available systems were selected as examples of the wearable systems available to detect and prevent excessive heat strain in the workplace (see Table 5-1). In the following subsections, these systems are described with respect to equipment parameters and their potential applicability as part of a heat-mitigation strategy for occupational use. It is important to note, however, that the review of these systems in this report is based solely on an assessment of their respective features and specifications. This report does not endorse or recommend the use of any specific product or manufacturer.

Table 5-1
Specifications of available wearable physiological monitoring systems

System	Measures[a]	Design	Dimensions[b]	Weight	Data storage capacity and sample rate	Run time	Operating conditions	Cost[c]	Other assets
Hexoskin (Carré Technologies Inc.)	HR, HRV, fb, V_T, V_E, location, motion	Sensor vest with logger	Logger: 13 x 42 x 72 mm	Logger: 40 g Garment: ~90 g	1 Gb at 1-256 Hz	≥14 hours with 1.5 hours recharge	n/a	$	Smart phone compatibility.
LifeMonitor EQ 02 (Equivital™)	HR, HRV, fb, T_{sk}, location, motion, T_{core} (GI pill)	Sensor chest belt with logger	Logger: 78 x 55 x 11 mm	Chest belt: 100 g Logger: 38 g	8 Gb at 15-256 Hz	≥24 hours with ~1 h recharge	-10 to +50°C; 0 to 95% R.H.	$$$$	Black Ghost software. Smart phone compatibility. Water and dust resistance. FDA and CE approval. Approved for hazardous areas.
Questemp II™ (3M)	T_{core} (aural canal)	Ear plug sensor wired to portable logger	Logger: 130 x 64 x 25 mm	Ear plug sensor: 4.2 g Logger: 283 g	12.5 h at 0.1 Hz	60 hours with disposable 9V battery	0 to 70°C; 0 to 95% R.H.	$$$	Water and dust resistance. Audible alerts. CE certified. Approved hazardous areas.
BioHarness™ 3.0 (Zephr performance systems)	HR, HRV, fb, location, motion, T_{sk} (to estimate T_{core})	Sensor chest belt with logger	Logger: 28 x 7 mm	Chest belt: n/a Logger: 18g	≤ 500 h at 1-250 Hz	12-28 hours with 3 hours recharge	-30 to 60°C; 0 to 95% R.H.	$$	Water and dust resistance. May be integrated into clothing.
BioNomadix® (Biopac Systems Inc.)	HR, HRV, fb, T_{sk}, muscle and brain activity, CO motion.	Data logger with receiver and transmitter module(s)	Logger: 94 x 58 x 23 mm; Receiver: 40 x 110 x 190 mm Module(s): 60 x 40 x 20 mm	Logger: 121 g Receiver: 380 g Transmitter modules: 54 g each	8 Gb at ≤2000 Hz	24 hours with 12 hours recharge	5 to 45°C; 0 to 95% R.H.	$$$$	Audible and vibration alerts. May be integrated into clothing. FCC and CE certified.
BioRadio™ (Great Lakes Neurotechnologies)	HR, HRV, fb, BP, SpO2, GSR, muscle and brain activity, T_{sk}, motion.	Hip-worn logger with wired accessory sensor(s)	Logger: 99 x 61 x 20 mm	Logger: 113 g	8 Gb at 250-1600 Hz	8 hours with 3-4 h recharge	n/a	$$$$	CE certified.

Notes:

[a] Does not include indirectly derived variables.

[b] Dimensions are length x width x height.

[c] Approximate system cost (<$1000 USD [$], $1000–2000 [$$], $2000–3000 [$$$], >$3000 [$$$$]).

Abbreviations: HR (heart rate), HRV (heart rate variability), *f*b (breathing frequency), V_T (tidal volume), $\dot{V}_E$ (minute ventilation), BP (blood pressure), T_{sk} (skin temperature), T_{core} (core temperature), BP (blood pressure), GI (gastrointestinal), R.H. (relative humidity), n/a (information unavailable or not applicable), FDA (U.S. Food and Drug Administration), CE (conformity to European health and safety standards), FCC (Federal Communications Commission certified), SpO_2 (oxygen saturation), CO (cardiac output), GSR (galvanic skin response).

