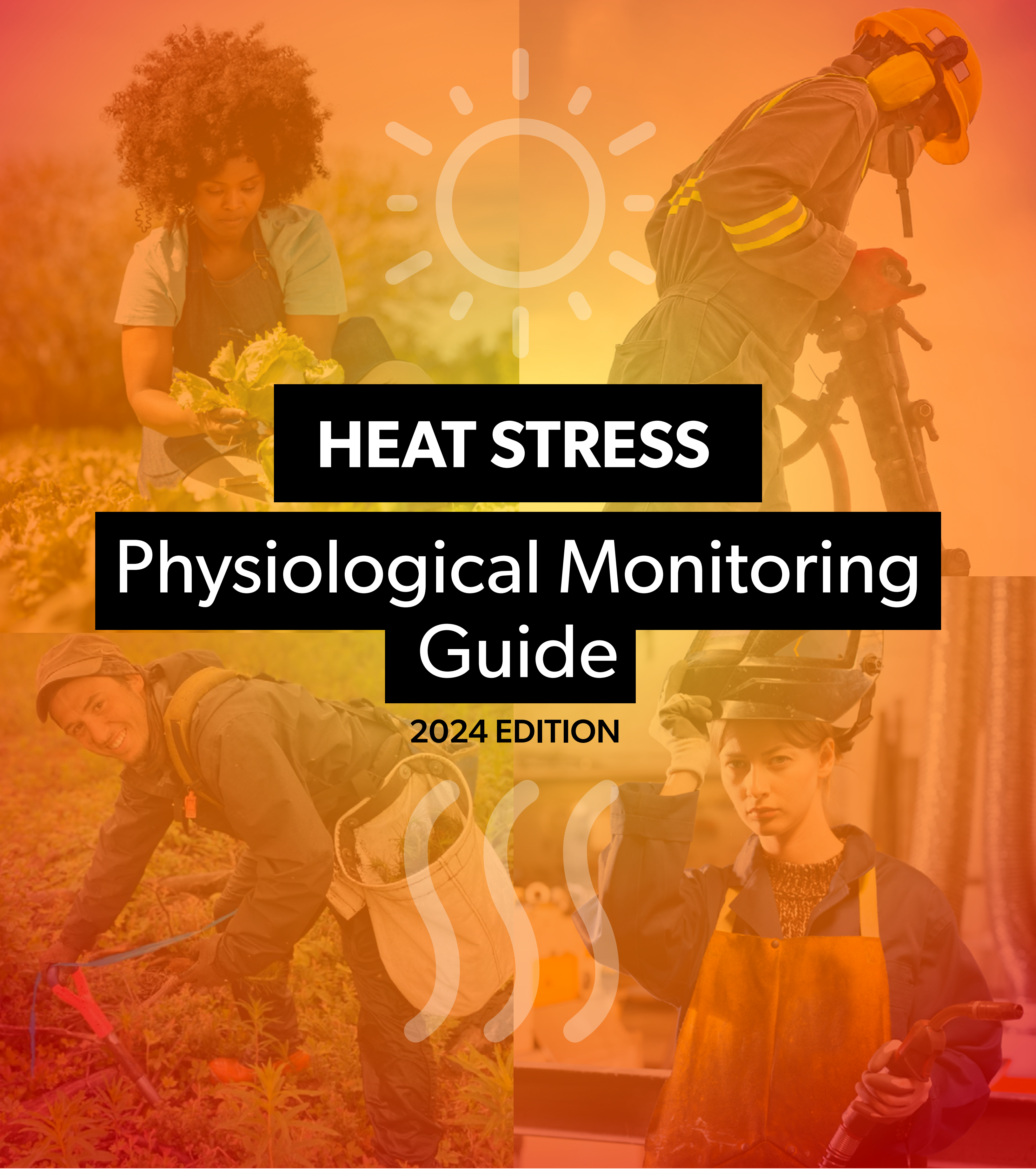

HEAT STRESS

Physiological Monitoring Guide

2024 EDITION

HEAT STRESS
Toolkit

Land Acknowledgment

The writers and contributers of this guide recognize that our work takes place on traditional Indigenous territories across the province. We acknowledge that there are 46 treaties and other agreements that cover the territory now called Ontario. We are thankful to be able to work and live in these territories. We are thankful to the First Nations, Métis and Inuit people who have cared for these territories since time immemorial and who continue to contribute to the strength of Ontario and to all communities across the province.

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About this Guide

OHCOW partnered with CROSH to review and update the existing *Heat Stress Awareness Guide* that was developed by OHSCO back in 2009. With the support of the Ontario Health and Safety Prevention System partners (through the Occupational Illness Prevention Steering Committee) and local labour unions, we identified areas that required improvement or revision and the concept of a toolkit was born!

We developed the Heat Stress Toolkit to help those supporting and protecting heat exposed workers including:

- employers • managers • supervisors • fellow workers
- Joint Health & Safety Committee (JHSC) members
- health and safety representatives
- workplace union representatives

Unions, employer associations, and health and safety professionals may also find this information useful.

The *Heat Stress Toolkit* includes this *Heat Stress Physiological Monitoring Guide*, a new *Heat Stress Awareness Guide*, and an updated *Heat Stress Prevention Tools and Strategies Guide*. It also includes several posters and infographics, videos, and an updated, online *Heat Stress Calculator*.

A list of additional resources is also available online on the project webpage.

Disclaimer

The information in this reference guide is for information and reference purposes only and not intended as legal or professional advice. Laurentian University (LU), the Centre for Occupational Safety and Health (CROSH), and Occupational Health Clinics for Ontario Workers (OHCOW) recognize that individual companies must develop heat stress policies and plans that apply to their workplaces and comply with appropriate legislation. While information provided is current at the time of printing, including references to legislation and established practice, it may become out of date or incomplete with the passage of time.

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INTRODUCTION

...the increase in temperature has and will continue to result in increased risk for health effects for workers

Introduction

In Canada, the growing need to combat heat exposure in workplaces, is becoming an increasingly important issue. Unfortunately, due to the consistent deterioration in environmental conditions, caused by global warming, the number of people becoming ill, or dying from heat stress, continues to grow (*Romanello et al. 2023*). In fact, in 2013-2022 compared to 1991-2000, there were 241 additional hours annually during which ambient heat posed a moderate or higher risk of heat stress during light outdoor physical activity. Heat exposure in the workplace led to the loss of 490 billion potential labour hours in 2022, a nearly 42% increase from 1991-2000. In 2013-2022, compared with 1991- 2000, the estimated average heat-related mortality increased by 85%, driven by both warming and changing demographics (aging population) (*Romanello et al. 2023*). "Annual and seasonal mean temperatures across Canada have increased, with the greatest warming occurring in winter. Between 1948 and 2016, the best estimate of mean annual temperature increase is 1.7°C for Canada as a whole and 2.3°C for northern Canada" (*Zhang et al., 2019*). Based on a synthesis of the literature by Kipp et al., (*2019*), the increase in temperature has and will continue to result in increased risk for health effects (frequency and severity) for workers (in both indoor and outdoor work settings). Furthermore, the literature highlights indigeneity, age, sex, socioeconomic status, and the increased number of people employed in outdoor occupations as key factors influencing workers and workplace vulnerability to climate change in Ontario, particularly in Northern Ontario.

Heat Stress

Heat is already a recognized concern in many workplaces, including, but not limited to:

- In foundries, steel mills, smelters, glass factories, and furnaces, where extremely hot or molten material is the main source of heat.
- In outdoor occupations, such as construction, road repair, open-pit mining, wildland firefighting, tree-planting and agriculture, where summer sunshine is the main source of heat.
- In laundries, restaurant kitchens, bakeries, and canneries, where high humidity adds to the heat burden.

Acute heat-related illnesses include, in order of increasing severity: heat cramps, heat syncope, heat exhaustion, and heat stroke *(Donoghue, 2004; Kenney et al., 2015; MLITSD, 2021; Taylor et al., 2014)*. Heat exhaustion and heat stroke are medical emergencies, which can lead to death *(Bouchama & Knochel, 2002; MLITSD, 2021)*.

*For a full description about acute heat illness see the *Heat Stress Awareness Reference Guide*.

In addition to these immediate effects, heat-related illnesses can also have long-term effects, with the severity of heat strain correlating positively with the severity of long-term symptoms and organ damage *(Bouchama & Knochel, 2002)*. While heat is accumulating in the body, heat strain may further cause damage to cells in the brain, heart, kidneys, and even muscles *(Cheung et al., 2000; McArdle et al., 2007)*. Importantly acute heat illness can increase the risk of future heat stroke events permanently *(Wang et al, 2019)*.

Recognizing the early signs/stages of heat illnesses is critical to preventing full-blown heat stroke and mitigating the short-term damage of heat stress *(CCOHS, 2024)*. Today, the only occupational reports collected about heat stress are when a heat exhaustion or heat stroke event occurs. However, workers in high-risk occupations regularly experience heat strains and heat illnesses, which are not reported, but could be used to predict or prevent the onset of heat exhaustion or heat stroke.

In fact, an estimated 220 workers in Canada die annually from occupational heat stress and an estimated 15% of workers who typically or frequently worked under heat stress (minimum of 6 hours per day, 5 days per week, for 2 months of the year) experienced chronic kidney disease or acute kidney injury (*Flouris et al., 2018*). Chronic kidney disease is a condition in which the kidneys are damaged and cannot filter blood as well as they should. This causes excess fluid and waste products to build up in the body and may cause other health problems such as heart disease and stroke.

Why is this guide necessary?

Under the *Occupational Health and Safety Act (OHSA)*, the workplace must take every reasonable precaution for the protection of a worker *(OHSA, 1990);* this fundamentally includes having a heat stress control plan. Workplaces that are hot due to process heat (e.g. bakeries or smelters), are required to follow the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLVs) for heat stress and to set up a heat stress control plan in consultation with the workplace's joint health and safety committee or worker health and safety representative(s). The purpose of the heat-related TLVs is to prevent acclimatized workers' core temperatures from rising above 38°C (*ACGIH, 2022*). TLVs are given separately for heat-acclimatized workers who are adequately hydrated and for unacclimatized workers; called Action Limit (AL) values. TLVs and ALs is are determined by considering the level of physical activity performed by the worker, in the context of the environmental temperature and humidity and applying a series of graphs to interpret the estimated level of metabolic output (physical activity), which can be accomplished for a set period of time, given ambient conditions and personal protective equipment (PPE) requirements.

There are three challenges with this approach. First, it does not account for individual differences, which can dramatically impact susceptibility to, and protection from, heat stress (e.g. sex, age, health status, and medication use). Second, the ACGIH guidelines do not apply to dynamic environments, or outdoor environments where weather on the ground can be affected by shade, topography, wind, etc. Third, the current strategy does not incorporate real-time feedback, on physiological responses, to prevent heat stress events.

Although largely unused, the ACGIH does provide guidance on what physiological indicators should be monitored to prevent heat illness. According to the ACGIH *(2022)*, heat stress can be defined by the following conditions:

- Sustained (several minutes) heart rate is in excess of 180 beats per minute (bpm) minus the individual's age in years (180 - age), for healthy individuals with normal cardiac response.
- Measured or estimated core temperature increases by more than 1°C from pre-job temperature, if the pre-job temperature is less than 37.5°C.
- Recovery heart rate at one minute after a peak work effort is greater than 120 bpm.
- Exposure should stop with signs and symptoms of heat exhaustion or heat stroke

or with a request to stop regardless of what physiological monitoring may indicate.

With the rapid development of technologies, workers and workplaces are now poised to implement novel systems to monitor physiological symptoms, in real-time, in a preventative framework. However, while technologic capability has improved, implementation specific to heat illness and validated policies and protocols have not kept pace. There exist important gaps in information for workers and workplaces that need to be bridged, for the incorporation of technologies developed to prevent heat strain.

