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Wearable Physiological Monitoring to Assess Heat Strain in Response to Heat Exposure

White Paper

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Developed by members of the AIHA Thermal Stress Working Group.

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Legal Disclaimer

FDA oversight of physiological monitoring devices is outside the scope of this white paper; however, there are ongoing discussions regarding the FDA's jurisdiction on such matters (Dunmire, 2024). This white paper does not address FDA or legal matters.

Acronyms

ACGIH: American Conference of Governmental Industrial Hygienists

NIOSH: National Institute for Occupational Safety and Health

OEHS: Occupational and Environmental Health and Safety

PSI: Physiological Strain Index

WHO: World Health Organization

AL: Action Limit

ANSI: American National Standards Institute

HRR: Heart Rate Recovery

OSHA: Occupational Safety and Health Administration:

PPE: Personal Protective Equipment

RH: Relative Humidity

TLV: Threshold Limit Value

WBGT: Wet Bulb Globe Temperature

REL: Recommended Exposure Limit

OEL: Occupational Exposure Limit

EXECUTIVE SUMMARY

Climate change has led to more frequent and severe extreme heat events, increasing workers' risk of heat-related injuries and fatalities. To adequately protect workers from the dangers of heat exposure, a comprehensive heat stress management plan is imperative. A successful heat stress management plan should integrate physiological measures, subjective measures, and environmental assessments to protect workers in indoor and outdoor environments. Examining physiological measures using wearable physiological monitoring systems can address the considerable intra- and inter-individual variability among workers' responses to the same heat load. Wearable physiological monitoring to assess heat strain allows for timely, continuous, individualized monitoring of employees through various sensors and variables. The purpose of using this technology include use for risk assessment and decision making (i.e., set thresholds to alert users and safety professionals to perform a certain action), conduct assessments of interventions, and inform workers of their own physiology (i.e., use for educational purposes). The most common variables utilized to evaluate heat strain include:

- Core body temperature
- Heart rate
- Physiological Strain Index (PSI)

Limitations of the use of physiological monitoring to assess heat strain include cost, user acceptance, data analysis and management, data privacy, and physiological monitoring performance. Occupational and Environmental Health and Safety (OEHS) professionals are encouraged to examine the validity of the physiological monitor and quality of a decision that emerges from the physiological monitoring (i.e., validity of decision) before implementation. The effective use of wearable physiological monitoring in heat stress management results from a collaborative approach with an interdisciplinary team who can work together to establish the assessment purpose, develop clear guidelines on using data to modify or stop work, implement the program, and adjust accordingly. As advancements in physiological monitoring are still being made, OEHS professionals will need to actively pursue updates and recommendations.

Introduction

Heat stress is a serious problem for workers around the world. Heat stress is the net heat load to which a worker may be exposed due to the combined effects of metabolic heat (i.e., physical activity), environmental heat (e.g., ambient temperature, solar radiation, humidity), and clothing (e.g., lightweight cloth clothing versus vapor-resistant protective coveralls). The combination of these job factors dictates the level of heat stress. In turn, the level of heat stress influences workers' overall physiological response known as heat strain. (Astrand et al., 1975; Bernard et al., 2024; Binazzi et al., 2019; Borg et al., 2021; Flouris et al., 2018; Gubernot et al., 2015). An individual exposed to extreme levels of heat stress can be subjected to severe physiological responses that can manifest with short and long-term health outcomes such as kidney disease, heat-related illnesses, and impaired cognitive and neurological function (Culp and Tonelli, 2019; Gubernot et al., 2014, 2015; Houser et al., 2021; López-Gálvez et al., 2021; Mazloumi et al., 2014) Severe physiological responses resulting from high heat stress can also lead to reduced productivity and poor safety outcomes on worksites (Axelson, 1974; Flouris et al., 2018; Spector et al., 2019)

Extreme temperatures will continue to rise as the frequency, intensity, and duration of heat waves increase due to climate change (Chen et al., 2020). Climate change is a major public health priority that places many individuals at risk for life-threatening heat-related injuries and illnesses. Workers are a particularly vulnerable population as many frequently engage in heavy physical exertion in hot environments for prolonged periods of time (Astrand et al., 1975; Binazzi et al., 2019; Borg et al., 2021; Flouris et al., 2018; Gubernot et al., 2015).

Few countries have promulgated legislation that requires employers to implement evidence-based strategies and heat-related emergency response procedures to prevent, recognize, and treat heat-related illnesses. Some countries such as Gabon, Mozambique, Cameroon, and South Africa require employers to offer rest breaks, personal protective equipment and medical monitoring (NRDC, 2021). Six European Union countries (Belgium, Hungary, Latvia, Montenegro, Slovenia, and Spain) have legislation that prohibit physical work at certain temperature thresholds (NRDC, 2021). Currently, there is no federal heat stress standard in the United States, however, the proposed rule was submitted to the Office of the Federal Register for publication on July 2nd, 2024. The General Duty Clause covers heat stress hazards as it requires employers to "furnish to each of his employees' employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm." This faces several challenges when issuing citations as the Occupational Safety and Health Administration (OSHA) must "prove" the existence of a recognized heat hazard, which is left up for interpretation (Occupational Safety and Health Administration, Heat Stress Hazards, 2024).

In the absence of a federal standard (as of July 2024), several US states including California, Washington, Colorado, Oregon and Minnesota have instituted heat stress regulations (Occupational Safety and Health Administration, Heat Standards, 2024). In most cases, employers, supervisors, and occupational and environmental health and safety (OEHS) professionals are responsible for implementing a heat stress management plan and determining what specific interventions and strategies are appropriate for their given work environment and workers. Managing heat stress and strain is critical to ensuring health and safety, and it is informed by a comprehensive approach that involves timely assessment and early intervention.

Although current heat stress and strain management recommendations may be considered effective, heat-related illnesses and fatalities continue to occur at alarming rates (Davis 2022). The urgency of advancing current methods cannot be overstated as the human cost of inaction is simply too high. Shortcomings of current heat stress management recommendations include the reliance on subjective measures and environmental assessments, which do not account for individual physiological variations in response to a given heat load (ANSI/ASSP A10.50, Standard Stress Management, 2024). This is a major shortcoming as individual factors such as fitness level, heat acclimatization status, disease status, pre-existing health conditions, medication use, biological sex, and age influence the human physiological response to heat stress (Bedno et al., 2014; Brearley et al., 2017; Cramer and Jay, 2015; Morrissey et al., 2020; Schmeltz et al., 2015). A cohesive heat stress management plan should integrate physiological measures, subjective measures, and environmental assessments to holistically assess workers and their working environment.

In recent years, wearable monitoring devices that measure physiological responses to heat stress have emerged for inclusion in heat stress management plans to account for inter-individual variability among workers (Notley et al., 2018). Evaluating heat strain experienced by individual workers can provide timely, continuous data to inform health and safety decisions based on workers' physiological responses alongside other mitigation strategies. Although current technology advancements make it easy to monitor and make decisions based on physiological data, there is limited guidance on the benefits and limitations of its use, what variables are appropriate, and what steps should be considered when selecting devices and variables.

Therefore, the objectives of this white paper are to educate OEHS professionals on:

1. The physiological effects of working in the heat (Chapter 1)
2. Variables to consider when evaluating physiological heat strain, safety outcomes, and behavioral changes (Chapter 2)
3. Benefits and limitations of using wearable physiological monitoring to assess physiological strain in response to heat stress (Chapters 3 and 4)
4. How to build an effective assessment team to assist with data integration and interpretation (Chapter 5)

This white paper will offer a detailed exploration of the above aspects, laying the groundwork for a holistic understanding of the incorporation of wearable physiological monitoring into heat stress management. The term "wearable physiological monitoring" will be used in this paper but has alternative names, such as "personal physiological monitoring" and "wearable technology." The authors of this paper believe that a wearable physiological monitoring systems is one component that must be used as a complement to an existing heat stress management plan that includes strategies such as work-to-rest ratios, environmental monitoring, appropriate hydration and access to toilets, body cooling strategies, and heat acclimatization. The systematic collection of exposure data and observation of physiological or perceptual responses to heat is an essential element of the heat stress management program (ANSI/ASSP Z10.0 Standard; ISO 45001, 2018). By bridging technological advancements with traditional safety measures, we aim to contribute to the ongoing efforts to mitigate heat strain and foster safer environments across various fields and applications. Because technology progresses rapidly, this white paper is expected to undergo continuous evolution.