The information presented was extracted from website documentation (Hexoskin: https://www.hexoskin.com/pages/downloads; Equivital™: http://www.equivital.co.uk/products/tnr/sense-and-transmit; Questemp II™: http://www.raeco.com/products/heatstress/questemp-II.html; BioHarness™ 3.0; https://www.zephyranywhere.com/resources/documentation; BioNomadix®: https://www.biopac.com/product-category/research/bionomadix-wireless-physiology/; BioRadio™: https://glneurotech.com/bioradio/bioradio-specifications/).

Hexoskin

The Hexoskin (https://www.hexoskin.com/pages/downloads) by Carré Technologies Inc.©, is a lightweight vest and compact logger (41 x 73 x 13 mm) with a combined mass of <200 g. The system includes an integrated three-lead electrocardiogram; triaxial accelerometer; and breathing sensors for the derivation of heart rate, heart rate variability (HRV), breathing and ventilation rate, activity intensity, peak acceleration, steps, cadence, and sleep positions. Although the X-model contains an additional skin thermistor and pulse oximeter (integrated into a head band) for the measurement of skin temperature as well as systolic blood pressure and oxygen saturation (respectively), at the time this report was written, this system was not available for purchase. The sensor vest is suitable for use during intense activity and is manufactured in multiple male and female sizes to optimize fit and therefore measurement resolution. The logger can store more than 157 hours of data (recorded at up to 256 Hz HRV) and may record for long durations before charging (14 hours [the classic model] to 24 hours [the X-model]). Data may be monitored in real time and synced to an online server for storage using a Bluetooth-enabled mobile device, although recording is restricted to one logger per device. Further, although the device has been validated during various ambulatory activities [210], it has not yet, to the authors' knowledge, been used to assess heat strain in an occupational setting. Regardless, as outlined previously, the continuous measurement of physiologic responses during work in the heat can provide valuable insights about the worker's level of physiological strain.

Equivital™ LifeMonitor

The Equivital™ EQ02 LifeMonitor (http://www.equivital.co.uk/products/tnr/sense-and-transmit) is a torso-worn sensor for real-time logging and transmitting of multiple physiological responses. The monitor comprises a chest belt and shoulder strap with integrated sensors (100 g) as well as a miniaturized logging device (78 x 55 x 11 mm; 28 g) positioned on the left side of the chest with 14 hours of battery life that may be extended to 48 hours with an external battery pack. The sensor belt is lightweight and available in multiple male and female sizes to ensure high measurement resolution even during high-intensity activity. The logger can simultaneously record and store ~8 weeks of data on heart rate, HRV, respiratory rate, skin temperature, and body position. Moreover, when combined with third-party wired or wireless devices, additional data on oxygen saturation, galvanic skin response, gastrointestinal pill (body core temperature), dermal temperature patch (skin temperature), and global positioning may be recorded. The manufacturer indicates the system is also fully operational in temperature (-10–50ºC) and humidity (0–95% relative humidity) extremes, possesses water- and dust-proofing, has both U.S. (Food and Drug Administration [FDA]) and European (European Conformity [CE]) safety certifications, and is claimed to be suitable for use in hazardous environments—although it is uncertain whether the system is arc-flash resistant.

An additional feature of the Equivital™ system is the Black Ghost real-time monitoring interface, which incorporates sensor, environmental, and global positioning data to provide managers and supervisors with a heat strain index to identify workers experiencing excessive heat strain or who may be likely to experience a heat-related event if work is continued. This software also allows individualized alert thresholds to prevent excessive heat strain in heat-intolerant workers while maximizing productivity in more heat-tolerant workers. This technology is therefore capable of simultaneously protecting multiple workers or employees in remote locations (for example, mining, offshore drilling platforms, and so on) who may have limited supervision or access to medical attention. The Equivital™ system has been used to assess the physiological strain associated with various industries, including firefighting, electric utilities, and emergency health care [203, 211, 212] and has been proven to prevent heat-related injury during military training activities [59, 188, 213, 214]. As such, the combined use of the Equivital™ system and Black Ghost monitoring interface provide a suitable way to monitor occupational heat strain and mitigate heat-related illness in one or more workers. Although the high cost of the system and non-reusable accessory devices for directly monitoring core temperature (that is, gastrointestinal pills) may prevent company-wide use in some industries, limiting the use of the unit for high-risk work and/or weather conditions would be an effective approach to mitigate these costs.