These include, but are not limited to:

1) creating heat-strain-specific monitoring applications and software, tied to validated equipment;
2) testing any technology in field-specific applications to address compliance issues related to hygiene, comfort, physical safety, psychosocial safety and legal protection issues;
3) developing training materials for implementing and assessing any other needed support systems; and
4) ensuring that any monitoring system is incorporated into a comprehensive workplace Heat Stress Management Program (HSMP).

In addition, assuming physiological monitoring will soon be incorporated into the highest-risk work groups, information needs to be provided now, to allow workers and workplaces to understand and examine the opportunities for individual monitoring and to apply meaningful strategies on how to incorporate monitoring, aligning with workplace risk. Therefore, the goal of this guidebook is to review the application of the ACGIH parameters to prevent heat strain, in the context of available technologies, and their capability to assess these parameters.

It is the employer's responsibility to identify and implement controls for workplace health hazards

Who is this guide for?

It is the employer's responsibility to identify and implement controls for workplace health hazards *(OHSA, 1990)*. This guide was primarily developed to help Occupational Health & Safety Specialists understand the available technology to inform decision making within their organization related to Heat Illness Prevention. Although comprehensive, this guidebook may not encompass all possible ways of monitoring personal health, or minimizing and preventing exposure to heat illness hazards, and therefore is intended to be used in conjunction with other resources (e.g., confidential interview with trained health and safety professionals) to address all concerns in this area. The material contained in this guidebook is not intended as legal or professional advice. The adoption of practices described in this guidebook may not meet the needs, requirements, or obligations of all employees or individual workplaces.

For compliance purposes, the Ministry of Labour, Immigration, Training and Skills Development (MLITSD) recommends the current TLV for heat stress and heat strain, published by the ACGIH. See the MLITSD web document "Managing heat stress at work" for details. Additionally, as of August 1st, 2023 a new heat stress regulation was proposed (Proposal No. 23-MLITSD003) in Ontario; the proposal is for a stand-alone heat stress regulation, under the OHSA, with specific requirements that would apply to all of the workplaces where the OHSA applies. The proposed heat-stress regulation is currently undergoing a Regulatory Impact Analysis.

OCCUPATIONAL CONTEXT FOR PREVENTION MONITORING

What is prevention monitoring?

Prevention monitoring encompasses administrative-based efforts that enforce screening for signs and symptoms of heat strain; either in a prescribed timeline or through continuous monitoring during a period of heat stress risk.

Levels of prevention monitoring

Individual workplaces experience different patterns of heat stress (e.g. seasonal versus constant) as well as different levels of risk, pending temperature, humidity, physical workload, shift-length, PPE use, and other workplace factors.

To assist your organization in understanding your risk, we encourage the use of a risk matrix, commonly employed in formal risk assessments *(Joy, 2004; Komljenovic & Kecojevic, 2007)*. We recommend that, where possible, quantitative data and onsite expertise (qualitative data) be used in combination to select the likelihood of heat illness and the severity of the consequence. Consideration should be given to: 1) heat illness as a regular occurrence; 2) incidence of heat exhaustion or heat stroke; and 3) likelihood of developing a heat illness as a long-term occupational disease (e.g. risk of kidney disease). Using a Risk Matrix (*Table 1*) can help guide parties in applying a schedule and system of monitoring that best aligns with their workplace needs.

RISK MATRIX		HAZARD EFFECT / CONSEQUENCE			
		1 Minor	**2 Moderate**	**3 Major**	**4 Maximal**
		First aid case: exposure to minor health risk; little to no economic costs incurred	Medical treatment; lost time injury; reversible impact on health; exposure to major health risk; economic costs are low.	Loss of quality of life; irreversible health impact; economic costs are moderate.	Single/Multiple fatalities; health impact is ultimately fatal; economic costs are high.
LIKELIHOOD		RISK RANKING			
1 **Unlikely** (<10%*)	The incident has happened in the past (rarely), and may occur in exceptional circumstances	LOW	LOW	MEDIUM	HIGH
2 **Possible** (<10-30%*)	The incident has happened at some time (infrequently), and will occur under some circumstances.	LOW	MEDIUM	MEDIUM	HIGH
3 **Likely** (<3-75%*)	The incident has occurred frequently, and is expected to occur	LOW	MEDIUM	HIGH	EXTREMELY HIGH
4 **Almost Certain** (>75%*)	The incident occurs with regularity and will continue to occur	MEDIUM	HIGH	EXTREMELY HIGH	EXTREMELY HIGH

*Likelihood

Table 1. Risk matrix (adapted from: *Bui et al., 2017*).

Once you have used the risk matrix to determine your risk level, you can consider appropriate tools to use to monitor workers for heat illness (e.g. *Table 2*).

MONITORING TOOLS			
LOW	MEDIUM	HIGH	VERY HIGH
Self-monitoring checklist	Self-monitoring checklist Temperature monitoring Second person monitoring checklist	Worker-alerted continuous monitoring Self-monitoring checklist Second person monitoring checklist Recovery monitoring checklist Temperature monitoring	Worker- and workplace-alerted continuous monitoring Self-monitoring checklist Second person monitoring checklist Recovery monitoring checklist Temperature monitoring

Table 2. Levels of prevention monitoring, as assessed by applying a risk matrix. See Appendices C - E for sample monitoring checklists.

Frequency of prevention monitoring

Periodic

Periodic monitoring requires the implementation of scheduled screening practices to capture early signs of heat illness to drive prevention. The addition of app- or paper-based checklists for scheduled screening of signs and symptoms can be a cost-effective strategy to prevent the progression of heat strain, identify near-misses, and better understand organizational practices and their effects on heat accumulation in a worker.

Screening can include any or all of the following: worker-based self-monitoring; post-shift recovery monitoring, second person (e.g., crew leader/managerial) monitoring, and temperature monitoring (See "Screening Tools for Physiological Markers of Heat Stress" for considerations on tools for temperature monitoring). The choice of screening should be guided by the assessed level of risk.

Continuous

Continuous monitoring requires the application of wearable technology and should be considered in workplaces or tasks with high or extremely high heat-related risk. Personal health monitoring devices are defined as "devices that can be worn or mated with human skin to continuously and closely monitor

an individual's activities and responses, without interrupting or limiting the user's motions" *(Haghi et al., 2017; Gao et al., 2016)*. In most cases, the sensors within the health monitoring device connect to computational platforms that can store, analyze, and share data *(Hussain & Hussain, 2016; Kaisti et al., 2019)*. Often these devices use (proprietary) algorithms to estimate measures of physiological function *(Goldsack et al., 2020; Manta et al., 2020)*.

To date, most devices were developed to be worn by the public, or athletes, with the goal of providing a wealth of data to the individual. Some have been developed with the aim of providing information to a health care professional or other entity *(Carrier et al., 2020)*. Deciding how an organization will share the data (i.e., the personal data is only shared with the worker, or the workplace receives the data directly) is critical, as this decision will have broad implications, including but not limited to: worker compliance with the tool, legal requirements of the company, range of data analysis that can be conducted, and safety outcomes.

At the forefront of consideration are the sensor technologies that are currently available to measure physiological symptoms of heat strain, specifically:

- elevated Core Temperature (T_{core}),
- elevated Skin Temperature (T_{skin}),
- increased Heart Rate (HR), and
- reduced Heart Rate Variability (HRV).

In addition, devices must be considered for their ability to meet the practical needs of a workplace, which include:

- no additional burdens to existing PPE;
- hygienic and comfortable for extended wear;
- accurate (valid) and precise (repeatable) measurements (few 'false' alarms or 'missed' alarms);
- ability/need to pair via Bluetooth to connect to a secondary device;
- data access;
- battery life; and
- no additional hazards introduced.

Further for the purposes of device consideration, it is recognized that individual variations (including sex differences) cause different people to experience the risk of heat illnesses differently despite the same level of heat stress. This means across individuals, heat stress symptoms (T_{core}, T_{skin}, and HR) will vary under the same environmental conditions.

Individual differences include level of acclimatization, fitness level, age, sex, medicated/unmedicated, pre-existing medical conditions, body anthropometry and composition, and genetics. Due to individual and sex-based differences, workplaces may need to establish baseline data for each worker, so they can compare changes from 'normal' as a component of heat stress symptoms. To establish this baseline, workers will need to be monitored or screened regularly, including during peak hot/humid days. In addition, workplaces will need to develop and implement training sessions on the use of any monitoring devices they implement.

THERMOREGULATION AND THE PHYSIOLOGY OF HEAT STRESS

Thermoregulation is the adaptive physiological response designed to prevent the body from becoming either too cold or too hot *(Kenney et al., 2015)* via homeostatic mechanisms such as vasoconstriction, vasodilation, shivering, and sweating. This section is not a comprehensive review of thermoregulation, but rather an overview, of relevant physiological changes, in context of the primary markers of heat stress, that are monitored (i.e., HR, HRV, T_{skin}, T_{core})

The body is always balancing heat production and heat loss, with the outcome being the maintenance of body temperature at approximately 37°C. Measurement of body temperature can be important to avoid dysfunction due to high internal temperatures (e.g. heat exhaustion/stroke)*(Dias & Paulo Silva Cuhna, 2018; Teng et al., 2008)*. Body temperature can be represented by T_{core} and T_{skin}, although most personal health devices only measure T_{skin}, since direct measurement of T_{core} can be difficult without an invasive, internal sensor. T_{skin} is related to both HR and metabolic rate, as it is affected by the circulation of blood *(Buller et al., 2010; Diaz & Paulo Silva Cuhna, 2018)*: these measures together can allow for calculated estimations of T_{core}.

Measurement of body temperature can be important to avoid dysfunction due to high internal temperatures

T_{core} is the temperature of the deepest structures of the body; and is maintained through various homeostatic mechanisms (e.g. sweating, shivering, and redistribution of blood flow through vasoconstriction or vasodilation of blood vessels) *(Cheung, 2010; Kenney et al., 2015)*. The body starts to activate heat loss mechanisms when T_{core} increases. There are four mechanisms of heat loss: radiation, conduction, convection and evaporation.

The first mechanism, radiation, accounts for a significant amount of the body's heat loss *(Gagnon, 2011; Kenny, 2010; Cramer, 2022; Lim et al., 2008)*. Radiation operates based on the thermal gradient that exists between the skin and the ambient environment (heat radiates from hotter to cooler places); in most places the environment is cooler than body temperature *(Díaz & Becker, 2010; Lim et al., 2008)*. In occupations where workers are in a hot environment, as well as wearing PPE, this method of heat dissipation is impeded because the thermal gradient is small, and because PPE interferes with it. In an external environment that is very hot, the thermal gradient is reversed, such that heat can be transferred from the ambient air into the worker *(Levy & Roelofs, 2019)*.

Heat loss via conduction and convection are similar and together account for a small amount of total heat loss. For conduction, objects must be in **direct** contact *(McArdle et al., 2007)*. As such, the body loses heat by exchanging it with surrounding air molecules or through contact with any cooler surfaces in the environment (e.g. cooling vest). With conduction, the dissipation rate depends on: the length of time the objects are in contact; and the thermal properties of the objects.

Convection, on the other hand, depends upon contact with **moving** air (e.gs. wind or a fan) or fluid (i.e. water), and dissipation rate depends on: the rate of flow (faster flow, higher dissipation), the temperature gradient, and the thermal properties of the fluid *(Kenney et al., 2015; McArdle et al., 2007)*.

The last mechanism is evaporation, which is another important way for the body to lose heat *(Díaz & Becker, 2010)*. Evaporation operates by **transforming** the sweat on the skin from a liquid into a gas; the transformation requires a lot of energy, which is taken from the body as heat and lost to the environment, cooling the body. Environmental humidity plays an important factor in the effectiveness of this method since high moisture content in the air impairs water conversion from liquid to gas, thereby making sweating less effective in humid environments. The use of PPE can also severely compromise the body's ability to use evaporation to reduce overall body temperature. For example, sweat can be absorbed or wiped off by the PPE; consequently the sweat that gets wiped off or absorbed does not contribute to cooling *(Cheung, 2010)*.