Chapter 1: Physiological Effects of Working in the Heat

Working in high temperatures triggers a progressive series of physiological responses to protect the body from extreme hyperthermia. A continuous rise in core body temperature, the global internal temperature of the body, eventually results in an overload of these control measures, which may result in heat-related symptoms, illnesses or a fatality (e.g., exertional or classical heat stroke) (Casa et al., 2015). The onset of physical activity elicits a rise in core body temperature, skin temperature, heart rate, sweating, perceived exertion, and subsequent premature onset of fatigue (Périard et al., 2021). During work under heat stress, one of the ways the body dissipates heat is by increasing blood flow to the skin to regulate core body temperature through heat exchange with the environment. This is accomplished primarily through an increased heart rate (Bernard and Kenney, 1994). The skin is the primary thermal interface between the body and the environment for heat exchange. Heat exchange mechanisms include conduction, convection, radiation (i.e., dry heat transfer) and at greater heat loads, evaporation (i.e., through sweat). Evaporation of eccrine sweat from the skin surface leads to energy release from the body to the environment, which attenuates the rise in skin temperature and blood redistribution to blood vessels. This makes it one of the most effective physiological mechanisms to transfer heat from the body during physical work under heat stress (Périard and Racinais, 2019). However, prolonged work in the heat without adequate fluid replacement will result in a loss of body water from sweat, which can further increase heart rate. As a result, for every 1% body mass lost during exercise in the heat, the mean increase in heart rate is approximately 3-4 beats per minute (Adams et al., 2014).

When physical work is performed under *compensable heat stress*, metabolic heat production can be matched by heat loss. In this event, heat can be lost to the environment so that the body is not in a continuous state of heat gain. Therefore, increases in core body temperature depend only on metabolic rate (Lind 1963; Bernard et al., 2023). However, as physical activity duration, intensity, or environmental conditions (i.e., ambient temperature, humidity, solar radiation) increase, there is a shift from a state of *compensable* heat stress to *uncompensable heat stress*. Under uncompensable heat stress, heat gain exceeds heat loss and cardiac output can no longer successfully meet the thermoregulatory demands (Epstein and Yanovich, 2019). Uncompensable heat stress increases risk of developing heat-related illness as core body temperature continues to rise and presents with increased physiological strain (i.e., high skin temperature, heart rate, perceived exertion, fatigue). The body's ability to alleviate heat strain is impaired and it is imperative that heat stress and strain management strategies are employed to ensure workers are safe under uncompensable conditions.

Outcomes that present under uncompensable heat stress are detectable by multiple physiological variables through physiological monitoring, which can be used to evaluate the magnitude of heat strain and identify the degree to which workers are being adversely affected by heat. These same variables may also inform decisions regarding worker rest and recovery. Variables that can be used to monitor and assess heat strain in an individual to mitigate rise in physiological strain are outlined in this document.

Chapter 2: Common Variables to Consider When Assessing Heat Strain Using Wearable Technology

Evaluating heat strain requires an understanding of physiological variables that can be monitored. This section provides an overview of variables such as core body temperature, heart rate, and physiological strain index (PSI) and their significance in assessing heat strain. Other important variables related perceptual and subjective responses to physical work in the heat will not be discussed but should be considered in a heat stress management plan.

Core Body Temperature and Estimated Core Body Temperature

Core body temperature is the main regulated variable in thermoregulation and presents as the strongest predictor of heat-related illness during physical work in the heat in both the laboratory and field settings (Périard et al., 2021). Monitoring core body temperature can provide early detection and intervention to reduce the likelihood of reaching critically high core body temperature values that are associated with heat illness or performance decrements (Dolson et al., 2022).

Non-exercising core body temperature in a thermoneutral environment (e.g., room temperature) ranges between 97.5°F – 99.5°F (36.4°C - 37.5°C) (Tansey and Johnson, 2015). When performing work with added stressors (e.g., high ambient temperature, high relative humidity, personal protective equipment, strenuous exercise) without proper rest breaks and hydration, core body temperature will continue to rise (Montain et al., 1994). Core body temperature is used as one of the two diagnostic criteria for exertional heat stroke, which is a life-threatening medical emergency (Casa et al., 2015). Exertional heat stroke presents with central nervous system dysfunction reflective of symptoms of heat strain (e.g., confusion, garbled speech, unusual behavior, altered consciousness) and a core body temperature above 104/105°F (Casa et al., 2015). These critically high core body temperatures are linked to decrements in physical and cognitive performance and can produce life-threatening complications (Casa et al., 2015). While the threshold at which exertional heat stroke occurs varies among individuals, sustained hyperthermia can also hinder productivity and contribute to an unsafe working environment even in the absence of heat injury (Flouris et al., 2018).

There are several organizations and governing agencies who have proposed physiological monitoring guidelines to limit rise in core body temperature (NIOSH, 2016). The World Health Organization (WHO) and the American College of Governmental Industrial Hygienists (ACGIH) recommend that core body temperature should not exceed 38°C (100.4°F) when performing work in the heat. Many threshold recommendations and standards to prevent excessive heat strain were created based on this principle (see Table 2). These thresholds can be utilized to assess individual heat strain or population averages (Bernard et al., 2023). Although core body temperature thresholds exist, researchers are still working to develop appropriate thresholds that account for individual factors that influence core body temperature responses (e.g., biological sex, age, heat acclimatization, etc.).

Table 1. Examples of Core Body Temperature Thresholds to Limit Excessive Heat Strain

Source	Thresholds
ACGIH (ACGIH, 2023)	Measured or estimated core temperature increases by more than 1°C from pre-job core temperature < 37.5 °C.
NIOSH (NIOSH, 2016)	Mild Heat Stress Threshold: When the core body temperature reaches 100.4°F (38°C), employees should be given a mandatory break, be encouraged to drink water, and rest in a cooler environment.
	Moderate to Severe Heat Stress Threshold: A core body temperature of 101.3°F (38.5°C) should trigger more extended breaks, mandatory hydration, and monitoring for any signs of heat-related illnesses.
	Critical Heat Stress Threshold: If the core body temperature hits 104°F (40°C) or above, immediate medical intervention is required if central nervous system dysfunction is present, and the worker should be removed from the heat source and given first aid (i.e., rapidly cooled).
The World Health Organization Technical Report 1969 (WHO)	Core body temperature should not exceed 38°C (100.4°F) when performing work in the heat.

Direct measurement of core body temperature assessed by rectal thermometry is the gold-standard method for diagnosing and treating exertional heat stroke (Casa et al., 2007). While utilized in research and clinical practice, its utility in the field setting to monitor heat strain in workers is not practical. A measure of core body temperature that has been consistently validated against rectal thermometry is gastrointestinal thermometry (i.e., gastrointestinal pill ingestion). When gastrointestinal pills are ingested ~6-8 h prior to an exposure, gastrointestinal thermometry has been reported as a method with high validity compared to rectal thermometry in both a laboratory and field setting (Bongers et al., 2015; Hosokawa et al., 2016; Travers et al., 2016). However, the utilization of gastrointestinal thermometry can be difficult due to cost and acceptability, reducing its feasibility in the workplace. It is also difficult to time the ingestion of the pill to allow for appropriate migration to the gastrointestinal tract for accurate measurement of core body temperature. Unfortunately, indirect measurement of core body temperature through methods such as aural, axillary, oral, temporal, and tympanic measurements have poor validity for assessments of body core temperature when performing physical activity in the heat, particularly when core body temperature has reached or exceeded 40°C (104°F) (Casa et al., 2007; Ganio et al., 2009; Morrissey et al., 2021b). For practical purposes, OEHS professionals are encouraged to look for validation studies showing good agreement between gold standard assessment and the selected physiological monitoring device in the 37.5°C-39.5°C (99.5°F-103.1°F) range with the intent that workers will no longer be in that exposure before they reach 40°C.

To overcome the challenges of implementing direct core body temperature measurements, new emerging devices have been developed. These new devices are most often wearable technologies that can be placed on an individual worker. Many of these devices use curated algorithms (e.g., Kalman filters, regression, etc.) and machine learning to estimate core body temperature using single or multiple variables such as heart rate and skin temperature (Dolson et al., 2022). Machine learning platforms have been successfully incorporated into sports science with the intent to reduce risk of injury by identifying patterns in data (Dolson et al., 2022). However, the validity and reliability of wearable devices to estimate core body temperature continues to develop, and caution should be taken when interpreting estimated temperature readings and utilizing monitoring alerts (see Chapter 5).