Questemp™ II

Marketed as a miniature instrument for the personal monitoring of heat strain, the Questemp™ II (3M™) (http://www.raeco.com/products/heatstress/questemp-II.html) quantifies heat strain from estimates of body core temperature using a small, ear sensor assembly (4.2 g) with a water- and dust-resistant portable logger encased in aluminum (130 x 64 x 25 mm; 283 g). The ear sensor assembly is wired directly to the logger and comprises a speaker and disposable, ear-molded plug that surrounds a thermistor along with a second sensor to monitor environmental temperature. The aural thermistor provides real-time estimates of body core temperature from the aural canal, while the second sensor compensates for external temperature artefacts (that is, high or low ambient and surface temperatures). Data may be logged at 0.1 Hz and managed using companion software (QuestSuite™ Professional). The logger may be mounted to a belt or pocket and is powered by 9V disposable batteries, providing up to 60 hours of use. Another feature of the unit is its ability to provide audible alerts with the integrated speaker when excessive heat strain is detected. The user is notified with an initial alarm when aural temperature is between 38.0ºC and 39.0ºC (recall that the ACGIH TLVs limit work beyond a body core temperature of 38.0ºC, although brief periods above this threshold is permitted); it will automatically produce a secondary alarm when that temperature increases by a further 0.5ºC. Further, the unit may be calibrated to body core temperature as estimated from the mouth with a separate oral temperature thermistor before use for increased precision. Most importantly, the unit is both water- and dust-proof, has CE (European Conformity) safety certification, and is approved by the manufacturer for use in hazardous environments. In the absence of large deviations in ambient temperature

(±10.0ºC), the unit is said to quantify body core temperature with an accuracy of ±0.1ºC across the 32.0–40.0ºC range in a variety of environmental conditions (0.0–70.0ºC; 0–95% relative humidity). However, although others have suggested that the unit does not provide the precision required to act as a surrogate to rectal temperature [215], even with additional insulation around the ear canal (for example, ear muffs) [63], its compact and robust design makes it a suitable method for monitoring occupational heat strain in most instances.

BioHarness™

Using a similar design to the Equivital™ LifeMonitor (https://www.zephyranywhere.com/resources/documentation), the Zephyr Performance Systems BioHarness™ 3.0 comprises a lightweight, 50 mm chest strap with an integrated monitor (28 x 7 mm; 90 g) positioned at the level of the axilla. The system incorporates electrodes, triaxial accelerometer, and capacitance sensors for the measurement of heart rate, motion, and breathing rate, respectively, as well as a skin thermistor for the prediction of body core temperature. Data may be recorded for 12–28 hours before recharging, even in harsh environments (-30.0ºC to 60.0ºC; 0–95% relative humidity). With the addition of wireless modems, data from multiple workers within a 2-mile range may be remotely monitored and recorded. The unit has proven valid in a laboratory setting [216, 217] and may provide a lightweight and relatively non-invasive way to monitor physiological strain in multiple workers across the workplace.

BioNomadix®

The BioNomadix® (https://www.biopac.com/product-category/research/bionomadix-wireless-physiology/) by BioPac Systems Inc. is a modular, wireless physiological monitoring system designed for both laboratory and field use. The system comprises a logger (94 x 58 x 2.3 mm; 121 g), signal amplifier (40 x 110 x 190 mm; 380 g), and one or more transmitter modules (each 60 x 40 x 20 mm; 54 g). Each transmitter module possesses two channels and, with compatible accessories (for example, transducers, electrodes, and vest with integrated sensors), can be used to measure multiple physiological variables (for example, heart rate, breathing rate, skin temperature, cardiac output, activity level, and muscle and heart activity) for long durations (~24 hours). However, although the BioNomadix® gives the user the ability to measure several physiological responses as indices of heat strain, the external wiring associated with the transmitting modules may be cumbersome in an occupational setting—particularly when those devices are worn underneath personal protective clothing. Further, the system possesses CE certification, and the electromagnetic interference from the device adheres to limits approved by the U.S. Federal Communications Commission (FCC), making it suitable for use in most occupational settings.