Three of the mechanisms of heat dissipation (radiation, conduction, convection) depend on increased blood circulation from the warm core of the body to the skin surface; putting additional load on the heart. One of the primary cardiovascular challenges when performing physical labour in the heat is to simultaneously provide sufficient cardiac output (maintenance of delivery of oxygen to organs and cells) to both the skeletal muscles (to perform physical work), and to the skin (to dissipate heat) (*Périard, et al., 2016*). Cardiac output (CO) is defined as the product of stroke volume (SV: blood volume pumped per beat) and HR (number of cardiac contractions per minute) expressed in L/min (CO [L/min] = SV [L/beat] x HR [beats/min]). Physical exertion under the presence of heat induces a tremendous load on the cardiovascular system as skin and muscle are competing for blood flow. Skin vasodilation during heat stress redistributes blood volume away from working muscles, limiting oxygen access and requiring additional work from the cardiovascular system via an increase in heart rate. This blood volume redistribution may further affect other internal organs with limited blood flow and oxygen supply (*Jacklitsch et al., 2016*).

In addition, sweating is a requirement for heat dissipation over an extended period of heat exposure and increases risks of dehydration. Fluid losses from **sweating cause the blood to lose water (plasma volume); the result of this decrease in total blood volume is that Stroke Volume is further decreased, and a compensatory increase in Heart Rate is observed to maintain the body's demand for blood and oxygen supply** (*Davies & Maconochie, 2009; Jacklitsch, et al., 2016*). Eventually, if the reduction in blood plasma volume is severe enough, the increased cardiovascular strain results in a decreased ability to perform aerobic work *(Périard et al., 2016)*.

As heat strain increases, the body loses its capacity to maintain a normal temperature, causing elevations in T_{core}, and T_{skin}. **Meanwhile, the heart will continue to increase its rate to try to lower temperatures, leading to the associated signs and symptoms of heat illness. As such, prevention monitoring that includes monitoring Heart Rate, and body temperature (T_{core}, or T_{skin}), in real-time are ideal.**

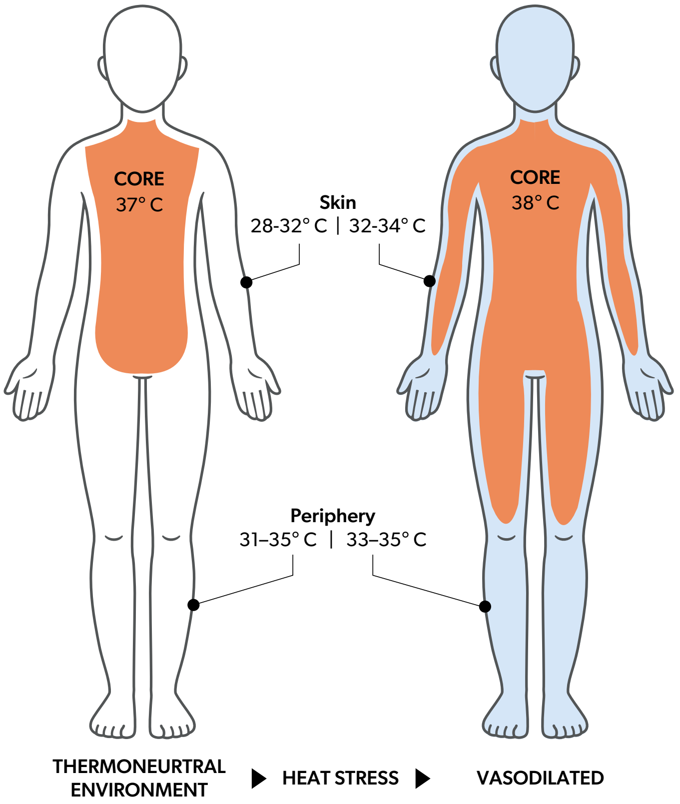

Figure 1. Illustration of changes in skin temperature and heat distribution, as core temperature rises.

SCREENING TOOLS FOR PHYSIOLOGICAL MARKERS OF HEAT STRESS

Survey monitoring

Beyond direct monitoring of physiological factors, indirect monitoring, via survey, may provide useful information to assess risk of heat stress in workers. Screening for heat stress subjectively can provide a quick and accessible tool. The literature has shown that workers are discerning about their personal perceptions of heat accumulation (*Cheung, 2007; Dehghan et al., 2013)*, and that workers' thermal perceptions should be considered *(Cheung, 2007; Dehghan et al., 2013)*. As such, posing questions can bring further awareness to workers about "what" they are feeling and to help them respond appropriately and in a timely fashion. Surveys are also an inexpensive and non-invasive means to enhance a heat-illness prevention program. Importantly, information gathered through surveys can provide workplace decision-makers with more information about: the incidence of milder expressions of heat illness (e.g. heat cramps); as well as assist in the development of policies to enhance daily recovery from high-heat/humidity days. However, given the added burden of survey collection in the workplace, consideration should be given to the length, the time-of-day for surveying, and the method used to collect data, to minimize disruption of work- and personal-time, while enhancing the recognition of early signs of heat stress *(OHSCO, 2009)*.

A stand-alone survey for heat stress monitoring has yet to be developed and published in the literature. Therefore, Appendicies C - E profile questions with supporting literature that could be considered for use by workplaces.

Heat stress screening

Considering factors such as long shift hours, in association with outdoor work in high heat/humidity, or at indoor workplaces with high process heat, screening for heat stress should be considered by some workplaces. The research literature provides insight into the personal factors people feel and describe when they become too hot. For example, in wildland firefighters, fatigue has been identified as a concern and a positive correlation has been shown between shift duration/working hours and experiencing one or more symptoms of heat stress including: headache, dizziness, nausea, and muscle cramps *(Kim et al., 2019)*. Additionally, according to a study that surveyed 1,719 people in the Australian labour force, three-quarters of the heat stress respondents experienced fatigue and headaches *(Zander et al., 2018)*. More severe symptoms such as: dizziness, skin rashes, confusion, and nausea were also reported by individuals who were exposed to high levels of heat stress. In addition, according to NIOSH *(Jacklitsch et al., 2016)*, rapid heart rate, extreme weakness or fatigue, dizziness, confusion, and muscle cramps are evident in different levels of heat exposure that could lead to different heat illnesses.

A study done by Dehghan and colleagues *(2013)* highlighted the correlation between workers' perceptions of heat illness and measurement of heat accumulation through the validation of a questionnaire for heat strain evaluation in women. In this study, researchers measured HR and oral temperature every five minutes for 120 minutes while the women worked. They also gave a 45-item survey, to be filled out during breaks, as well as during working conditions, every 30 minutes. They found a significant correlation between the questionnaire scores and oral temperature as well as Heart Rate. Their identified cut-off point was 17, which indicated the existence of heat strain in a person. Sixteen variables in their questionnaire were found to be effective in identifying the onset of heat stress; these were personal perceptions of:

- workplace air temperature
- workplace humidity level
- personal temperature (e.g. I feel comfortable)
- work intensity/physical activity level
- workplace airflow
- level of sweating
- level of fatigue
- level of thirst
- intensity of heat suffering
- performance of workplace ventilation system
- if there are heat sources at the workplace – what do you feel when exposed to them
- sunlight exposure (i.e., full, partial, shadow)
- how long the person spent in the warm environment (hours)
- had they previously experienced heat stroke
- most frequent body posture when at work (sitting, standing/low mobility, standing/high mobility, walking)
- spaciousness of workspace

Other studies have suggested similar themes for implementing a subjective measurement to detect heat stress. Bethea and Parsons *(2002)* suggested parameters including: ambient temperature, humidity, radiant temperature average, air movement, and rate of physical activity. Rodriguez *(2010)* showed sweat rate as a prominent cooling response to heat stress; consequently, parameters including: ambient temperature, air velocity, and humidity were considered important factors related to the rate of sweating. These studies support the fact that heat stress is a multifactorial by-product and in a dynamic environment, multiple parameters should also be considered to assess risk; this should include subjective methods, even with advances in wearable technologies, as an additional tool. Taken together, we have proposed a Heat Stress Screening Questionnaire that can be used by individual workers or secondary persons to assist them in deciding whether a worker is experiencing symptoms of heat illness and guide them in actions to take (See

Appendix C).

Alternatively, Tikuisis and colleagues (*2002*) have developed a Perceptual Strain Index (PeSI), which measures the thermal strain in individuals through their perceived thermal sensation and the Borg Rating of Perceived Exertion for physical activity intensity level. This index is another survey method that can be used to assess the real-time risk of thermal strain through perception, and it can be used to determine whether action is required (e.gs., cooling, rest break) (*Tikuisis et al., 2002*). This index has been tested and shows an acceptable correlation with reliable indices of heat stress; (r=0.94 between PeSI and physiological strain index and (r=0.9) between PeSI and heart rate (*Dehghan & Sartang*, 2015) (See Appendix D).

Heat stress recovery survey

In addition to symptom screening on identified high heat/humidity days, considerations should be given to daily recovery screening, for example, with long work hours (e.g. prolonged deployments) across multiple high heat days *(Kim et al., 2019)*. The importance of screening has been emphasized by the fact that a heat casualty in a group signifies and suggests that the rest of the team are also in danger of heat stress *(Kelley, 2003)*. Given that daily exposure to high heat conditions can induce chronic effects of heat fatigue, these should also be monitored as a component of a heat-illness prevention program *(Budd et al., 1997; Ruby et al., 2002)*. For example, by applying the Humidex Calculator, such as when the humidex value hits 37°C+, workplaces could implement a daily heat stress recovery questionnaire. Furthermore, workplaces could consider using this questionnaire based on work intensity, where a daily recovery screen may be meaningful for higher-intensity work days, while heat-stress screening could be implemented for lower-intensity work days.

A proposed Heat Stress Recovery Questionnaire can be found in Appendix E. It is recommended that this survey (or a similar survey) be performed at the end of each shift day, to track both subjective perception of environmental and physiological status to guide workers to take action if needed. Further consideration could be given to Heat-Recovery-Specific Activities. For example, using showers or water submersion techniques at the end of each shift could act as an effective recovery method from acute high-heat days, as well as a prevention strategy for chronic high-heat days and nights.

Creating an app-based program that workers could complete on a personal device would streamline this process and should reduce administrative burden.

In conclusion, personal perception of heat stress is an important component of a Heat Stress Management Program, especially in dynamic work environments where additional empirical monitoring is problematic (i.e., Wet Bulb Globe Temperature). Personal perceptions can strengthen workplace screening programs and provide workers with specific heat-symptom questions to guide their actions, as well as a recovery monitoring program, during periods of high temperature. Incorporating these

surveys into an app, can further facilitate survey implementation and provide a novel data source for long-term policy development and planning.

Core temperature monitoring

Heat illness is a major cause of preventable morbidity and mortality. Workers exposed to intense heat can become unable to activate compensatory mechanisms, putting their health at risk. The sources of heat stress in some dynamic occupations (e.g. wildland firefighters, farmers etc.) include both physiological and environmental heat production and are likely compounded by the presence of PPE. Consequently, in these occupations, measuring and screening for physiological markers that are indicative of the onset of heat strain and stress are paramount, and can prevent injury and save lives. For compliance purposes, the Ministry of Labour, Immigration, Training, and Skills Development (MLITSD) recommends that heat stress guidelines prevent unacclimatized workers' T_{core} from rising above 38°C *(Deming et al., 2020; Hunt et al., 2019b; Jacklitsch et al., 2016; Petruzzello et al., 2009)*.