Heart Rate, Heart Rate Recovery, and Heart Rate Reserve

While performing work under heat stress, the body dissipates heat by increasing blood flow to the skin, which is accomplished primarily through an increased heart rate (Bernard and Kenney, 1994). Heart rate is measured as the number of times that a person's heart beats per unit time (typically in beats per minute (bpm)) and can be measured using wearable sensors, including sensors within chest, arm, or wrist straps. Heart rate is a useful variable for workers exposed to heat stress because it is significantly associated with wet bulb globe temperature and core body temperature (Ioannou et al., 2022). Heart rate is also impacted by the stress of dehydration; heart rate has been shown to increase an average of 3 bpm for every 1% decrease in body mass lost (Adams et al., 2014).

Multiple wearable devices exist that measure heart rate in addition to other parameters. By monitoring heat rate, workers can be prompted to moderate their exposure to heat by taking necessary breaks, seek cooler environments, and increase or maintain their fluid intake. While the root cause of change in heart rate is indistinguishable (i.e., performing work vs. heat stress vs. performing work under heat stress), heart rate reflects physiological strain earlier than core body temperature and can be measured very accurately with existing wearable technologies (Rua et al., 2020). Therefore, establishing core temperature limits based on measured heart rate can signal when to implement heat stress mitigation strategies with the intent to prevent subsequent elevations of core body temperature that could lead to a heat-related event (Rua et al., 2020).

Heart rate has been recommended for monitoring workers for heat strain, but specifics of recommendations vary. According to ACGIH (ACGIH, 2023), monitoring peak and average heart rate are useful approaches in evaluating heat strain among workers (Table 3). In many cases, an individual's maximum or peak heart rate is often used as the threshold to warn of possible overexertion (Bernard and Kenney, 1994).

Establishing a worker's maximum heart rate can be done through a variety of equations, or observations, and are as follows:

Max HR = 220 – age, which underestimates maximum heart rate in persons older than 40 years (Sammito et al., 2016)

Max HR = 195 – 0.67(age – 25) (Bernard and Kenney, 1994)

Max HR = 217 – (0.85 x age) (DenHartog et al., 2017)

Max HR = 207 – 0.7 x age, for healthy adults (Tanaka et al., 2001).

An additional equation used to detect physiological stress in the heat is: 180 bpm - age, which represents a cardiovascular demand of approximately 75% of estimated maximum aerobic capacity (ACGIH, 2023). This equation has been used to detect when exposure to heat stress is excessive if a sustained (i.e., over several minutes) heart rate remains above this value.

An individual's maximum, peak and average heart rate are influenced by many factors such as age, biological sex, physical fitness, body composition, hydration status, and work output (Ioannou et al., 2022). Additionally, resting and working heart rate values can be sensitive to changes in physical and mental fatigue, (Bustos et al., 2021) and acclimatization status (Mazlomi et al., 2017). When using fixed thresholds for heart rate monitoring, OEHS professionals should pay close attention to sustained (i.e., several minutes) of maximum or peak heart rate values rather than transient peaks (i.e., brief periods of maximum or peak heart rate). Transient peaks are typical during physically demanding work but may not represent a significant physiological strain. Using average or sustained peak or maximum heart rate as heart rate monitoring thresholds can mitigate the impact of short bursts of physical activity on heart rate. Various investigators have proposed taking practice field measurements every several minutes and 8-h average heart rate thresholds of 120–125 bpm for program feedback.

Table 2. Examples of Work Heart Rate Assessment Methods Limit Excessive Heat Strain

Source	**Thresholds**
ACGIH (ACGIH, 2023)	Sustained (several minutes) heart rate is in excess of 180 bpm minus the individual's age in years (180-age), for healthy individuals with normal cardiac response.
The World Health Organization Technical Report 1969 (WHO)	110 bpm for an allowable maximum at low metabolic rates

Employers who use heart rate to monitor workers for heat strain should be aware that criteria of average heart rate should be applied to young, healthy workers (ACGIH, 2023); older workers and those who take medications that affect heart rate (i.e., beta blockers) should use more conservative criteria (e.g., longer rest breaks). Additionally, caution should be applied to workers with underlying medical conditions. Persons with diabetes and hypertension have lower tolerance for heat stress, although neither diabetes nor hypertension have demonstrated a significant effect on heart rate response (Kenny et al., 2013; Notley et al., 2021). While average and maximum heart rate variables are useful tools to monitor workers for heat strain, those using this tool must understand the limitations.

Heart rate recovery (HRR) is the heart rate measured in a seated position in a quiet, non-stimulating environment following a physical work bout. HRR is typically assessed one, two, and three minutes after peak work. An example of the use of HRR includes workers sitting down directly after the end of a work cycle and recording the heart rate at one, two, and three minutes into recovery. For manual measurement, workers should sit down after a work cycle and use a watch to count the number of beats during the final 30 seconds of the first (P1), second (P2), and third (P3) recovery minutes (i.e., from 30 seconds to 1 minute, 1:30 to 2 minutes, and 2:30 to 3 minutes), multiplying each count by two to estimate the beats per minute (Maxfield and Brouha, 1963). Investigators have proposed different thresholds for the 1-minute HRR. A P1 HRR of <110 bpm generally represents low strain where heat stress or excessive workload are minimal and manageable (Fuller and Smith, 1981). In contrast, a P1 HRR > 120 bpm is generally indicative of high strain where workload and excessive heat strain likely prevail among workers (Logan and Bernard, 1999). HRR is strongly influenced by aerobic fitness and dehydration status, and the influence of these parameters must be considered.

Heart rate recovery is a good indicator of cardiovascular strain from workloads or environmental stress; higher workloads under environmental stress leads to higher heart rates that take longer to recover (Maxfield and Brouha, 1963). Heart rate from high intensity work or environmental stress should return to near normal values after three-four minutes of seated rest (Lumingu and Dessureault, 2009); not to be confused with an indication of adequate rest. Heart rate recovery may not be useful in certain occupations where workers are unable to sit down directly after peak work; for example, some agricultural workers preferred leaving the field for a cooler rest area rather than sitting directly on the field to collect this variable (Lumingu and Dessureault, 2009).

Heart rate reserve, or heart rate capacity, is another variable used to estimate physiological strain. In this variable, heart rate is inputted to an equation and the outcome, heart rate reserve, is the suggested heart rate range available to support work; it is the difference between the maximum and resting heart rates (Bernard and Kenney, 1994). The percentage of heart rate reserve is equal to [(HR – HRrest) / (HRmax – HRrest)] x 100 (Bernard and Kenney, 1994). In this equation, HR is the heart rate at a given time point, HRrest is heart rate at rest (after at least 5–15 minutes of rest), and HRmax is age-predicted maximum heart rate.

Although some investigators have recommended using a heart rate reserve of 25% as the threshold under which work activities should be performed over an eight-hour shift, this threshold might be conservative as it is has been demonstrated that outdoor workers exhibit moderate or high heart rate reserve on more than 50% of the days at work, with environmental conditions contributing to high heart rate reserve more than workload (Al-Bouwarthan et al., 2020).

Physiological Strain Index

Multiple investigators have developed indices or scales that combine parameters into one measure to assess heat strain (Moran et al., 1999; Moran, Shitzer, et al., 1998). Indices that include multiple physiological parameters such as core body temperature, skin temperature, heart rate, and sweat rate carry more information and thus may be more predictive of impending heat-related illness. However, the use of each of these parameters in real-time, using a wearable technology device, is limited. To mitigate the complexity of many indices, the physiological index (PSI) was created and is characterized as the most widely used index that combines two well-recognized physiological parameters (Moran et al. 1998). Of note, there are multiple proposed PSI equations (Ioannou et al. 2022). In this paper, we will discuss the PSI developed by Moran et al. 1998 and modifications to this index.