BioRadio™

Similar to the BioNomadix®, the BioRadio™ (https://glneurotech.com/bioradio/bioradio-specifications/) by Great Lakes Neurotechnologies is a fully portable and wireless physiological monitoring system comprising a compact, hip-worn logger (99 x 61 x 20 mm; 113 g) with multiple channels for accessory sensors such as a pulse oximeter, electrocardiogram, electromyogram, skin thermistor, blood pressure cuff, and spirometer. With these additional sensors, several physiological responses can be simultaneously recorded and collected via a Bluetooth-compatible portable computer, including heart rate, skin temperature, and muscle and brain activity. The logger also contains a triaxial accelerometer for the measurement of activity level and movement. Data may be collected for up to 8 hours; the system may be recharged in 3–4 hours. However, like the BioNomadix®, the external wiring associated with the transmitting modules may be cumbersome in an occupational setting—and previous attempts to use the BioRadio™ to monitor physiological strain outside the laboratory are sparse [218]. It therefore remains uncertain whether the system is suitable for use in harsh industrial environments.

Key Challenges to Implementing Wearable Physiological Monitoring in the Workplace

Unlike physiological monitoring systems for sporting or patient monitoring use, a heat strain monitor for use in occupational settings must possess several unique features to act as a successful strategy to mitigate heat-related injury. To obtain a better sense of these features, a survey containing three open-ended questions was administered to 19 health and safety managers from the electric power generation industry across the United States through EPRI's Heat Stress Working Group (Program 62). Each question was aimed at gathering information related to the complications associated with using the physiological monitoring systems (described previously) in their workplace, features of a heat strain monitor they perceive as desirable, and the factors that may reduce worker compliance with heat strain monitoring. From the responses obtained, four key challenges to the use of each were identified: 1) the accuracy and durability of each system in harsh industrial environments; 2) the method of data collection, transmission, and interpretation; 3) the potential costs of implementing heat strain monitoring; and 4) the possibility that physiological monitoring may modify worker behavior (also known as *reactive error*). These challenges are summarized in the following subsections.

1) Accuracy and Durability in Harsh Industrial Environments

The portable physiological monitoring systems discussed previously are primarily designed for wireless patient monitoring in a laboratory, hospital or home setting, or for the ambulatory monitoring of physiological data in a sporting context. However, because of the nature of many industries, workers are exposed not only to hot and humid environments, but also to noxious gases, dirt and debris, high surface temperatures, proximity to or contact with energized equipment and materials, and water immersion. These harsh work conditions present a challenge for the operation and function of all equipment—including portable physiological monitoring systems. As such, for a physiological monitoring system to function as part of a potential strategy to mitigate occupational heat strain, the logging device and integrated sensors in each system must be able to retain their functionality and precision under such conditions. Although some manufacturers claimed that their systems were suitable for use in hazardous areas and possessed water- and dust-resistance, no investigators to our knowledge have evaluated whether the measurements obtained are valid and reliable in such conditions. For instance, high surface temperatures can rapidly modify skin temperature independently of body core temperature and therefore introduce bias into the approximation of heat strain from temperature measures at the skin surface [163] or aural canal [154]. As such, research is needed to evaluate the utility and durability of these physiological monitoring systems in harsh industrial environments to determine whether wearable physiological monitors may be successfully implemented as part of a heat strain management program.

2) Data Collection, Transmission, and Interpretation

Of greatest concern for the immediate implementation of a heat strain monitor is the method of data collection. First, it remains uncertain whether wearable monitors can be incorporated into the personal protective clothing systems worn in all industries. Further, in many industries—particularly electric power generation and delivery—materials that are non-flammable or flame-resistant, non-combustible, hypoallergenic, and resistant to arc flash and electromagnetic fields must be used in the construction of a heat strain monitor to satisfy safety requirements. In addition, given that a work shift may last ≥12 hours, the run time (battery life) and subsequent recharging time represent important considerations for successfully protecting workers over the course of an entire work shift. Nonetheless, almost all manufacturers claimed a run time of ≥12 hours, with a recharge time of <8 hours or the use of disposable batteries, which is generally consistent with requirements for use during prolonged, consecutive work shifts.

The method of data transmission and integration represents an additional challenge to the implementation of personal heat strain monitors in the workplace. Each monitoring system provides partner software that can be used with a portable computer or smartphone to track physiological data from the worker(s) being monitored. However, although some devices provide audible alerts to notify the wearer when a given heat strain index (for example, core temperature or heart rate) exceeds a predetermined level, relying on a single physiological variable to quantify excessive heat strain can increase the likelihood of identifying false negatives and false positives. For instance, healthy, asymptomatic individuals often display body core temperatures that are the same as or higher than those who have collapsed from heat-related illnesses [188]. As such, the data transmission and integration software available with some systems must be directed at providing guidance to workers and safety managers to assist in identifying excessive heat strain that may compromise health.