Measuring T_{core} is considered the gold standard approach to assessing and preventing heat stress, however, there are numerous technical and practical challenges for doing this, which makes this approach in the field impractical. Nevertheless, given that monitoring T_{core} is recognized as the gold standard in preventing heat illness, the following measurement methods are reviewed: rectal, oesophageal, pulmonary, and telemetric. Alongside suitability for field use, the following sections endeavor to describe the accuracy (i.e., closeness of the measurements to the actual value; validity) and precision (i.e., closeness of the measurements to each other; reliability) of these measurement techniques.

Rectal temperature

Rectal temperature (T_{rec}) is one of the gold standard representations of T_{core} and the most frequently used method in laboratory settings *(Casa et al., 2007; Hunt et al., 2016, 2019a; Seo et al., 2016)*.

T_{rec} is measured by inserting a temperature probe past the anal sphincter. Although it has frequent use in laboratory settings; its use in an occupational setting is limited. For example, the application of T_{rec} measurements among structural firefighters and a group of wildland firefighters who were performing wildland firefighting tasks in simulated fire conditions has been evaluated *(Golbabaei et al., 2013; Hunt et al., 2016, 2019a)*. However, for field applications, key limitations for this method include personal preference, sanitary concerns, and data streaming. Although the literature reports ease and comfort of use in laboratory settings, convincing workers to use this method for regular temperature monitoring in the field would be difficult. Related to this is the risk of bacterial contamination; although sanitary conditions are relatively easy to maintain in a laboratory setting, this can be challenging in an occupational setting. Lastly, temperature data would need to be communicated wirelessly to a wearable system for the data to be meaningful in real-time. To date this technology does not exist for field use. Therefore, despite producing both accurate and precise T_{core} estimates, the impractical nature of this method prohibits its use in an occupational setting.

Oesophageal and pulmonary temperature

Oesophageal and pulmonary thermometry are also considered to be gold-standard measures of T_{core} because of their central body location (close to the heart) and rapid response to thermal changes. For oesophageal telemetry, one can use a flexible temperature monitoring tube, a lubricant, and a calibrated thermometer *(Pasquier et al., 2020)*. For pulmonary artery measurements, a catheter is required. Whereas these methods produce accurate and precise readings *(Bootsma et al., 2022; Launey et al., 2016)*, both methods are invasive due to the difficulty of: 1) inserting the thermometer past the nasal passages and into the oesophagus (causes irritation to the nasal passage, and general discomfort); or 2) into the pulmonary artery, causing general subject discomfort. Neither would be feasible for use in an occupational setting.

Telemetric core capsule

Given that T_{core} is defined as the temperature of the deep structures of the body *(Cheung, 2010; Hunt et al., 2016; Kenney et al., 2015; Taylor et al., 2014)*, devices that can be situated close to the internal organs of the body report a more precise T_{core}. An innovative approach to this is an ingestible thermometer pill. These capsules are swallowed and pass undigested through the digestive tract. They are equipped with Bluetooth technology and continuously measure internal temperature, relaying the information back to a secondary device, sometimes, in real-time. This tool not only provides high-quality measurements in comparison to the gold standard measure of heat stress (T_{rec}), but also ingesting the capsule does not cause any discomfort and allows continuous measurement for up to 12 hours *(Easton et al., 2007; Roossien et al., 2020; Steck et al., 2011; Towey et al., 2017).* Research has shown that T_{core} measurements from a thermometric pill were not significantly different from T_{rec} under both rest and dynamic conditions *(Bogerd et al., 2018; Bridges & Thomas, 2009; Casa et al., 2007; Easton et al., 2007)*. However, studies do report that values of T_{core} can be influenced by 'where' in the gastrointestinal tract the capsule is, or by the interaction of the capsule with fluids or foods in the body, thereby providing false readings *(Casa et al., 2007; Taylor, 2014; Taylor et al., 2014; O'Brien et al., 2024)*. For example, it has been shown that consuming a cold beverage triggered an error in measurements for up to 32 minutes after consumption *(Taylor et al., 2014; Wilkinson et al., 2008)*. It also takes approximately two hours after ingestion to obtain an accurate temperature reading; therefore, an administrative component is required to administer the capsule during a time that will align with measurement needs.

Despite its limitations, telemetric core temperature capsules for measuring and assessing T_{core} are commonplace in field research, and have been validated as a practical and non-invasive method of measuring T_{core} in comparison to T_{rec} probes *(Al-Bouwarthan et al., 2020; Bogerd et al., 2018; Budd, 2001; Casa et al., 2007; Easton et al., 2007; Gumieniak et al., 2018; Hunt et al., 2019a; Materna et al., 1992; Parker et al., 2017; Petruzzello et al., 2009; Steck et al., 2011; Taylor et al., 2021; West et al., 2020; Wilkinson et al., 2008; Williams-Bell et al., 2017)*. In one study, data from 301 wildland firefighters for one full work shift (of various lengths) were analysed; firefighters were given one core temperature capsule (VitalSense) before shift start. Researchers observed that the more arduous the tasks, the higher the risk of heat related illnesses, as indicated by a consistent increase in T_{core} above 38°C *(West et al., 2020).*

In summary, although measuring T_{core} as a regular component of a heat illness prevention plan would be useful; there are key incompatibilities for this method as a tool in the workplace. Notably, the only practical option is the telemetric capsule; however, because the capsule passes through the digestive tract within 24-48 hours; to regularly monitor T_{core} with this method, workers would need to ingest a capsule almost daily, which would be expensive (approximate cost of

$75-100 CAN) and impractical. Consequently, these devices are not meant for continuous use. Finally, telemetric thermometry is contra-indicated in people with bowel disease or a pacemaker *(Monnard et al., 2017; Taylor et al., 2014; Wilkinson et al., 2008)*. Consideration might be given for high risk or emergency situations, or in situations where workers are required to go beyond normal workload intensities or time frames.

Therefore, although direct assessment of T_{core} is a gold standard method and can provide valuable information for heat stress monitoring, if provided in real-time; there is currently no practical way to implement it in an occupational setting.

Estimates of core temperature for monitoring

Given the potential, and the limitations, of real-time monitoring of T_{core} (previous section); efforts have been made to non-invasively but accurately **estimate** T_{core}, with the goal of heat illness prevention/mitigation by preventing T_{core} from rising above 38°C. Methods for estimating T_{core} typically aim to measure locations on the body, or arteries, where minimal heat dissipation occurs, so that the measured temperature value is a close estimate of T_{core}. The following methods for estimating T_{core} are reviewed below: oral/sublingual; temporal (forehead); axillary (armpit); ear-based (tympanic or aural canal); and skin (head, chest, wrist, or arm).

Oral/sublingual temperature monitoring

The sublingual pocket in the mouth is close to the sublingual artery; as such, an estimate of T_{core} can be gleaned by placing a thermometer on the posterior part of the tongue for five minutes. Whereas oral temperature has been shown to have acceptable precision (repeated measure), this approach does not provide high accuracy (true measure) *(Mazerolle et al., 2011)*. The oral method can be affected by internal and environmental factors such as hot and cold drinks and mouth diseases, making it a poor estimate of T_{core} *(Mazerolle et al., 2011)*. It is also altered by breathing, making it impractical for use during or after exercise, and oral temperature has hygienic challenges in many occupational settings. In summary, sublingual temperature monitoring is not recommended as a standard method for temperature monitoring in occupational settings.

Temporal temperature monitoring

Forehead temperature can be taken using multiple tools including liquid crystal thermometers, self-contained data loggers, and non-contact infrared thermometers.

Liquid crystal thermometers

Liquid crystal thermometers are sticky strips that are placed on the forehead, above the eyebrows, for 30 seconds; during which time their colour bar changes indicating T_{skin}. During clinical testing, this method has yielded high precision, but low accuracy; therefore, this approach is not recommended for use *(Casa et al., 2007; Imamura et al., 1998; Kimberger et al., 2007; Lacoumenta & Hall, 1984; Scholefield et al., 1982; Yaron et al., 1995)*. In addition to its limitation in reporting accurate measurements, this method is not practical for many occupations, especially ones requiring the use of head PPE (e.g. helmet, hardhat), or dynamic occupations.

Self-contained data loggers

Self-contained data loggers are composed of thermo-sensitive computer chips enclosed in durable, stainless steel that can be programmed to log temperatures while worn (-40 to 85°C) *(Langer & Fietz, 2014; Roossien et al., 2020)*. These devices can be adhered onto the skin and worn in multiple locations on the body but are commonly placed on the forehead. An advantage of these data loggers is that, unlike thermistors (used to measure temperature in equipment), they are wireless, small (16 X 6 mm^2), and can record the temperature data off-line; as such, they are capable of long measurement periods and have easy hygiene maintenance *(Langer & Fietz, 2014; Raymann et al., 2005; van Marken Lichtenbelt et al., 2006)*. Research examining the validity of different models of self-contained data loggers has shown high accuracy of -0.09°C; however, a key disadvantage is their inability to measure and report the data live, which would be essential to provide information for fast responses (i.e., heat stress mitigation) *(Langer & Fietz, 2014; Raymann et al., 2005; Stoop et al., 2020; van Marken Lichtenbelt et al., 2006)*. Until data can be transmitted wirelessly and in real time, these data loggers have limited applications in many dynamic occupational settings.

Non-contact infrared thermometers (NCITS)

NCITs measure temperature from a distance using a laser. Skin, including the forehead, emits infrared radiation, as heat is dissipated from the blood outward. NCITs measure T_{skin} according to the amount of infrared energy emitted. Recent advances and innovations in technology have increased the affordability of NCITs and they have become a common tool for assessing temperature in relation to infectious disease (i.e., for the detection of fever). The advantages of NCITs include: measuring a wide range of temperatures; the possibility of a built-in alarm system; immediate readings, and a single laser pointer to target the centre of the measurement area. However, the accuracy of using forehead T_{skin} as a proxy measure to estimate T_{core} is debatable.

A systematic review between 2002-2015 compared the accuracy and reliability of invasive thermometry methods, including NCITs, for adults who were hospitalized *(Kiekkas et al., 2016)*. This study is of value since it not only reports on the performance of NCITs, but also on the agreement between infrared temporal artery thermometry with both invasive and non-invasive thermometry methods. Measuring radiated heat (NCIT method) from the temporal artery in the forehead and temporal regions is considered one of the best methods to measure T_{skin} in the forehead region, but its ability to detect hyperthermia is debatable *(Kiekkas et al., 2016)*. The study reported that the precision and accuracy of infrared temporal artery thermometers was not satisfactory, and the authors suggested an inability for these thermometers to replace either invasive and other non-invasive thermometry methods *(Kiekkas et al., 2016)*. In addition, the location of the temporal artery on the forehead is not an ideal measurement location for T_{skin} to estimate hyperthermia. In other studies, temporal artery measurements had 0% sensitivity (accurate identification) to hyperthermia in comparison with invasive and non-invasive temperature measurements *(Fountain et al., 2008; Furlong et al., 2015; Kiekkas et al., 2016; Kimberger et al., 2007; Stelfox et al., 2010; Sulemon et al., 2002; Winslow et al., 2012; Wolfson et al., 2013)*. In summary, NCITs, including temporal artery thermometry do not provide an accurate or precise measurement of the T_{skin} as an estimation for T_{core}.

Axillary temperature monitoring

The axillary method involves placing a thermometer into the armpit for five minutes to acquire a reading. The probe has to be positioned carefully over the axillary artery and the arms positioned at the patient's side *(Wartzek et al. 2011)*. Axillary temperature measurement has acceptable precision, but poor accuracy, in comparison to actual measures of T_{core}, by approximately 1–2°C *(Chaturvedi et al., 2004; Insler & Sessler, 2006)*. So, although the axillary method is a common, simple, and accessible method, it is not a good alternative for estimating T_{core}.