The PSI is a simple calculation based on heart rate and estimated core body temperature, which are assumed to contribute equally and are evenly weighted (Moran, Shitzer, et al., 1998). Equal contribution of heart rate and core body temperature was proposed to reflect the combined strain by the cardiovascular and thermoregulatory systems. The PSI was created to evaluate heat stress on a nominal scale for ease of use and as a counter to other scales that generated a large number of values that were difficult to interpret (Moran, Shitzer, et al., 1998). The original calculation is as follows:

$$PSI = \frac{5(Tret - Tre0)}{(39.5 - Tre0)} + \frac{5(HRt - 60)}{(180 - HR0)}$$

Where T_{ret} and HR_T = rectal temperature and HR taken simultaneously at any time (i.e., real time measures), and Tre0 and HR0= initial (i.e., resting) rectal temperature and HR. The PSI was scaled within the limits of the following values 36.5-39.5°C (97.7-103.1°F) and 60-180 bpm. Temperatures of 39.5°C (103.1°F) and 180 bpm are referred to as the core body temperature and HR critical constants, respectively.

In the event that resting heart rate cannot be obtained, HR0 is assigned a value of 60 bpm (Tikuisis et al., 2002). Additionally, heart rate may exceed the limit of 180 bpm that was set in the original equation, and thus maximal heart rate (HRmax) can be incorporated in place of 180 in the original equation (Tikuisis et al., 2002). The modified PSI in this study therefore became the following:

$$PSI = \frac{5(Tret - Tre0)}{(39.5 - Tre0)} + \frac{5(HRt - 60)}{(HRmax - 60)}$$

Based on this calculation, a number from zero to ten is generated, with the following interpretation of values (Moran et al., 1998a):

- 0–2: no/little heat strain
- 3–4: low heat strain
- 5–6: moderate heat strain
- 7–8: High heat strain
- 9–10: Very high heat strain

Several assumptions accompany this equation. The PSI assumes a maximum change of 3 °C (5.4°F) and 120 bpm for core body temperature and heart rate, respectively (Moran et al., 1998b). Specifically, the maximal rise in core body temperature is assumed to occur from 36.5 to 39.5 °C, and the maximal change in heart rate is assumed to occur from 60 to 180 bpm. Another assumption is that the maximum core body temperature and heart rate values of 39.5°C (103.1°F) and 180 bpm are relevant to all individuals, and that the calculated value of PSI represents equivalent strain for all persons (Tikuisis et al., 2002). It has been demonstrated that the perceived heat strain among endurance trained individuals underestimated their actual level of physiological strain using a modified PSI. Some endurance trained individuals can tolerate higher increases in core body temperature, and the PSI temperature limit of 39.5 °C (103.1°F) may not be the true maximum for these persons, suggesting that fitness level alters PSI (Tikuisis et al., 2002; Singh, G., et al. (2023). Moreover, the PSI does not account for the level of clothing impermeability or age (Buller et al., 2023).

These limitations have led to proposed adaptations of PSI (Buller et al., 2018). For example, Buller et al. (2023) proposed an adaptative PSI (aPSI) that changes the critical constants (39.5°C, 103.1°F and 180 bpm) within the equation. The purpose of the aPSI is to accurately quantify physiological strain by accounting for the effects of characteristics such as physical fitness and clothing. In aPSI, the critical constants change based on the delta between core body temperature and skin temperature. The delta between core body temperature and skin temperature is incorporated since a higher skin temperature (smaller core body temperature to skin temperature gradient) will increase cardiovascular strain.

Benefits to using the PSI are that it can be assessed in real-time and is easy to calculate. Additionally, studies have demonstrated the capability of PSI to distinguish levels of heat strain between various climates, hydration status, biological sex, age, and exercise intensities (Buller et al., 2023; Moran et al., 2002; Moran, et al., 1998; Moran, et al., 1998). Despite these benefits, PSI may not be applicable to many occupational settings until valid measurement devices for body core temperature are available. Therefore, a rigorously assessed PSI may be impractical for use on a wide scale basis.

Emerging Physiological Variables to Assess Heat Strain

Although core body temperature, heart rate, and PSI appear to be the most studied variables to assess heat strain using physiological monitoring systems, there are several others emerging. Importantly, such variables do not directly measure heat strain but rather assess variables that contribute to heat strain, such as hydration status. Although there is very little research on how these variables can be utilized to capture occupational heat strain, OEHS professionals should closely monitor heat stress management recommendations as researchers continue to collect data.

Emerging variables to assess heat strain using wearable physiological monitoring systems include:

- Hydration status (i.e., percent dehydrated)
- Sweat concentration (i.e., electrolyte status)
- Energy expenditure
- Blood pressure
- Biomechanics (ie., gait and stability analysis)
- Sleep quantity and quality
- Respiratory rate
- Blood oxygen saturation
- Heart rate variability

Chapter 3: Benefits of Physiological Monitoring to Assess Heat Strain

This chapter focuses on how wearable physiological monitoring systems can enhance heat stress management. By providing timely data on useful variables, physiological monitoring can offer a personalized, dynamic approach to physiological heat strain assessment in response to heat exposure and provide feedback on heat strain management. The implications for early intervention, adaptability, and overall safety enhancement will be outlined to assist principles of good practice.

Wearable technology allows for real-time, continuous, individualized monitoring of employees through various sensors and variables (Muniz-Pardos et al., 2019; Notley et al., 2018). Each monitoring device examines the physiological responses of one worker. Methods of wearable technology focused on physiology in the industrial setting are most often worn as wrist bands, arm bands, and chest straps that measure variables assessing heat strain (see Chapter 2). Devices may also use algorithms to provide numerical or scalar values assessing heat strain on the body. In addition to the physiological variables, anthropometric variables such as age, biological sex, height, and weight may also be included within the wearable technology algorithm to enhance the accuracy of the individual wearing the device (Mazgaoker et al., 2017; Mazloumi et al., 2014).

To recognize the benefits of wearable technology, it is important to consider what heat stress mitigation strategies exist and their potential pitfalls when used in the absence of wearable devices. Evaluating the limitations of current heat stress mitigation strategies does not suggest they are ineffective, but rather, highlights areas for improvement that could be addressed by the additional implementation of physiological monitoring.

Historically, measurements of environmental heat, such as the Heat Index or the Wet Bulb Globe Temperature (WBGT), have been used to evaluate the heat stress hazard present in the workplace (NIOSH, 2016). WBGT is considered the gold standard assessment as it accounts for ambient temperature, humidity, and radiant heat load (NIOSH, 2016). The purpose of environmental monitoring is to quantify the level of heat stress within a given workplace using variables associated with the environment. Environmental monitoring can be performed to:

- Prepare for future heat stress conditions to occur
- Create timely environment-based work modifications (e.g., work-to-rest ratios)
- Inform evaluation of the adequacy of current heat stress control measures
- Implement additional heat stress prevention strategies triggered by thresholds established by previous exposure assessments.

Environmental monitoring is an effective method to evaluate risk and prescribe an effective solution for a group of workers. ACGIH® recommends the use of environmental monitoring as a screening criterion to determine an appropriate allocation of work (i.e., work to rest ratio) under specific WBGT values that are adjusted for clothing ($WBGT_{eff}$) (ACGIH, 2023). Additionally, ACGIH has created a Threshold Limit Value® (TLV®) using $WBGT_{eff}$, to determine heat stress exposure limits. These heat stress exposure limits are functions of WBGT and estimated metabolic rate (ACGIH, 2023). The TLV is established as an exposure limit above which it can no longer be said that nearly all workers may be repeatedly exposed, day after day, over a working lifetime, without adverse health effects (ACGIH, 2023).

An advantage of using environmental monitoring is that it incorporates environment variables into a single value or scale, which corresponds to a degree of physiological impact and risk. The WBGT measurement along with metabolic activity, clothing adjustment factors and acclimatization status is used to assess risk for exposed workers (ACGIH, 2023). ACGIH provides the following disclaimer: "Warning: The TLV is based on the ability of most healthy hydrated acclimatized workers to sustain thermal equilibrium. The Action Limit (AL) is similarly prescribed for healthy hydrated unacclimatized workers. This TLV has a small margin of safety, and some workers may experience heat-related disorders below the TLV or AL" (ACGIH, 2023). The ACGIH Warning identifies a limitation of exposure assessment methods which is the inability to account for the least tolerant portion of the population. This can include both inter- (i.e., differences between workers) and intra-personal variability (i.e., differences within the worker, day-to-day differences in response to the same level of heat stress).

Although the link between heat stress, health, and performance on the macro level is well established, the biophysical and physiological factors that impact the vulnerability of the individual worker are still debated (Foster et al., 2020).