3) Cost

A physiological monitor with the capacity to detect excessive heat strain and mitigate heat-related illness is a benefit for both the health and well-being of employees and for reducing the costs associated with heat-related injuries. Physiological monitoring also maximizes productivity by ensuring that more heat-tolerant workers do not cease work in conditions that may approach or exceed safe work limits (for example, ACGIH TLV®). However, the high costs associated with purchasing wearable monitors for all employees may be prohibitive for companies. Many of the systems evaluated also require additional ongoing costs such as the purchase of different sizes of integrated clothing to fit each worker, non-reusable gastrointestinal pills for the measurement of core temperature, and repair and maintenance costs. These costs could be reduced by monitoring workers only for work and/or weather conditions considered “high-risk” and/or employees who, because of their age, health status, or physically demanding occupation, may be more vulnerable to heat-related illness. However, although we possess some knowledge of the inter-individual factors (for example, age, sex, or chronic disease) that may make a worker more susceptible to heat-related injury [38], it is challenging and perhaps impossible to consider the intra-individual factors (for example, dehydration, alcohol consumption, or sleep loss) that may predispose a worker who is ordinarily at low risk of heat-related injury. As such, there is a general need for more cost-effective systems for physiological monitoring to be used as a company-wide strategy to mitigate heat-related illness.

4) Modification to Worker Behavior

Although most of the heat strain monitors identified are relatively small and lightweight—and would therefore be less likely to encumber a worker during activity—it is possible that physiological monitoring per se may modify worker behavior (reactivity). Though speculative, this may be characterized by an increase in activity level and a reluctance to cease work even when experiencing excessive heat strain or perhaps a reduction in work effort to avoid displaying greater fatigue than their coworkers. Unfortunately, the former may counterintuitively exacerbate heat strain, while the latter may reduce productivity particularly in more heat-tolerant workers. Although such behavior modifications may be minimized if physiological monitoring were routine or if the supervisory team intervened, research is needed to identify whether and to what extent physiological monitoring may modify worker behavior.

Further, it is known from anecdotal evidence obtained during field studies in the mining and electric utilities industry conducted by the project team [68, 69, 106, 108, 219] and comments from industry safety experts that many workers express a general displeasure with having their physiological responses monitored. This stems from several factors, including the perception that heat strain does not adversely influence their health or work performance, that wearing a heat strain monitor in addition to their already extensive protective clothing system is inconvenient and uncomfortable, and the belief that their physiological data may be used to assess their work productivity. It is possible that this perception may be modified through more extensive education on the dangers of excessive heat strain or the integration of a heat strain monitor in protective clothing (for example, within coveralls, radio, or work shirt). However, it remains uncertain whether such factors may reduce worker compliance with physiological monitoring—and this represents an important area of future research for successfully implementing heat strain monitoring as part of a greater heat-management program.

6
CONCLUSIONS AND RECOMMENDATIONS

In this project, the team 1) reviewed the physiological responses that may be monitored at the workplace as precursors or indicators for heat-induced physiological strain, 2) reviewed available personal heat strain monitoring systems with respect to equipment parameters and the applicability of each system for use in occupational settings, and 3) identified potential challenges to implementing these devices in physically demanding occupations. The main conclusions are as follows:

1. In most industries, occupational heat stress originates from harsh environmental conditions, the requirement to wear heavy and impermeable protective clothing, and the high metabolic heat load from performing physically demanding tasks.
2. Intense work in high heat stress conditions is associated with progressive rises in body core temperature, cardiovascular strain, and fluid depletion, which can lead to heat stroke or death. Excessive heat stress may also cause psychophysical strain and lead to labor losses by compromising worker productivity and safety.
3. Strategies to mitigate occupational heat stress may be classified into four levels:
    a. Level IV: self-monitoring, providing low-level protection.
    b. Level III: monitoring using environmental parameters, providing moderate protection.
    c. Level II: monitoring using environmental parameters, clothing, and metabolic rate, providing moderate protection.
    d. Level I: monitoring of heat strain, providing the highest level of protection.
4. The physiological responses mostly measured in occupational settings as ways to quantify excessive heat strain include body core temperature (directly or indirectly), skin surface temperature, fluid loss, and cardiovascular strain.
5. Monitoring one or more indices of heat strain using a wearable physiological monitoring system in high heat stress conditions represents a significant advancement in our ability to detect and mitigate heat-related illness in an occupational setting. These systems provide individualized and real-time protection from excessive heat strain during arduous work in hot conditions and may be particularly valuable for workers who are more susceptible to heat-related injury because of their age, health status, or physically demanding occupation.
6. Despite the benefits of available wearable monitoring systems, in the team’s review, at the present time these systems do not appear to provide a cost-effective solution to manage heat strain in each individual worker (recall that their use may be limited to heat-vulnerable individuals and/or high-risk work or weather conditions to reduce cost) and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy existing safety requirements (for example, flame and arc resistance). Further, most systems lack effective guidance in the interpretation of recorded physiological data to identify workers who may be experiencing excessive heat strain or who are likely to develop heat-related injury if work is continued.
7. It remains unknown whether workers will tolerate physiological monitoring or whether wearing these devices may adversely affect their behavior. For these reasons, research and