Ear-based (tympanic and aural canal) temperature monitoring

The tympanic method is non-invasive and has a strong correlation with T_{core}, and brain temperature because the tympanic membrane receives blood from the internal carotid artery. The carotid artery also feeds the hypothalamus, which is the brain region responsible for regulating body temperature. Tympanic measures are repeatable with measurement error from one reading to the next to be acceptable at about 0.1 to 0.2°C. Goggins et al. (*2022*) demonstrated that tympanic temperature was the most consistent measure of core temperature in non-febrile adults, regardless of the environmental temperature with an average reading of 36.8 (±0.18)°C. However poor agreement between the right and left ear exists, likely due to user technique and therefore measurements should be restricted to one of the ears whenever possible (*Childs et al., 1999*). The accuracy also depends on the skill of the person taking the reading due to the positioning of the device, in relation to the membrane. Childs et al. (*1999*) demonstrated characteristic fever patterns using tympanic, axillary, and rectal temperature measures in febrile children suggesting tympanic measures reflect T_{core} changes. However there remains concerns because tympanic measurement has not been tested on people in extreme heat (*Casa et al., 2007*) and Casa and colleagues (*2007*) found that as T_{rec} increased during exercise, the tympanic temperature remained significantly lower. As such, although this method is easy to use, accessible, and can prevent infection through the use of disposable tips. Key disadvantages are that it cannot be used for continuous monitoring of T_{core} and its role as part of a prevention strategy in a dynamic workplace has not been tested in the field. However, it may have an application in some occupations for after-shift assessment for suspected heat illness.

Real-time skin temperature monitoring

Skin temperature plays an important role in thermal comfort, driven by the stimulation of afferent thermosensors. Skin also plays a major role in dissipating heat, particularly when performing physical labour in high temperatures (*Périard et al., 2016; Taylor et al., 2014*) and is highly accessible as a measurement location; making it a common point of interest for estimating T_{core}. T_{skin} is most often measured by using wired sensors that are attached to the skin surface (*Taylor et al., 2014*). In general, single-point T_{skin} measures are not accurate representations of T_{core}. During exercise, particularly in a hot environment, blood flow to the skin increases, causing sensations of warmth, sweating and discomfort. Schlader and colleagues (*2011*) stated that before an individual begins to exercise, they use their T_{skin} and thermal perception, as determinants for self-selected work intensity. Previous studies show that T_{skin} and Heart Rate also influence an individual's ratings of perceived exertion and risk (*Casa et al., 2007*). As such, information about thermal perceptions should be incorporated into educational training on signs of heat strain.

Monitoring T_{skin} at multiple sites (e.g. head, chest, arm, wrist) seems to provide better estimates of T_{core} and the onset of heat illness, particularly when taken in combination with other physiological measures. Location is important because the gradient of the skin-to-core temperature will differ depending on the types of arteries that are flowing past that location, as well as the proximity of the skin site to core body structures *(Taylor et al., 2014)*. This concept led to the division of different body tissues into "thermally stable, deep-body (core) and more variable, superficial (shell) structures" *(Benedict & Slack, 1851; Jay et al., 2007; Kenny & Jay, 2013; Taylor et al., 2014)*. Therefore, different parts of the skin are perfused with different blood vessels from different locations of body structures. Additionally, some regions in the body, such as hands and feet, have exclusive characteristics that help them to act as "physiological radiators" *(Taylor, 2014; Taylor et al., 2014, 2021)*. As such, T_{skin} monitoring is a common application for heat stress monitoring in the field. However, since different locations offer different sensitivities for estimating T_{core}, the following sections will consider devices that measure continuous T_{skin} on the head, chest and wrist.

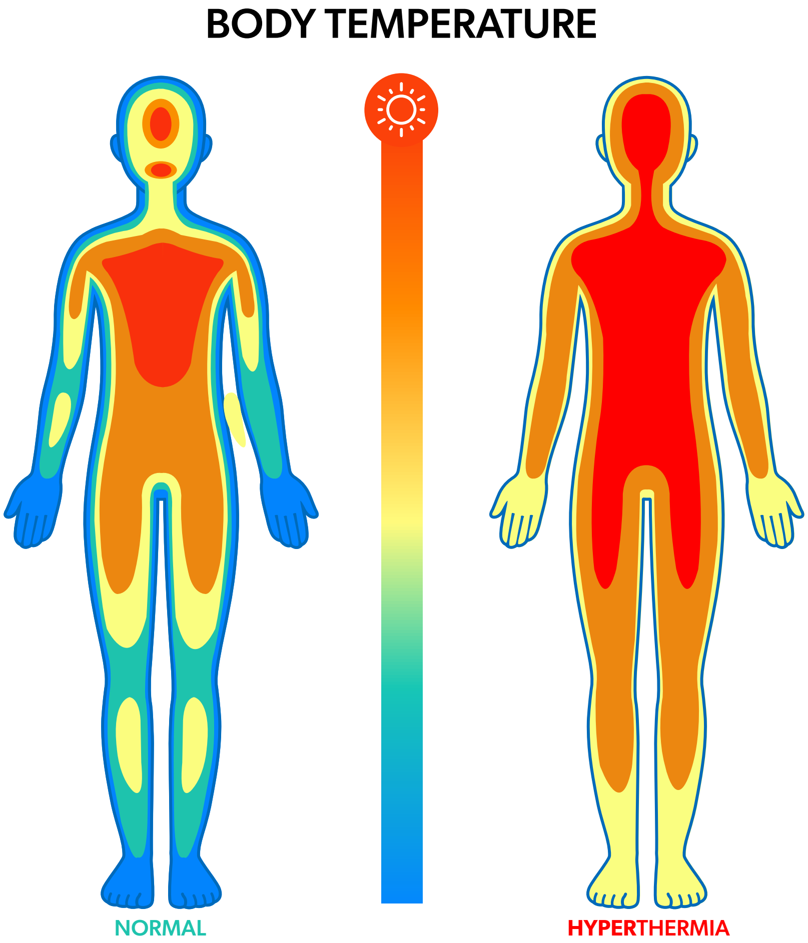

Figure 2. This figure illustrates how the body's core temperature remains stable; while the shells around it change (get hotter); relating to environmental heat and internal heat production/dissipation. This effect impacts the difference in T_{skin} readings from T_{core} and the interpretation of the data. T_{skin} has been shown to correlate with the direction-of-change for T_{core} for any site and algorithms are then applied to estimate T_{core}. However, correlations between the two will improve with locations closer to the centre of the body (chest, head, arm) than other body parts (wrist, leg, arm).

Head temperature monitoring

The head contributes 7% of the body's mass and total surface area *(Cross et al., 2008; Elabbassi et al., 2002; Hindle et al., 2015; James, 2013; Rasch et al., 1991; Shin et al., 2015; Wickwire et al., 2012).* The large surface area, low volume of subcutaneous fat tissue, and extensive vasculature allow for rapid heat dissipation *(Cross et al., 2008; Elabbassi et al., 2002; Hindle et al., 2015; James, 2013; Rasch et al., 1991; Shin et al., 2015; Wickwire et al., 2012)*.

Brain temperature is a critical factor affecting decision making and motor activity during exercise in hot conditions. During exercise under high temperatures, heat production in the brain is estimated to be 7±2% higher, while brain temperature is estimated to be 0.2°C higher than T_{core}, as a heat protective mechanism, during sustained aerobic exercise in either normal or hot humid conditions *(O'Hara et al., 2008)*.

As such, wearing a helmet (or a hard hat) can adversely affect thermoregulation by reducing evaporative, convective and radiant cooling. Given the potential impact of helmet design on thermoregulation, careful consideration should be made around helmet choice, that includes characteristics around enhancing heat dissipation (e.g., venting). The head is also an accessible and non-invasive location for monitoring temperature in occupational settings where workers are already required to wear a helmet, as it provides a location for insertion of a temperature monitoring device.

A thermistor, which assesses temperature as a change in the resistance of semiconductor material, can be inserted under the padding of a standard helmet that continuously monitors head temperature while transmitting data in real-time to a handheld Personal Digital Assistant (PDA) field monitoring device. Ideally, the sensor should be encapsulated, to protect it from the influence of sweating and ambient temperatures which can skew the data *(James, 2013; Mitchell et al., 2015; Wickwire et al., 2012)*. These devices estimate T_{core} using a proprietary algorithm (formulated by the manufacturer based on in-house testing and validation protocols). The precision and accuracy of some models have been tested under laboratory conditions, against a true T_{core} measure, such as T_{rec}. Head temperature monitoring, in a helmet, and protected from the influence of sweating does correlate with changes in T_{core} better than other single T_{skin} measures (except the chest). However, this was not consistently reflected under all testing or workplace conditions (reviewed in *Falcone et al., 2021*).

In summary, head-temperature monitoring may offer real-time monitoring and some devices have shown precision and good correlation with T_{core} in laboratory testing (James, 2013; Mitchell et al., 2015; Wickwire et al., 2012). However, the limitations related to factors such as long-distance transmission of temperature data, and battery-life, should be considered.

Chest measurement methods

The chest is the body area closest to the internal structures of the body and is therefore an ideal location for measuring T_{skin} as an approximation of T_{core}. This site provides pairing with devices that accurately measure HR, respiratory rate, and HRV. However, unlike the head, where devices can be attached to the helmet, chest monitoring requires that workers wear an additional device under their work wear, typically in the form of some kind of strap worn around the chest. Different technologies to measure T_{skin} in the chest area have been developed to date.

Chest monitors are non-invasive and are attached to the chest either with an elastic strap, or medical-grade adhesive pads, to provide continuous measurement of T_{skin}. The devices are able to continuously monitor, and can also transmit data in real-time to secondary devices. Battery life will be a consideration, as are comfort, skin reactions to constant wear, and device hygiene, related to length of wear-time. These devices were primarily developed for athletes, coaches, and sport scientists to monitor T_{core} as an enhancement for performance, but they have since been adapted for workers and occupational settings.

Laboratory studies have been conducted on some brands and validated their estimates of T_{core} against T_{rec}.*(Eggenberger et al. 2018; Kim & Lee 2019).* Falcone and colleagues *(2021)* hypothesize that the higher correlation was probably due to the isolation of the sensors from the environment provided by clothing for the chest. In addition, the literature has reported that, in general, the precision of the device heat flux sensors to estimate T_{core} is good. For example, Zhang and colleagues *(2015)* examined a collection of heat flux sensors for their accuracy, precision, and response; the results indicated an increased proficiency in response time for these sensors, as well as high accuracy and precision.

Several considerations are required for workplaces considering the implementation of a chest monitoring device as part of a heat stress monitoring system. First, the accuracy and precision of heat flux sensors have not been studied in an occupational setting. However, similar devices have been worn by firefighters continuously in the field for a study *(Robertson, 2015)*, and Adventure Leaders on an extended camping trip *(S. Ritchie, Laurentian University: Personal Communication)*. These devices did not hold up well in the field, largely due to failure of the strap, or skin irritation from chronic wearing of adhesive medical patches. In addition, little consideration has been given to female workers who have some challenges in wearing their brazier over the harness, potentially causing more discomfort than for male workers. Importantly, almost none of the studies to date examining the prediction of T_{core} from T_{skin} have included female workers (reviewed in *Falcone et al., 2021*).

However, through collaborative dialogue with the manufacturer, occupation-specific belts could help resolve these issues. As such, workplaces could consult with their research and development department to collaborate with developers to design a device that is compatible with the workers and occupational environment. Additionally, given the limited use of Bluetooth technology in the field, these devices will have constraints regarding battery life, and transmission distance, although satellite-based technology does exist *(Banos et al., 2014; Equivital, 2023)*.

In summary, chest-temperature monitoring can offer real-time monitoring and some devices have shown promising results in laboratory testing. However, the limitations related to factors such as comfort, long distance transmission of temperature data, and battery-life, should be considered.