Some of individual-level factors that may impact response to heat stress include (Foster et al., 2020; Nelson and Allen, 2019; Schmeltz et al., 2015):

a. Age: Older individuals are generally more susceptible to heat stress due to reduced thermoregulatory capacity (Kenney and Hodgson, 1987).

b. Fitness level: Physically fit individuals tend to have better heat tolerance and adaptability (Westwood et al., 2021).

c. Health status: Underlying medical conditions such as cardiovascular diseases, pulmonary diseases, skin disorders and infections, and metabolic diseases (e.g., obesity diabetes) can increase vulnerability to heat stress (Kenny et al., 2013; Morrissey et al., 2021c; Notley et al., 2019; Tustin et al., 2021).

d. Acclimatization status: Individuals who are acclimatized to hot environments have improved heat tolerance (Hosokawa et al., 2019).

e. Medications: Certain medications, often used to treat chronic conditions that also affect the response to heat stress, can result in a worker's inability to feel heat or affect their ability to sweat (Pescatello et al., 1987).

f. Hydration status: Adequate hydration is essential for thermoregulation and mitigating the effects of heat stress (Piil et al., 2018).

g. Alcohol, caffeine, and supplement Use: Drinking alcohol, energy drinks, caffeine, or consuming stimulating supplements prior to or during the workday can exacerbate the effects of heat stress. Alcohol is a diuretic, which can affect hydration status, and caffeine (also a mild diuretic) is a stimulant that can increase metabolism and body temperature (NCCEH, 2010).

h. Illicit drugs: Use of some drugs, such as opioids, methamphetamines, or cocaine, can predispose workers to the effects of heat stress (Puga et al., 2019).

It is important to note that these factors interact and can have a synergistic effect on an individual's response to heat stress. Additionally, physiological variations, genetic factors, and personal susceptibility also contribute to the diversity of responses among individuals. This issue is addressed by NIOSH in their *Criteria for a recommended standard: occupational exposure to heat and hot environments* (NIOSH, 2016). In discussing the correlation between heat exposure and its effects, models that have been developed to predict when any combination of heat stress factors are likely to result in heat illness NIOSH (2016) concludes that "because of the variability in the human physiological response to heat stress (metabolic and/or environmental), the current models do not provide information on the level of heat stress at which one worker in 10, in 1,000, or in 10,000 will incur heat exhaustion, heat cramps, or heat stroke."

Occupational exposure limits are based on protecting populations of workers, not on one individual worker. Moreover, many of the exposure limits were created from data derived from healthy and hydrated men, which is not an accurate representation of the U.S. workforce. Therefore, limits based on individual physiological responses to heat stress, such as heart rate, both sustained and recovery, and core body temperature may be more protective of individual workers.

Monitoring individual responses to heat stress is possible using wearable physiological monitoring devices. These devices may consider environmental factors, anthropometric data, physiological variables, as well as develop specific and individualized recommendations based on a variety of these factors (Dolson et al., 2022). Additionally, wearable technology can provide the necessary physiological information to monitor individual employees and provide information directly to those employees or others monitoring the work to enable them to rapidly make necessary adjustments to reduce the level of heat stain. Devices are often easy to use and can be placed on individual workers with little interference with their daily work output.

The purpose of physiological monitoring to assess workplace heat strain is multi-faceted (Figure 1). Wearable physiological monitoring devices can supplement their perceived strain with the ability to assess time points by which their measured physiological responses are too high referenced to a given threshold. The ability for the user (i.e., worker) to review and respond to their own data can serve as an educational tool and facilitate behavioral changes such as a reduction in work capacity, increased consumption of fluids, increased rest, and/or adjustment of clothing (Notley et al., 2018). Providing numerical values or ordinal judgement to employees regarding these variables aids in visualizing and quantifying their ability to adapt to heat stress and mitigate heat illness and injury.

The use of physiological monitoring devices for education purposes requires little preparation and action for employers and environmental and OEHS professionals. However, workers may ignore data that are consistent with increased risk of a heat-related event, potentially due to job jeopardy (i.e., fitness for duty) or productivity incentives (Notley et al., 2018).

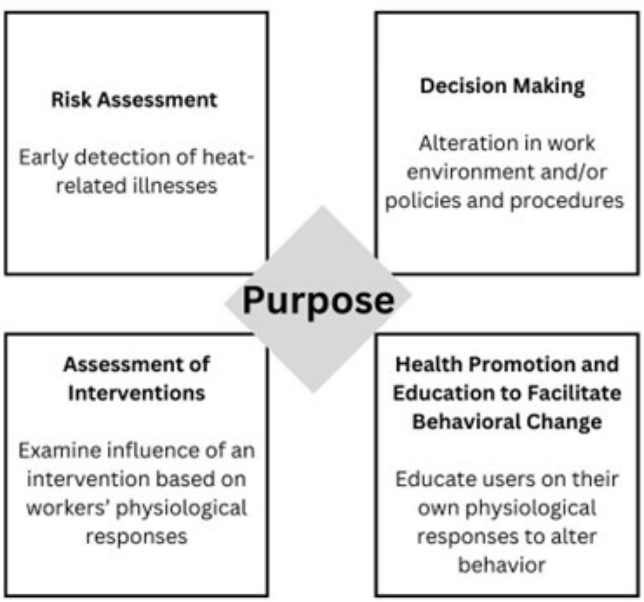

Figure 1. The Purpose of Using Physiological Monitoring to Assess Heat Strain.

For the purposes of risk assessment and decision making, devices can have "silent evaluators," where there is no warning trigger (e.g., a datalogger). Devices may also have specific set thresholds that alert users or safety professionals to perform a certain action (e.g., stop work; Figure 1). Many devices provide automatic data interpretation or warning alerts, however, these thresholds may over or underestimate the need for intervention (see Chapter 4). For heat-related illnesses, users and safety professionals should not rely solely on the devices, as no device is a complete substitute for the human judgment of signs and symptoms indicating impending or occurring heat illness. The role of physiological monitoring systems for risk assessment is to provide objective data to aid in the decision-making process to stop or modify an exposure.

Physiological monitoring provides timely information for safety leaders to make data-driven, personalized decisions regarding work-to-rest ratios, extended breaks, and early recognition of increased heat strain before heat-related illness occurs (Notley et al., 2018). Real-time data can also help identify locations within worksites where workers may be at a higher risk for greater heat strain, thus warranting targeted worksite heat stress management adjustments.

Information from physiological data can inform OEHS professionals on the physiological "burden" of personal protective equipment (if it does not interfere with the sensor system), varying environmental conditions, and work intensity. Data collected from workers can also be utilized to assess the effectiveness of specific heat safety interventions. For example, data can be collected before and after the implementation of a body cooling solution to determine if the body cooling solution can serve as a method to alleviate heat strain. The use of physiological monitoring to assess interventions may require the consultation of data analysts who assist and train OEHS professionals to interpret the magnitude of change in physiological responses (see Chapter 5).

Overall, the addition of physiological monitoring to the heat stress management plan offers several benefits to both the employer and worker. Wearable devices have the potential to change how we monitor our physiological health by providing timely data, convenient portability, and user-friendly interfaces. However, it becomes essential to acknowledge the limitations that accompany these devices. The next section will explore these challenges and shed light on the potential limitations of wearable technology to assess heat strain.

Chapter 4: Limitations and Weaknesses of Physiological Monitoring to Assess Heat Strain

Despite the many promising benefits, adopting wearable physiological monitoring systems comes with various limitations and weaknesses. This chapter will identify potential pitfalls such as device accuracy, data security, user compliance, and the complexity of individualized management, along with suggestions for overcoming these challenges. The chapter will reinforce that there is no one solution for all barriers and that a comprehensive heat stress management plan that includes multiple heat safety mitigation strategies must be implemented to adequately protect workers from heat stress. The challenges and limitations of wearable devices to assess heat strain are listed below.

Cost

Wearable devices vary in cost depending on the intended use and number of devices necessary to deploy

(Notley et al., 2018). Wearable technology must be selected based on the location of the device on the body (arm, chest, wrist, etc.) and the features required for use (e.g., Bluetooth, Wi-fi or cellular connectivity, internal vs. cloud storage). The cost of wearable technology may vary based on the intended location, number of devices deployed, and type of software used. Cost may become a burden for smaller employers. For instance, many outdoor jobs are performed in landscaping and construction, and these are often small enterprises. The costs for personal physiological monitoring may become prohibitive when the capital investment, professional expertise, training, operations, maintenance, and replacement are considered.