product development should be directed at physiological monitoring solutions that are cost-effective, compliant with safety regulations, and well-tolerated by workers to be suitable for use as part of a company-wide heat strain management strategy.

Based on the knowledge gained from this project, the following recommendations are offered:

1. It is inadvisable to rely solely on the workers themselves to modify their behavior (for example, reducing work output or increasing rest) to mitigate occupational heat injury when heat strain is perceived to be excessive or when symptoms of heat illness are experienced. Indeed, the evidence presented in this report suggests that self-monitoring provides only low-level protection to worker health during heat stress.
2. It is recommended that industries use caution when assessing the level of heat stress using environmental parameters alone (for example, WBGT) or environmental and clothing parameters as well as the estimated rate of metabolic heat production as ways to mitigate occupational heat injury. Although heat stress assessment provides better protection to worker health than relying solely on self-monitoring, this approach cannot account for the inter- and intra-individual factors both within and beyond the worker's control that can modify a worker's level of physiological strain to a given heat stress. As such, the assessment of heat stress using only environmental parameters may result in the early termination of work and a reduction in productivity in more heat-tolerant workers (false positive), or it may compromise the safety of less heat-tolerant workers who may develop heat-related illness even in mild conditions (false negative).
3. The project team suggests the use of physiological monitoring within a greater heat injury mitigation program. Monitoring one or more indices of physiological strain provides more individualized protection by considering both the intra- and inter-individual factors that may independently modify heat strain. This ensures that productivity is maximized in more heat-tolerant employees when working in high heat stress conditions and that heat injury is prevented in less heat-tolerant workers when working in temperate conditions. However, although occupational heat strain may be quantified from measures of body core temperature, skin surface temperature, fluid loss, and cardiovascular strain, it is recommended that safety managers and personnel consider the precautionary steps discussed in this report to ensure that these measures are representative of a worker's state of heat strain.
4. Although there has been a recent surge in wearable technology that purports to provide a non-invasive means of quantifying one or more indices of physiological strain, they are costly and, for the most part, have not yet been validated in harsh industrial environments or designed to satisfy safety requirements (for example, flame and arc resistance). These costs could be reduced by monitoring workers only during "high-risk" work and/or weather conditions and/or those who, because of their age, health status, or physically demanding occupation, may be more vulnerable to heat-related illness; however, most systems also lack effective guidance in the interpretation of physiological data to identify signs and symptoms of excessive heat strain. It also remains unknown whether physiological monitoring may adversely affect worker behavior. As such, it is recommended that future research be conducted to identify systems that are compliant with existing safety guidelines, offer acceptable precision in harsh industrial environments, and are well-tolerated by heat-vulnerable employees in high-risk conditions.

Although physiological monitoring can serve as an important tool to manage the health and safety of a worker during exposure to hot environments, more work must be done to evaluate the efficacy of monitors in the context of overall heat stress management strategies and options. This will require the assessment of the physiological responses obtained from select monitoring systems against gold-standard measurements performed in a controlled laboratory setting employing work intensities, ambient conditions, and clothing systems (factors that define the level of heat stress) typical of jobs performed by workers in the power generation and delivery sectors. Verification of laboratory-based findings will be required and should be conducted in a field setting under "real-work" conditions. This should be followed by validation trials to develop, finalize, and implement appropriate physiological measurement strategies and guidelines for heat stress management in electric utility workers.

7
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