Wrist measurement methods

Wrist-worn devices are considered easy to use and wear, often with a lower price range, making their use more widespread *(Cosoli et al., 2020; Kamišalić et al., 2018; Sim et al., 2016*). Top models for wrist band technologies are typically designed for HR monitoring, energy expenditure and monitoring sleep; but some models also contain body temperature sensors. However, the feasibility of using wrist T_{skin}, for the purpose of monitoring subjective thermal sensation and estimating T_{core}, is currently limited *(Choi & Loftness, 2012; Jacquot et al., 2014; Sim et al., 2016).*

Advantages of wrist-worn devices are that data monitoring is in real time and can be viewed by the wearer on the device-face. They can also connect to other monitoring systems via Bluetooth. As such, relayed data can be analysed by a secondary system to decide if the users' thermal or stress state has changed from predefined values *(Appelboom et al., 2014; Dias & Paulo Silva Cunha, 2018; Lukowicz et al., 2002; Pantelopoulos & Bourbakis, 2010; Scheffler & Hirt, 2005)*. However, the ability to draw a correlation between reported T_{skin} and T_{core} has not been successful in laboratory testing *(Anliker et al., 2004)*. This is partly due to the location of the sensor (wrist) as well as its temperature variability in comparison to T_{core} due to different factors such as ambient temperature, physical activity, and health conditions *(Anliker et al., 2004)*. Other writs-worn models that attempt to estimate T_{core} are equipped with other sensors (e.gs., HR, estimated energy expenditure, blood flow, galvanic skin response, etc.) but remain unable to successfully demonstrate reliability from many of these secondary variables including T_{skin} *(Bai et al., 2016; Cosoli et al., 2020; Ferguson et al., 2015; Lee, 2013; Storm et al., 2015; Tucker et al., 2015)*.

The commercial use of wrist-worn devices has been advancing in the past few years and they are well-accepted by the public as health monitoring devices. As such, workplaces could still consider wrist-worn technology as a personal tracker of baseline data to assist in personal symptom assessment and screening of individuals at work for heat stress prevention and mitigation. Although wrist based T_{skin} measures are a poor estimate of T_{core} they may still be useful for the workplace; but: 1) likely only in the context of hybrid measurements (see following section); and 2) the workplace may need to partner with a company that has already validated their other measurements to add a T_{skin} sensor. Finally, for practical consideration, the workplace would need to consider the safety aspects of wearing a wrist-worn device, and whether workers are willing to replace any current devices they may wear on their wrist.

Table 3. Summary assessment of various T_{core} measurements and estimates, according to: accuracy; reliability; practicality; data streaming; and cost.

		Accurate	Reliable	Practical for Field Use	Real Time Data Streaming	Relative Cost
Direct Measures of T_{core} (Continuous Monitoring)	Rectal	✔	✔	✘	✘	Low
	Oseophageal	✔	✔	✘	✘	High
	Pulmonary	✔	✔	✘	✘	High
	Telemetric Core Capsule	✔	✔	✘	Possible	High
Estimates of T_{core} (Periodic Monitoring)	Oral / Sublingual	✘	✔	✘	✘	Low
	Liquid Crystal Thermometers (temporal)	✘	✔	✘	✘	Low
	Self-Contained Data Loggers (temporal)	✔	✔	✘	✘	Low
	NCITs (temporal)	✘	✘	✘	✘	Low
	Axillary (armpit)	✘	✔	✘	✘	Low
	Ear-based	✔	✔	✔	✘	Low
Estimates of T_{core} (Continuous Monitoring)	Head (skin) Temperature Monitoring	✔*	✔	✔	✔	Moderate to High
	Chest (kin) Temperature Monitoring	✔*	✔	✔	✔	Moderate to High
	Wrist-Worn (skin) Temperature Monitoring	✘	✔	✔	✔	Moderate to High
	Arm-Worn (skin) Temperature Monitoring	✘	✔	✔	✔	Moderate to High

* Studies comparing continuous monitoring of T_{skin} at these sites have been shown to correlate well with core temperature (meaning they reliably change in the same direction at T_{core}). However, at any given time point, the T_{skin} may be higher or lower than T_{core}. As such, these estimates are better than estimates at other sites, but not as accurate as direct measures of T_{core}.

Hybrid monitoring: Heart rate, and heart rate variability monitoring

Measuring other physiological factors may provide further information which can help workplaces monitor for, and therefore mitigate, heat stress, either as a stand-alone measure or in the context of body temperature measures. Two well-established key variables used are: HR, and HRV.

HR is the number of heartbeats per unit of time (usually in minutes); and HRV is defined as the variation in time interval (milliseconds) between consecutive heartbeats. In a normal, healthy heart, heartbeat length varies from beat-to-beat. HR and HRV are influenced by exercise, respiratory sinus arrhythmia, hormonal reactions, metabolic processes, cognitive processes, stress, recovery, and environmental temperature; which for the purposes of this report will focus on heat.

Heart rate

It is well documented that passive heat stress increases HR *(Crandall & Wilson, 2015)*. Research shows a 7.15 ± 0.19 bpm increase in HR per 1°C elevation in internal body temperature at rest. These changes are due to: direct increases in heart temperature, and the activation of the sympathetic nervous system (increased HR) with withdrawal of the parasympathetic nervous system (decreased HR) from the heart *(Liu et al., 2015; Ren et al., 2011; Yamamoto et al., 2007)*. During environmental exposures to heat, the cardiovascular system must also compensate for increased demands in blood supply associated with the increased need for heat dissipation requiring enhanced blood flow to the vasculature of the skin. However, increased blood flow to the skin may be accompanied by a relative decrease in blood flow to other internal organs. In addition to dehydration, lower blood return to the heart requires HR to increase to maintain oxygen delivery across the body. Of note, workers with high physical demands will require their hearts to work even harder when dehydrated, which may alter the cardiovascular response to postural changes. Lower orthostatic tolerance (changes in posture) and decreased cerebral blood flow from heat stress may lead to syncope (loss of consciousness caused by a temporary drop in the amount of blood that flows to the brain).

In general, heart rate is higher when working in the heat because it is working harder to sustain heat loss mechanisms and maintain T_{core} within a normal range. As such, in the staging of heat illness, early stage (i.e., heat rash, heat cramps, heat syncope, and even heat exhaustion) temperature monitoring may not capture meaningful changes in T_{core}; however, HR will increase dramatically and as such can be used as an early warning sign for prevention.

The average resting HR is 60-80 beats per minute (bpm) (although some athletes have resting rates as low as 30-40 bpm). Resting HRs vary based on many factors including age, fitness level, environment, emotion, medical condition, and medication *(Arena et al., 2016; Ross et al., 2010)*. A person's maximum HR is the highest number of beats your heart can sustain, expressed in beats per minute (bpm). Maximum HR can be estimated by calculating your Age Predicted Maximum HR (APMHR): using either Fox's simple "220-age" estimate *(Fox et al., 1971)* or Tanaka's more robust "208-(0.7*age)" calculation *(Tanaka et al., 2001)*. Another useful reference is 80% maximum HR, since working or exercising at 80% of your maximum HR is "hard-to-very-hard" and is not recommended to be maintained for long periods *(Arena et al., 2016)*.

Moran and colleagues *(1998)* found that T_{core} follows a similar trend to HR, and in experiments involving 100 young adults, a T_{rec} of 38°C was associated with a HR of 140 bpm, while a T_{rec} of 38.6°C was related to a HR of 159 bpm during exercise in the heat at 25-30% of maximum work.

The authors stated that T_{rec} reflects the body heat storage, which is elevated when working in heat and HR reflects the elevated demands on the circulatory system. It was consistently shown that there is a direct relationship between T_{rec} and HR under heat stress conditions. In fact, several studies have looked at HR as a single input to estimate T_{core}. As reviewed in Falcone and colleagues *(2021)* four studies *(Buller et al., 2013, 2015; Hunt et al., 2019; Seo et al., 2016)* estimated T_{core} from HR measurements, using the Kalman

Filter "…obtaining reasonably promising results in terms of performance." This algorithm has also been tested under multiple conditions including environment, clothing, hydration, activity, and acclimatization *(Buller et al., 2013, 2015)*. The method appears to present a similar agreement with the measured T_{core} in both exercise and recovery phases *(Hunt et al., 2019)*, but seems to underestimate the T_{core} for low work rate *(Buller et al., 2013; Seo et al., 2016)* and overestimate it for very high work rates *(Buller et al., 2013)*. Applying these guidelines and incorporating personal physiological variables offers a potentially meaningful approach to preventing heat stress, through HR monitoring.

In summary, evidence currently exists for the successful use of HR monitoring in workforces, where heat stroke is a risk, primarily as a guide to alert workers of the need to take active measures to cool off or take a break to avoid health risks *(Ruas et al., 2020)*.

Heart rate variability

It is well documented that passive heat stress decreases HRV in healthy males *(Carrillo et al., 2016)*. This section discusses the potential role for HRV to be employed as an indicator for heat stress prevention.

HRV refers to the variation in the R-R interval of sequential heart beats (i.e., the interval from the initiation of one beat, to the initiation of the next beat) and indexes neurocardiac function as dictated by a heart-brain communication system and dynamic autonomic nervous system pathways *(Carrillo et al., 2016)*. HRV measurement is a non-invasive method of monitoring cardiac autonomic modulation and is a useful indicator of cardiovascular health and well-being. In this context, there may be an opportunity to use HRV measurement in workplaces, not as an immediate predictor of an incipient heat stroke event, but as an indication of harmful chronic accumulations of stressors, including heat stress, that may enhance the predisposition of workers to a heat stroke event, when in other circumstances, they may not have been at risk *(Flouris et al., 2014)*. In practice, measuring and interpreting HRV data is emergent and therefore applications are exploding in the literature; at the same time interpreting HRV data remains challenging and would require, at minimum, a capable software system to interpret the data, in addition to staff training on the use of the software.

Assessing HRV requires that the R-R intervals intervals (peaks of signals on electrocardiogram to assess intervals between heart beats) to be continuously measured, and these data are analyzed by specialized software using algorithms to calculate and compare the differences in beat lengths over specific periods of time. For this reason, HRV data can be considered over variable durations which can be very short (e.g. 2 min) to very long (e.g. 24 hrs). HRV measurements are presented using three types of analysis: Time-Domain; Frequency Domain; and Non-Linear Measurements *(Shaffer & Ginsberg, 2017)*. See Appendix F.

Given the above information, typically HRV measurements are used in research studies with workplaces as an indication of workplace stressors and/or adequate recovery, applying both Time and Frequency Domain calculations. For example, measurements taken over predetermined periods, such as at the end of a shift or first thing in the morning, could be used to assess the readiness and recovery of workers. Repeated measures, in the context of environmental health warnings, might also guide workplace decision makers as to the implications of chronic days of heat strain or poor recovery to enhance policy guidelines. For example, Jeklin and colleagues *(2021)* investigated whether HRV could provide a measure of enhanced fatigue and decreased cognitive performance in a shift work environment. HRV values were measured each morning upon awakening, and they showed that HRV had an inverse relationship to both fatigue and total sleep time (*Jeklin et al., 2021*). This study supports the potential application for workplaces to use HRV as a repeated measurement (e.g. upon awakening before a work day) to gauge effects of accumulated fatigue and possible increased susceptibility to heat stress and heat-related events.

In summary, although the immediate application of capturing HRV data to prevent heat stress per se would be limited, the incorporation of this measure as a means to track fatigue, stress, or autonomic dysfunctions could be considered as part of a long-term strategy to develop nuanced responses to worker's needs.

HR and HRV monitoring technology (Photoplethysmography vs. Electrocardiogram)

Given that HR monitoring can provide an important tool for heat stress management, and that HRV monitoring may shape future efforts, it is important for workplaces to understand device capabilities, which use different technologies to measure HR and HRV, to make informed selections in choosing a device. The two critical sensors used in HR and HRV monitoring devices are: Photoplethysmography (PPG) and Electrocardiogram (ECG).