User Acceptance

User capability and compliance may be a potential barrier when implementing physiological monitoring methods. If the individuals are not capable of using the device, it will fail. Workers may be concerned about management of their personal information and where data is stored or distributed. Therefore, users may not want to comply due to data storage and distribution. Additionally, a worker may not agree with decisions made based on the values the device provides. For example, if a worker reaches the estimated core body temperature threshold and is asked to remove themselves from the heat stress area, the worker may disagree and insist they do not need a break. This is especially important when motivational conflicts in pay or performance may be involved in decisions about rest.

Employees should be able to "opt-in" and agree to their data being collected, which is consistent with the concept of informed consent (e.g., individual autonomy). This should include a stipulation that a person requiring a rest or water break will not be penalized for taking a break. Moreover, the monitoring program procedures and policies must be disclosed to all employees in a way that they can understand. Users and operators should check with applicable privacy policies and adherence by providers of physiological monitoring. Any changes in how data are interpreted or analyzed must be disclosed (Morley et al., 2017).

Physiological Monitoring Performance

This section uses the following operational definitions to characterize reliability, validity, sensitivity, and specificity. The first part of this discussion is specific to the quality of a decision that emerges from the physiological monitoring based on a recommendation between acceptable and unacceptable exposure. The second part addresses validity of a physiological monitor over a range of values beyond the decision point. (Note: The use of sensitivity and specificity in this section is based on decision quality. They should not be confused with the use of sensitivity and specificity in describing sensors/detectors.)

Table 3. Operational Definitions and Relevant Examples of Reliability, Validity, Sensitivity, and Specificity Related to the Monitor System and Its Decision Performance*

Term	Operational Definition	Relevant Example
Reliability	The ability to (re)produce a decision in accordance with expected dynamics.	A core body temperature monitoring device that can provide consistent, reproducible estimates of core body temperature at the decision threshold (or over a reasonable range of core body temperatures).
Validity - Decision	The degree to which a decision is likely to a produce a result similar to a gold standard.	When comparing an estimated core temperature measure to a gold standard assessment at the decision threshold, the absolute mean difference of repeated trials is near zero (accuracy or bias) and the precision (standard deviation of the differences) is small.
Validity – Method	The degree to which a measurement is likely to produce a result similar to a gold standard over a range of relevant values.	When comparing an estimated core temperature measure to a gold standard assessment between 37 and 40 °C, the absolute mean difference between methods is near zero (accuracy or bias) and the precision (standard deviation of the differences) is small (say less than 0.05 °C).
Sensitivity	The ability of a decision to yield a positive result for a person that has that condition; that is, "True Positive." Sensitivity is calculated as the number of True Positive observations divided by all the gold standard positive observations.	With a definition of hyperthermia as above 38.5°C (101.3°F), the estimated core body temperature monitoring device can confirm that the individual's core temperature is over the 38.5°C (101.3°F) threshold (e.g., hyperthermic) when the gold standard assessment confirms they are hyperthermic
Specificity	The ability of the test or instrument to obtain normal range or negative results for a person who does not have a that condition; that is, True Negative. Specificity is calculated as the number of True Negative observations divided by all the gold standard negative observations.	With a definition of hyperthermia as above 38.5°C (101.3°F), the estimated core body temperature monitoring device can confirm that the individual's core temperature is below the 38.5°C (101.3°F) threshold (e.g., not hyperthermic) when the gold standard assessment confirms they are not hyperthermic
DISCLAIMER: The diagnosis of a heat-related illness, specifically exertional heat stroke (a medical emergency), presents with central nervous system dysfunction in conjunction with a clinically assessed rectal temperature of over 104/105°F (40/40.5°C). It cannot be diagnosed with a surrogate method like a wearable device.		

** These definitions and relevant examples are specific to the physiological variables discussed in this white paper*

To illustrate the principles described in Table 1, the performance of a method to estimate body core temperature reported in the literature is described here. The reported regression line between the predicted and actual body core temperature had a bias of 0.03 °C and a standard deviation of 0.32 °C. The systematic difference between the predicted and measured was excellent at 0.03 °C. For reliability, a stand-in measure is the standard deviation of the data around the regression. This often includes both the intra- and inter-individual variation. The same information informs the precision. The 95% confidence interval would be ± 0.63 °C. This confidence interval includes the intra-individual variation assessed by repeated measures (within participant variation) and the inter-individual variation between participants. Thus, the precision is not within an acceptable range (e.g., 0.1 °C) and the reliability is weak, but difficult to assess directly (Verdel et al., 2021). A modest Monte Carlo simulation (120 simulated observations) was used to examine the physiological monitoring performance. The Bland-Altman plot in Figure 2 compares the predicted and rectal temperature values and demonstrates the overall low bias based on the simulation, which was expected. Figure 2 also shows the high variability (low precision). Using a measured body core (rectal) temperature as the gold standard, sensitivity and specificity of the decision depends on the cut point for the decision. Figure 3 illustrates the trade-off of sensitivity and specificity for this method. If the decision point is 38 °C, the sensitivity is about 0.95 but the specificity is only 0.15 with an attendant high number of False Positives. As the decision point is increased, the possibility of missing someone with a high core temperature (False Negative) also increases.

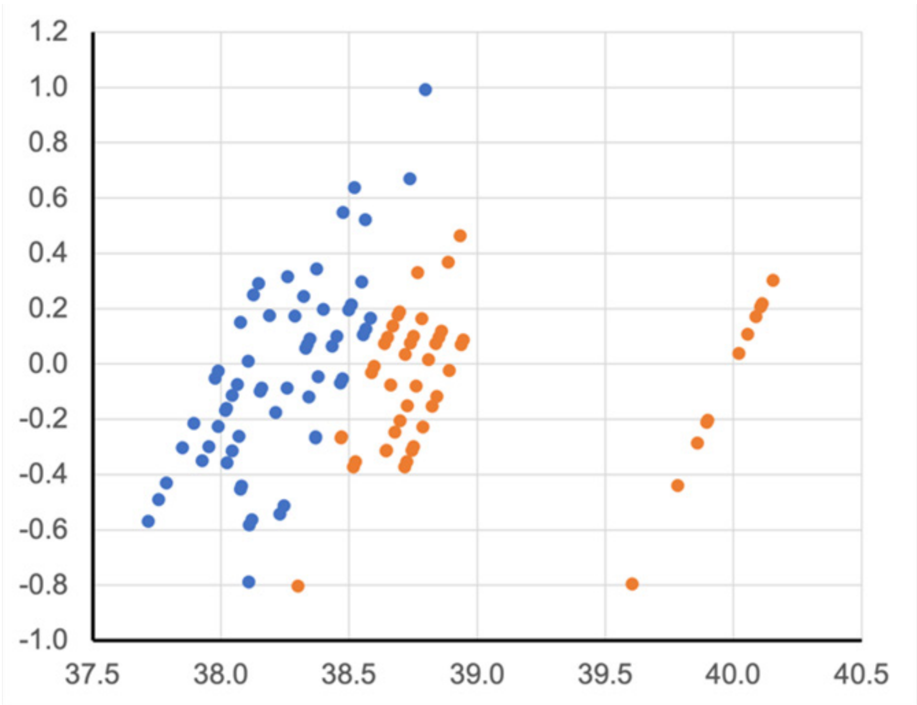

Figure 2. Bland-Altman plot of simple simulation of the physiological monitor. The mean bias/accuracy is –0.1 °C and the 95% confidence interval is ± 0.6 °C. Blue circles are the non-cases and the orange circles are the cases in the simulation.