PPG involves optical sensors with a small Light Emitting Diode (LED), which is shone onto the skin to detect volumetric changes in veins and capillaries under the skin. Given that each heartbeat causes a transient increase in blood pressure, and therefore volume, this pattern can be measured to derive HR. HR by PPG is measured by counting the number of blood pressure waves per minute, while HRV is calculated based upon the amount of time elapsed between each wave *(Castaneda et al., 2018).* Effective use of PPG requires continuous, direct contact with the skin. In addition, PPG can only be used to calculate time domain measures, not frequency domain measures of HRV.

In contrast, ECG detects the electrical activity of the heart via electrodes that are in direct contact with the skin. ECG-based methods directly detect the R waves in the QRS heart rate complex and from this, the frequency of, and period between, R waves allow for HR and HRV to be derived, respectively. Effective conduction of these bioelectrical signals requires moisture between the skin and the electrode, typically from sweat. As the heart beats, the electrical signals from the heart are conducted through the body fluids on the skin where they can then be detected by the electrodes. Electrodes are often embedded in chest straps or skin patches, which is why these devices need to either get wet to be used, or used with a conducting gel to ensure detection of the signals. The location of the electrode is important and should be worn as close as possible to the heart since ECG directly reads the electrical activity of the heart. These sensors might be uncomfortable to wear for a prolonged period and the quality of the collected data might be influenced by motion artifacts, which include noise caused by a sudden body movement that interferes with the ECG signal *(Castaneda et al., 2018)*.

ECG devices are considered the gold standard in measuring HR and HRV since they measure bioelectric heart activity directly, they have higher sampling rates, and can measure the entire QRS cycle, rather than just the estimated R. PPG devices that measure HR have demonstrated acceptable validity compared to ECG measure of HR for most common activities *(reviewed by Zhang et al. 2020)*. Whereas HRV measured by PPG has only been shown to be sufficiently accurate for healthy (and mostly younger) subjects at rest *(reviewed in Schäfer & Vagedes, 2013)*.

HR/HRV wearable technology types

HR/HRV wearable monitoring devices can be divided into two categories: chest worn-ECG; and arm/wrist-worn watches; using PPG. Due to the technological differences described above, chest monitoring devices are considered more reliable, but less practical than arm/wrist-worn devices *(Bai et al., 2016; Cosoli et al., 2020; Dias & Paulo Silva Cunha, 2018; Lee, 2013)*.

Chest worn

The accuracy and precision of chest-worn ECG technologies has been tested in multiple research settings investigating the real-time physiological parameters, and has been demonstrated as an effective collection of reliable physiological measurements to monitor workers' health *(Gatti et al., 2013; Gatti et al., 2014)*. Other studies have also shown that they can provide accurate measurements in hot and harsh workplace (e.g., construction) environments *(Lee et al., 2015; Moohialdin et al., 2018)* without causing personal inconvenience *(Lee et al., 2015)*. Providing comfort without interruption in work is an important feature of any wearable device, and these types of technology have the potential to provide that *(e.g. Buller & Karis, 2007)*.

Smart textiles are defined as textiles capable of sensing environmental stimuli via mechanical, thermal, chemical, electrical, or any other source, embedded in the cloth *(Ahrens, 2008; Dias & Paulo Silva Cunha, 2018)*. Smart textiles can be made into garments, which monitor physiological measures, including HR and HRV, and provide a level of comfort and fit not seen in other wearable technologies *(Ahrens, 2008; Dias & Paulo Silva Cunha, 2018)*. However, whether these garments would create further PPE burden, is unknown. In addition, daily wear of the same garment is not practical for workers, especially workers who have limited opportunity to clean their clothes (e.g. deployed wildland firefighters). In summary, while these devices are both accurate, precise, and comfortable to wear, practical issues may impair their use for workers.

Another non-invasive ECG-based method to monitor HR and HRV is the use of adhesive patches. Adhesive patches are skin wearable, capable of accurately measuring HR and HRV, as well as motion activities, estimated T_{core}, and respiratory rate *(Hernandez et al., 2019; Killian et al., 2021; Razjouyan et al., 2017*). They can wirelessly connect via Bluetooth and can log more than 500 hours of data. However, daily use of patches often causes skin irritation and soreness.

Arm/Wrist-worn devices

Arm/Wrist worn devices predominantly employ PPG to measure HR and HRV. As such, It is known that factors such as hand movements, wrist hair, and sweat can affect the measurement results of any arm/wrist-worn wearable *(Dias & Paulo Silva Cunha, 2018; Gillinov et al., 2017)*; accordingly, there is an inherent limitation to all the options within this category.

However, these devices can connect to different smartphone applications, and usually have messaging visible on the face of the device. For these reasons workers may prefer these devices, due to their interactive nature, familiarity of use, and their potential use for multiple goals, in addition to heat stress monitoring, such as fitness goals, sleep, and recovery.

Some arm/wrist worn devices are more accurate and precise than others, so it is important to choose a device that has had laboratory testing from an external facility *(Düking et al., 2020; Fuller et al., 2020; Germini et al., 2022; Koerber, et al., 2023; Martín-Escudero et al., 2023)*.

Arm-worn devices are newer than wrist-worn and may provide advantages in terms of safety, hygiene and comfort, from a wear-point perspective and improved contact with the skin (compared to wrist-worn). However, fewer studies have been conducted on these devices yet and like other body-worn devices, it is difficult/impossible to view the face of the device and therefore requires a secondary device (e.g. a smartphone) to send the data to for viewing or signaling via haptic messages (e.g. vibration or sound-based alerts).

A Final Comment

As presented in the opening of this guide, according to the ACGIH *(2022)*, heat stress can be defined by the following conditions:

- Sustained (several minutes) heart rate is in excess of 180 beats per minute (bpm) minus the individual's age in years (180 - age), for healthy individuals with normal cardiac response.
- Measured or estimated core temperature increases by more than 1°C from pre-job temperature, if the pre-job temperature is less than 37.5°C.
- Recovery heart rate at one minute after a peak work effort is greater than 120 bpm.
- Exposure should stop with signs and symptoms of heat exhaustion or heat stroke or with a request to stop regardless of what physiological monitoring may indicate.

Organizations should look to selecting validated tools that measure and apply any or all of these recommendations. Ideally, although single marker monitoring can be useful (e.g. Heart rate only), the literature shows that multiple physiological parameters (e.g. T_{skin} and heart rate) are needed to better predict core body temperature *(Niedermann et al., 2014)*. Furthermore, robust machine learning methods will soon offer the ability to develop more accurate, reliable, and personalized core body prediction algorithms by including additional data on worker characteristics, work intensity, and the surrounding environment. Additional sensors measuring and integrating indices such as the WBGT, work intensity and electronic medical records, may further prevent heat related illness and increase the availability and speed of data access during critical heat events, improving the decision-making processes for organizations *(Reviewed in Dolson et al. 2022)*.

LIMITATIONS TO PHYSIOLOGICAL MONITORS IN THE WORKPLACE

Limitations of device use in the workplace

This section identifies challenges associated with monitoring tools that need to be considered when choosing a tool(s) and addressed when implementing. Identified issues are listed in alphabetical order.

Company or workplace regulations

Some company, or workplace regulations inhibit the use of monitoring devices while at work. For example, a workplace's required PPE (e.g. hard hats, gloves, reflective shirts and jackets) may impede the ability to wear certain devices. Additionally, some job tasks may prevent the checking of devices for safety reasons (i.e., due to the attention loss that comes with checking the technology).

Data interpretation

Monitoring devices can provide a lot of different information, some of which can be difficult to interpret without certain knowledge *(Spook et al., 2019)*. Additional training may be required for workers to be able to fully interpret and use the information appropriately.

Data ownership and privacy/company information policy

A limitation of any system that employs the collection and/or transmission of data to a secondary site will have challenges associated with interpreting and legally managing the data. Although most companies selling these systems offer customizable interpretation of the data, any organization that allows second source access (i.e. beyond the worker themselves) will need to determine policy and practice for the implementation of this equipment. These policies should include 'who' will be responsible for monitoring data; and 'how' incidents will be managed. Workers must also be aware that these services upload data to servers that are owned and provided by the service company *(Paul & Irvine, 2014)*. In addition, this widespread data collection has ethical implications regarding 'who' has access to this personal physiological data, how, and for how long it will be kept, and whether it will be used for other purposes. To date, this has been a primary obstacle for implementing this type of broad scale safety monitoring system, except in military operations. It is important to review the "User Privacy" and "Data security" sections in the terms and conditions, as well as any specific privacy policies the service company provides for the health monitoring device chosen. These policies inform the user of their rights, and details if or how the data may be accessed or shared by the service company *(Paul & Irvine, 2014)*.

For these reasons, some companies choose technologies that only allow the individual worker to have access to the data, with perhaps a safety override alert system to an onsite supervisor, in the event of a faint, or imminent-event alert. These systems would require worker training on use and interpretation of the data, in addition to training on signs/symptoms and personal perceptions of heat and HR. Workers will also need to know how to maintain the equipment and use it within a comprehensive HSMP.

Feedback delivery

Devices that provide real-time feedback, may only provide the signal in one method (e.g. tactile or visual) and may not be suitable for all workplaces. For example, tactile feedback signals, such as a vibration, may not be felt when handling certain materials or working on certain machines *(Spook et al., 2019)*, while visual feedback may be blocked if the device is under clothing/PPE. Additionally, there may be instances where immediate feedback will distract from the work task, which could be a safety risk.

Monitor validity and reliability

The technologies for evaluating both physical and psychological health are at various stages of development and are constantly evolving. As new technology and devices are developed, it is important to assess the device's validity, including its ability to accurately and precisely assess the intended feature compared to the highest standard of measurement. Some health monitoring devices have been independently tested to determine reliability (produces consistent results) and validity (accurately measures what it was intended to measure). However, there are a large number of devices on the market that have not been properly tested *(Peake et al., 2018)*. This is primarily due to the popularity and demand of the devices, causing companies to produce and release devices faster than researchers can validate them *(Bunn et al., 2018; Carrier et al., 2020; Knowles et al., 2018)*. It should also be noted that even though the devices have been validated, they may not generate the same results in all workplace settings.

Robustness

Not all devices are suitable for all workplaces. For example, not all devices are resistant to water, rough handling, radiation, shock, dirt, or other elements in the workplace *(Spook et al., 2019)*. Of note, most are not certified intrinsically safe, which some workplaces would require (e.g. mining).

Size and weight of the device

The size (dimensions and weight), placement and fit of devices needs to be considered when implementing them in the workplace. Devices should not impede an individual's actions or ability to complete daily work activities.

System usability

System usability is important for operator acceptance. Wearable technologies should always be field-tested since site- or user-specific factors can change the usability and acceptance of any device *(Xing et al., 2020)*. Important considerations for usability are comfort, functionality, the perception of usefulness, and the ease-of-use. Functional considerations for wearable technology, including satisfaction with comfort, fit, and mobility *(Hwang, 2014)*, are also essential to workplace safety to ensure the device is not distracting to the user. According to Sontag *(1985)*, physical comfort can also be associated with physical attributes such as air, moisture and heat transfer properties, and mechanical properties such as elasticity, flexibility, bulk, weight, texture, and construction *(Frith & Gleeson,*

2004; Sontag, 1985). Therefore, considering the device's design and the unique environmental context in which it will be used, are influential. Since these determinants are common in technology acceptance *(Gao et al., 2015; Son et al., 2012; Wang et al., 2014)*, they require specific testing in unique occupational settings *(Choi et al., 2017)*.

Technology acceptance

Technology Acceptance Models (TAMs) *(Davis, 1989)* and other frameworks *(Venkatesh et al., 2003; Williams et al., 2015)* provide an understanding of the likelihood that individuals will adopt new technology in their personal life. Independent factors in these models include: normative beliefs, perceived ease-of-use or complexity, motivation to comply, need compatibility, relative advantage, self-efficacy, cost, subjective norms, fear of technological advances, perceived usefulness, attitude towards the device, perceived behavioural control, data accessibility, and appearance. Additional independent factors that are applicable in the occupational setting include: previous personal experience with technology, perceived privacy risk, subjective workplace norms, and perceived value (of the technology), occupational health and safety (OHS) need compatibility, and relative advantages. Dialogue and surveys with workers about these issues could improve adaptation of novel technologies *(Yang et al., 2016)*.

Time and training

The knowledge and time needed to operate the device may also impact its usability in the workplace. Regarding device use, some will need to be configured throughout the day or require data entry. Additionally, any monitoring tool requires training in order for the workers to understand why they are implementing the tool, how the device works and how to operate it, and how data will be used by the company.

Appendix A: Definitions

Cardiac Output (CO): The volume of blood ejected by the heart and the product of stroke volume (SV) and heart rate (HR) expressed as litres per minute (L/min).

Chronic Kidney Disease (CDK): CDK is a condition in which the kidneys are damaged and cannot filter blood as well as they should. This causes excess fluid and waste products to build up in the body and may cause other health problems such as heart disease and stroke.

Core Temperature (T_{core}): The temperature of the body's internal organs (i.e., heart, liver, gut).

Electrocardiogram (ECG): ECGs are often patches or chest straps that collect the electrical signals generated by the heart, often requiring specific placement on the chest to function correctly. They can detect heart rate and estimate respiratory rate, as well as having the capability of detecting heart rhythm abnormalities. These sensors may not be comfortable for long-term, continuous wear *(Jeffs et al., 2016; Manta et al., 2020)*, and the quality of the data can be impacted by motion artifacts (noise within the ECG signal that is caused by abrupt body movement).

Heart rate (HR): The number of cardiac contractions per minute expressed in beats per min (bpm). HR is a common measurement in both clinical and fitness activities. It can easily be extracted from ECG or PPG data signals and provides indications of changes in heart cycles *(Chan et al., 2012; Dias & Paulo Silva Cunha, 2018)*. Measures of HR are closely associated with activity level and can indicate how the heart performs during different intensities of physical activity and recovery *(Dias & Paulo Silva Cunha, 2018)*.

Heat strain: The physiological response to heat stress *(Donoghue, 2004; WSN, 2014; Xiang et al., 2014)*.

Heat Stress: The net load of heat to which a worker may be exposed (*Donoghue, 2004; WSN, 2014; Xiang et al., 2014*)

Heart Rate Variability (HRV): Variability in the time (milliseconds) between one heartbeat and the next. HRV can be used to evaluate the health of the cardiovascular and nervous system *(Young & Benton, 2018)*. Variability in heart rate is sensitive to changes in autonomic nervous system activity associated with psychological and physical stress. As such, HRV can also be used as an indicator of autonomic health and stress responses.

Heat-related illness: A spectrum of disorders, including heat cramps, heat exhaustion and heat stroke, caused by environmental exposure to heat.

Acute illnesses: Sudden-onset of heat-related illnesses that result immediately, or within a definite time-frame, of environmental exposure to heat and resolve within days.

Chronic illnesses: Heat-related illnesses that result from severe, prolonged, repeated, or continuous environmental exposure to heat and either take longer than 3 months to resolve, or never resolve.

Heat Stress Management Program (HSMP): Written plans that outline workplace policy around managing heat stress including, but not necessarily limited to: training, hygiene practices, monitoring, event documentation, and an emergency response plan. HSMP should include general controls, and job specific controls that are triggered when heat stress exceeds exposure limits, for example those in the TLV or AL *(ACGIH, 2022)*.

General controls: Actions that are taken, as part of the HSMP, to protect workers when heat stress is an expected hazard. These are broad actions that apply to workplaces overall *(ACGIH, 2022)*. Examples of general controls include: training and policies related to recognizing heat-related symptoms, alerts for high risk periods or activities, and learning first aid.

Job specific controls: Actions that are taken, as part of the HSMP, to control heat stress under specific exposure conditions. These actions are used to reduce heat stress exposure levels and include the application of the hierarchy of controls (e.g. engineering controls, administrative controls, personal cooling) *(ACGIH, 2022)*.

Photoplethysmogram (PPG): Sensors that use light scattering, absorbing and transmission properties to assess changes in blood volume. PPGs are commonly used to measure an individual's pulse to determine heart rate. Heart rate is calculated by measuring the amount of time between changes in blood volume (*Castaneda et al., 2018; Manta et al., 2020*). PPGs can also be used to estimate oxygen saturation (SpO_2: the amount of oxygen in the blood), using light absorption properties of oxygen-saturated hemoglobin (*Manta et al., 2020*). These sensors can be embedded within wristwatches, armbands, and unobstructed rings. They are capable of detecting heart rhythm abnormalities, but the quality of the data can be impacted by motion during assessment.

Skin Temperature (T_{skin}): The temperature of the outermost surface of the body. Skin temperature measures can be taken at various places on the body, for example the forehead, wrist, arm or chest.

Stroke volume (SV): Blood volume pumped at each heartbeat expressed in litres per beat (L/beat).

Thermoresistor: Temperature sensors that operate on the principle of resistance and require direct contact with the skin. As body temperature increases, the resistance decreases, and the change in resistance is computed into changes in temperature *(Manta et al., 2020)*.

Thermopile: A type of sensor that measures temperature from a distance by detecting infrared energy *(Manta et al., 2020)*. As the temperature rises, the amount of infrared energy emitted increases. Thermopiles are also known as infrared thermometers, and they do not require contact with the body.

Thermoregulation: An adaptive physiological response designed to prevent the body from becoming either too cold, by inducing vasoconstriction, shivering, increased metabolic activity, or too hot via vasodilation and sweating *(Kenney et al., 2015)*.

Appendix B: References

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Heat Stress **Screening** Questionnaire

(for self or second-person monitoring)

0 = No discomfort   1 = Mild discomfort   2 = Moderate discomfort   3 = Severe discomfort

How intensely are you suffering from the heat? (i.e. how hot do you feel?)   **NOTES**

0 1 2 3

Do you feel that your heart is beating very fast?

☐ **No   0   ☐ Yes   Rate Discomfort: 1 2 3**

Do you have any muscle pain/muscle cramps?

☐ **No   0   ☐ Yes   Rate Discomfort: 1 2 3**

Do you have a headache?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you have dizziness/drowsiness?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you feel unsteady when standing?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you feel fatigued?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you find it difficult to think?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you find it difficult to breathe or have a shortness of breath?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you feel nauseous?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Do you feel thirsty?

☐ **No   *0***   ☐ **Yes   *Rate Discomfort: 1 2 3***

Perceptual Strain Index (PeSi)

The PeSi is calculated as follows (as described in Dehghan et al. *(2008)*).

PeSI = 5 × ([Thermal Sensation Score – 1] / 4) + 5 × (Perceived Exertion Score /10).

Thermal sensation	Evaluate
1	**Comfortable**
2	**Slight warm**
3	**Warm**
4	**Hot**
5	**Very Hot**

Perceived exertion	Evaluate
0-1	**Extremely easy**
2-3	**Easy**
4-5	**Somewhat easy**
6-7	**Somewhat hard**
8-9	**Hard**
10	**Extremely hard**

Apply the PeSi to this table for interpretation:

Score	Evaluate
0-2	**No heat strain**
3-4	**Low heat strain**
5-6	**Moderate heat strain**
7-8	**High heat strain**
9-10	**Very high heat strain**

Heat Stress **Recovery** Questionnaire

(for self or second-person monitoring)

0 = No discomfort 1 = Mild discomfort 2 = Moderate discomfort 3 = Severe discomfort

NOTES

Do you feel that your heart is beating very fast?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you have any muscle pain/muscle cramps?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you have a headache?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you have dizziness/drowsiness?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you feel unsteady when standing?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you feel fatigued?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you find it difficult to think?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you find it difficult to breathe or have a shortness of breath?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you feel nauseous?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

Do you feel thirsty?

☐ **No** ***0*** ☐ **Yes** ***Rate Discomfort: 1 2 3***

HRV Data Collection and Processing

Time Domain indices quantify the variation in inter-beat intervals as the standard deviation of all captured R-R intervals in milliseconds. This can be further compared by five-minute segments (e.g. five minutes upon waking) or calculated as a mean of the Standard Deviations of all of the R-R intervals for each five-minute segment of a 24-hour HRV recording. Put simply, Time Domain graphs show you "how a signal changes over time." Using this method, a high HRV number is generally favourable during rest (HR should be low, therefore, the parasympathetic system is activated and the length of each heart beat is longer, with more variations in length between beats) *(Shaffer & Ginsberg, 2017)*.

Frequency Domain measurements consider the distribution of heart beat intervals that fall within specific frequency bands, expressed in Hertz (Hz) and divided into: Ultra Low (ULF: <0.003Hz), Very Low (VLF: 0.003-0.04Hz), Low (LF: 0.04-0.15Hz), and High (HF: 0.15-0.4Hz) frequency band groupings. Frequency Domain graphs illustrate "how much of the signal lies within each given frequency band," over a range of frequencies (in this case 0.003-0.4Hz). The measurement device needs to be sampling at a relatively high rate (e.g. 250Hz) to capture these data. Frequency data is analogous to a prism that refracts light into its component wavelengths; each component can tell you different aspects of heart health *(Electrophysiology, 1996)*.

The ULF and VLF bands are best monitored over 24-hours. ULF is thought to be primarily driven by slow-acting biological drivers, including T_{core}, which are believed to influence these readings. VLF bands appear to be regulated by the heart's intrinsic nervous system and poor readings on this band length are correlated with negative health outcomes *(Shaffer & Ginsberg, 2017)*, including arrhythmic death *(Bigger et al., 1992)*, and Post Traumatic Stress Disorder *(Shah et al., 2013)*. To date, application of these measures is limited, and until technological advances are made, this variable is not likely going to be of use to workplaces as a means to mitigate heat stress in workers.

The LF and HF bands are the most commonly reported frequencies and the best studied to date. The LF band primarily reflects baroreceptor activity, during resting conditions. LF power may be produced by both parasympathetic and sympathetic nervous system activation via blood pressure regulation; but LF is generally interpreted to be a reflection of sympathetic activation *(Bigger et al., 1992; Shaffer & Ginsberg, 2017; Shah et al., 2013)*. The HF band is also called the respiratory band, because it corresponds to HR variations related to the respiratory cycle; HR length increases during inspiration and decreases during expiration *(Bigger et al., 1992; Shaffer & Ginsberg, 2017; Shah et al., 2013)*. The HF band reflects parasympathetic activity and lower HF power measures are correlated with increased levels of stress, panic, anxiety, or worry. The HF band typically increases at night and decreases during the day; and is often used as an indicator of "readiness" as poor overnight readings suggest poor recovery from the previous day's stressors.

Appendix G: Research and Support

Training & technical support is available from your Health and Safety Association. Workplace-specific information, as well as training and consulting services for illness and injury prevention, are provided by the Health and Safety Associations of Ontario, the Workers Health and Safety Centre, and the Occupational Health Clinics for Ontario Workers. All OHS System Partners are part of the Occupational Illness Prevention Steering Committee that supported this project.

- Centre for Research Expertise in Occupational Disease
- Centre for Research in Occupational Safety and Health
- Infrastructure Health and Safety Association
- Institute for Work and Health
- Occupational Cancers Research Centre
- Occupational Health Clinics for Ontario Workers
- Ontario Ministry of Labour, Immigration, Training and Skills Development
- Public Services Health & Safety Association
- Workers Health & Safety Centre
- Workplace Safety North
- Workplace Safety & Prevention Services
- Workplace Safety and Insurance Board

Other sources of information on heat stress can be found in the list of additional resources from various sources at the bottom of the Heat Stress Toolkit page.