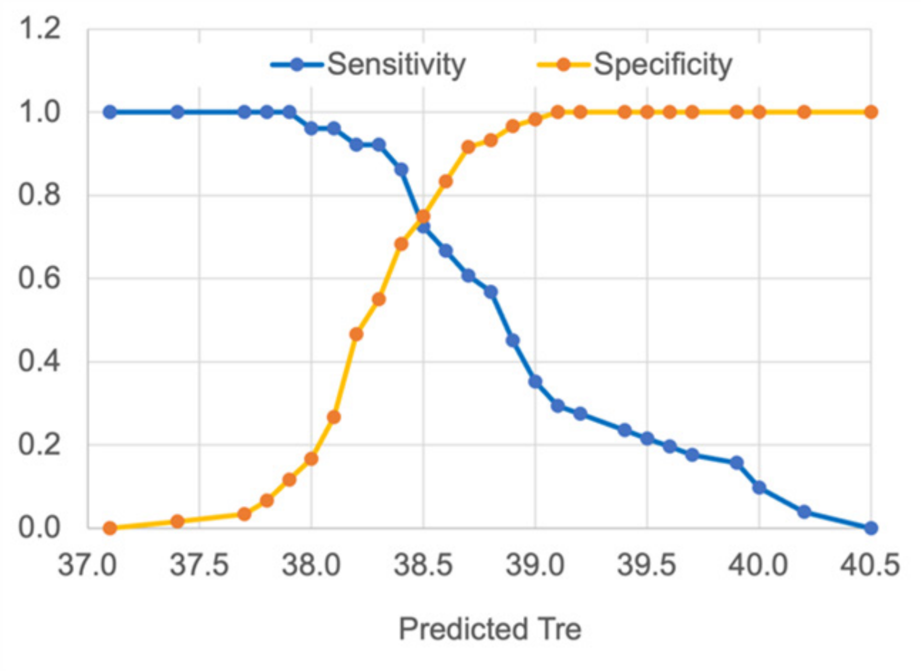

Figure 3. Trade-off between sensitivity and specificity when the gold standard core temperature is 38.5 °C where the decision point (e.g., cut point) is set by user.

While there are many wearable devices currently available to assess heat strain, it is important to examine available device decision performance data to evaluate its reliability, validity, and sensitivity/specificity. Further, the ideal physiological monitor provides objective data to make a decision on physiological state. In terms of making decisions in real time about modifying an exposure (e.g., stop or take a break), symptoms and perceived strain should also inform the decision.

If the purpose of personal monitoring is to track physiological change in groups of workers over minutes or hours, reliability and validity are key performance parameters. Reliability and validity provide the confidence that what is thought to be measured is in fact what is measured. This is especially helpful for understanding the demands on conventionally defined groups of workers (e.g., similar exposure groups) to help understand the exposure and guide interventions. If the purpose is to provide a user with a timely alert, the alert point and decision quality (sensitivity and specificity) are important. From a prevention perspective, high sensitivity (being able to identify most positive states or have True Positive decisions) is desirable. High sensitivity often means that there is low specificity, which also means there are many False Positive decisions. For young, healthy, hydrated, and acclimatized individuals, the occupational exposure limit (TLV or Recommended Exposure Limit [REL]) has a sensitivity above 0.95 with a very low specificity (Garzón-Villalba et al., 2017a). In practice, most healthy hydrated individuals can be safely exposed above the OEL, with half being able to tolerate exposures 6°C-WBGT above the Occupational Exposure Limit (OEL) (Garzón-Villalba et al., 2017a). It is this low specificity that drives the usefulness of personal monitoring. As an example of the problems with sensitivity and specificity for personal monitoring, Garzon and colleagues (Garzón-Villalba et al., 2017b) used as an end point, the upper limit of sustainable heat stress, which is widely different among individuals. They considered rectal temperature and heart rate as measures of physiological strain to predict when an individual had reached the limit, including data prior to and after reaching the limit. To select a decision point with high sensitivity (i.e., detect true positives), they found that specificity was low. When surrogate measures associated with inferred measures of physiology, like estimations of core temperature, are used, the imprecision of the surrogate measure to estimate the desired parameter will increase and the decisions will become more difficult.

Importance of Validity Assessments

Peer-reviewed publications on the utility of physiological monitoring to assess heat strain often evaluate the validity and reliability of the device and/or the efficacy of its use in the field (i.e., workplace setting). Current research assessing the validity of devices that measure heat strain remains limited. This is problematic as there are several factors that may influence the accuracy and precision of the reading:

- Hot, humid environment (e.g., sweat artifact due to loss of contact between skin instrumentation, or change in concentration of electrolytes in sweat that modify the instrumentation signal, as well as exceeding the operating temperature or humidity parameters of the device)
- Activity: (e.g., continuous vs. intermittent physical work, short vs. long duration physical work, motion artifact)
- Individual characteristics (e.g., physical fitness level, biological sex, anthropometrics, skin tone)
- Textiles/personal protective clothing (e.g., microenvironment created, material, pressure of the clothing)
- The nature of the job that may interfere (e.g., dirty conditions)

When evaluating validity data of heat strain variables, it is important to consider these effects. For example, a research study may validate a specific device in a thermoneutral environment (i.e., "room temperature;" 22°C, 50% relative humidity [RH]). However, that does not necessarily mean that it will accurately measure the intended variables in hot, humid, or cold environments. Moreover, research studies may assess the validity during continuous exercise in a controlled environment. Although this may be a prudent first step to evaluate device and decision validity, it does not necessarily determine that the device will provide valid measurements during intermittent work in a field setting. The white paper authors encourage technology validation in real world conditions.

When interpreting research, the following should be considered:

- What population is the document referring to?
    - Identify who was studied. What was their age range, sex, health status, and physical fitness status?

- What work setting is the document referencing?
    - Was the device studied in the lab or field setting?
    - Was simulated work or actual work performed?
    - What type of occupational work does the study specifically reflect?
    - What type of personal protective equipment (PPE) was worn?
    - What were the environmental conditions (e.g., hot and dry, hot and humid, room temperature)?
- Is the device valid?
    - What device served as the gold-standard for this device to be validated against?
    - Has the device been validated within multiple populations?
    - Has the device been validated between various levels of physical activity (low to high)?
    - Understand the trade-off between sensitivity and specificity for the proposed alert criterion.
- Is the device "fit for purpose" to be deployed within a specific heat stress management program?

The purpose of these considerations is to understand the limitations of the device or variables. This is not to discourage the use of physiological monitoring to assess heat strain but rather to assist in the selection and evaluation of variables and devices to assess heat strain based on its intended purposes (see Chapter 3, Figure 1). For example, a device or variable validated across multiple populations, variable levels of physical activity, and different environmental conditions with agreement between the device and previously validated assessment, could be considered to assess heat strain. Physiological monitoring to assess heat strain must be precise as severe heat-related illnesses such as heat exhaustion and exertional heat stroke use core temperature as diagnostic criteria.

However, given the limitations mentioned in this paper, tradeoffs must be made. Such is the case for using limited supporting validation (the process above) when selecting and deploying to real-world situations to use physiological data for other purposes, such as safety decision-making, assessing the effectiveness of interventions, education, and worker awareness. Readers are encouraged to do a thorough analysis, seek organizational concurrence, and pursue use of the technologies offered.

Data Analysis, Interpretation, and Management

To effectively utilize physiological monitoring in any heat stress management plan, the data collected must be transformed into actionable and useful information for decision-making in terms of health and safety. This objective may be best accomplished with the engagement of multiple individuals with specific roles and responsibility. The "Right Sensors Used Right" framework, an approach of the NIOSH Center for Direct Reading and Sensor Technologies, suggests the use of a data analyst (see Chapter 5, Table 4).

In relation to quantifying heat strain, the interpretation of the data can be very complex. The data analyst must be familiar with the physiological effects of heat on worker health and safety. In many cases, this requires the consultation of an experienced third party (e.g., physiologist, physician, athletic trainer, other medical professionals) to assist with determining specific physiological thresholds that indicate risk or when OEHS professionals must intervene. A variety of organizations (i.e., governing bodies, professional associations and academic institutions) publish literature providing evidence-based safety recommendations to keep workers safe (ACGIH, 2023; NIOSH, 2016; Morrissey et al., 2021a) and recommendations are characterized as "evidence-based" if they are rooted in high quality research (Morrissey et al., 2023). High-quality research often builds on original, peer-reviewed research that can include epidemiological research, laboratory-controlled studies, field research studies, case studies, systematic reviews, and meta-analyses. This data may be derived from other similar populations like athletes and warfighters. Although not peer-reviewed, recommendations can be created based on injury and fatality data, whether derived by industry or a governing body such as OSHA or the Bureau of Labor Statistics. While there is evidence to suggest that most of this data is underreported, understanding current incident rates and reports can prompt actions to proactively improve current safety procedures at the workplace.

Collectively, interpreting reported health-related data and technology data should drive evidence-based implementation of heat safety strategies to improve working conditions and protect workers. With any piece of literature, it is unlikely that the findings can be applied to all scenarios in all occupations. However, the appropriate use of well-vetted heat stress mitigation strategies and emergency response protocols can improve the safety of a workplace and then allow for the additional integration of wearable technologies to enhance health and safety.

Analysis of the data would provide feedback to those executing the heat stress management plan and guide decision logic for threshold assignments at the group and individual level. Given the potential individual variability in responses to heat stress among workers, some physiological data may need to be evaluated on a case-by-case basis to determine appropriate thresholds and/or interventions. In some cases, this may prompt a medical referral for abnormal or unusual physiological responses to a given heat stress level. The management of data is also a critical component as technology can generate extremely high volumes of data. A policy and procedure related to data retention (e.g., what and how long), the storage of data, destroying data, and data security should be created.

Data Privacy

As wearable technology advancements progress exponentially, there are several concerns related to data privacy and security. Rightfully so, workers may be concerned with the ownership of their data, sharing data with third parties, and/or using their data to make decisions related to their employment. Workers should be provided written informed consent in a language they understand that outlines data privacy and security regulations (Morley et al., 2017). All workers should understand and agree to the terms and have the option to "opt-out." The data environment should also be created to keep user information sufficiently confidential or anonymous. Alternatively, workplaces may choose to not provide workers with their own devices, but rather, require workers to share devices that do not contain any personal and identifiable information to avoid a privacy breach. In any case, the use of privacy agreements may be warranted to explicitly outline the limits of data use and discussion of data. OEHS professionals should also consult with resources in allied professions (such as legal and regulatory management) regarding data privacy management and protocols. Information on legal considerations can be found in additional references (Dunmire 2024; Scheid et al., 2023).

Chapter 5. Building Your Assessment Team

The effective use of wearable physiological monitoring in heat stress management results from a collaborative approach with an interdisciplinary team (Cauda and Hoover, 2019). This chapter outlines the roles and responsibilities of various team members, including occupational physicians, industrial hygienists, data analysts, and others, all essential to ensuring an efficient and safe monitoring system. Building a comprehensive assessment team is crucial for overall program management (Cauda and Hoover, 2019). The team's composition will depend on numerous factors, such as an organization's structure, established processes, and resources. There are many organizations, such as small businesses, that may only have the resources to include one to two team members. These individuals should still consider following the key steps outlined below.

This section provides guidance and considerations in the team building process and overall program management. If an organization already has processes in place for implementing a health and safety program and creating project teams, this section can be used as a supplemental resource. Each organization and program are different, and the process may vary, including revisiting steps and adjusting as needed.

Key steps to consider include the following:

- Establish the assessment purpose and objectives
- Determine stakeholders
- Determine what roles and members are needed on the assessment team, as well as their qualifications
- Determine responsibilities
- Develop the wearable physiological monitoring program as a supplement to an existing heat stress management plan
- Develop clear guidelines on using the data to modify or stop work
- Implement the program
- Monitor and adjust the program

Establish the Purpose and Objectives of the Assessment Team

Documenting the assessment team's purpose and objectives will help with program planning. This could be done in the form of a project charter, terms of reference, policy, etc. For example, the purpose could be to use

ACGIH-suggested core body temperature and heart rate thresholds to modify or stop work activity.

Identify Assessment Team and Stakeholders

Based on the team's purpose and objectives, determine the individuals and teams that should be involved in the program. Assessment team members might be the primary set of individuals who hold overall accountability of the program, while stakeholders may include representative team members that have ancillary responsibilities or are in scope for the program.

Stakeholders often have valuable insights into the project requirements and expectations. By engaging them early on, one can gather relevant information and ensure that the program aligns with stakeholder needs. Table 3 includes examples of team member roles, job titles, and responsibilities. It is important to have relevant workers (i.e., those working in the hot jobs) or "end users" as part of the team.

Determine Responsibilities

Ensure that each team member has clear, written, and agreed upon responsibilities and determine the best methods of collaboration, including meeting cadence, document management, change management, program approval process. For example, the role of physiologist could be to assist with the initial implementation of wearable physiological monitoring system and evaluate ongoing data for any potential modifications to the physiological monitoring plan.

Develop Program

Once the team is assembled, work together to formally develop the physiological monitoring program in preparation for implementation. The team will determine how the program will fit into an existing heat stress management plan.

- Program elements may include:
- Documentation of team's goals, objectives, and responsibilities
- Variables, corresponding safety thresholds, and intervention (Chapter 1)
- Device selection (Chapter 2)
- User testing and engagement
- Communication plan
- Training plan
- Implementation and monitoring plan
- Assessment and data analysis plan

Implement Program

Implementation of the program may be the most significant step as this can represent the biggest change to an organization's normal rhythm of business. Therefore, it is important to methodically build the program and consider the potential impacts to ensure a successful implementation.

Monitor and Adjust

The assessment team and stakeholders should monitor the program at an established cadence to ensure that it meets the established purpose and objectives and any emerging business needs. The plan may need to be adjusted depending on the work environment, on-site safety policies, and demographic of workers. Data analysts; which can include physiologists, consultants, ergonomists, physicians, athletic trainers, and OEHS professionals; will hold a critical role to assess the effectiveness of the program, advocate for adjustments based on physiological responses, and assess individual workers data. These individuals may be working within or contracted by the company.

Summary

Building an assessment team of knowledgeable individuals to effectively incorporate physiological monitoring to assess heat strain is key to the success of the program. Developing and implementing the program, systematically assembling a team, engaging stakeholders, monitoring the program, and adjusting it as needed, can help meet program objectives and business needs.

Table 4: Examples of Physiological Monitoring Assessment Team Roles, Job Titles, and Responsibilities. *(continued on p. 31).*

Assessment Team Role	Job Title / Category Examples	Responsibilities
Device Creator and Manufacturers	• Engineers • Sales representatives	• Create and manufacture the device to assess safety variables • Assist with recommendations on hardware, software, and processes • Share lessons learned and best practices from similar programs

Table 4: Examples of Physiological Monitoring Assessment Team Roles, Job Titles, and Responsibilities *(continued from p. 30).*

Subject Matter Experts / Stakeholders	• Health, safety, medical (e.g., physician, athletic trainer, nurse), healthcare professionals and on-site clinical staff • Quality assurance / data analysts • Procurement specialists • Physiologists • Workers • Bargaining unit representatives • Risk management representatives • End user leadership or representatives • Universities • Consultants • Human resources • Cybersecurity personnel	• Provide expertise and support the team with selecting appropriate interventions and thresholds • Align on physiological monitoring tools and variables • Communications and training • Explaining opt-in and opt-out options for monitoring • Addressing questions regarding to data security
Team Lead Executive Sponsor	• Health and safety specialists • Industrial hygienists • Project / program managers	• Lead team • Develop applicable procedures and programs • Identify key stakeholders and team members • Request executive support • Authorization of heat stress assessment program • Provide resources including funding, personnel, commitment
End User Representatives	• Field operations • Technicians	• Provide feedback for adoption of the tool or variable • Support the program and follow applicable procedures and programs
Data Analysts	• Physiologists • Medical professionals (e.g., physicians, nurses, athletic trainers) • Consultants	• Interpret data collected from end users to assess safety thresholds and interventions • Assess data on a case-by-case basis (e.g., evaluate individual end user responses)

Conclusion

Wearable physiological monitoring can provide timely data that quantifies how a worker responds to heat exposure and accounts for the considerable intra- and inter-individual variability of workers' physiological responses to the same heat load. These devices offer a personalized approach to heat strain assessment and management that can be used for risk assessment and decision-making, assessment of heat mitigation interventions, and for educational purposes (Ibrahim et al., 2023; Notley et al., 2018; Chapter 3, Figure 1). Before implementation, OEHS professionals must evaluate the validity of the physiological monitor and of the decision (i.e., quality of decision from the physiological monitor) and consider its limitations. Limitations can include physiological monitoring performance, cost, user acceptance, data analysis, data management, and data privacy. Lastly, the assessment process should consist of a collaborative team to make decisions on the purpose and use of physiological monitoring systems within a heat stress management plan. As advances in physiological monitoring are still being made, OEHS professionals will need to pursue updates and recommendations.

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