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Global Warming and Heat Stress Among Western Australian Mine, Oil and Gas Workers

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1. Introduction

The earth is currently experiencing a change in its climate which in some areas is resulting in warmer ambient temperatures. Globally the frequency and severity of heat waves have increased over the last few decades leading to an associated increase in the burden of morbidity and mortality associated with heat waves. Global temperatures are predicted to rise even further in the foreseeable future [1, 2].

Heat wave related research thus far has largely been focused on the health of the general population, in particular older people and little has been done to investigate its impact on occupational cohorts. Workers employed in outdoor occupations such as surface mining, construction and farming are deemed to be high risk groups, particularly those workers who are required to wear impermeable protective clothing and personal protective equipment (PPE) such as gloves and respirators [3]. During the 15 year period (1992-2006), 423 workers in the USA died as a result of occupational exposure to heat [4].

Three key factors influencing thermal balance among workers are: climatic conditions; metabolic demands; and clothing. Heat induced illnesses are related to and exacerbated by a combination of environmental work and clothing factors as well as sub-normal tolerance to heat, alcohol and drug abuse, dehydration (due to excessive sweating, diarrhoea, vomiting), being un-acclimatised to heat, electrolyte imbalance, and lack of sleep and fatigue [5]. When the body reaches a point where it can no longer maintain thermal equilibrium, core body temperature begins to rise and various forms of heat related illness (HRI) may develop. Types of HRI include heat oedema, heat cramps, heat syncope, heat exhaustion and 2 types of heat stroke (HS); Namely classical HS which results from extended exposure to hot environmental conditions and exertional HS which occurs sporadically in individuals with high metabolic output rates in combination (usually) with hot environmental conditions. Exertional HS has been reported in athletes, workers in the mining and construction industry, and military personnel [6].

Heat stroke generally occurs when core body temperature (T_c) exceeds 39°C. Symptoms include the cessation of sweating, red, hot, and dry skin, rapid and strong pulse, headache, dizziness, nausea and confusion, and this can lead to unconsciousness and death if left untreated [4]. The risk and severity of excessive heat strain varies widely among people.

In an occupational context heat strain is normally identified by various measures, including heart rate, core body temperature and the sudden onset of severe fatigue, nausea, dizziness and light-headedness. Generally people are at greater risk if they have experienced profuse sweating sustained over a number of hours, their net weight loss exceeds 3% of body weight, and their 24 hr urinary sodium excretion exceeds more than 50mmoles [7].

Repetitive exposure to hot working conditions usually enables workers to adapt to hot work environments leading to a reduction in heart rate and body temperature and an increase in sweating. Furthermore it has been demonstrated among heat acclimatised workers that core body temperature decreases by 0.1 – 0.5 °C during resting periods [8].

2. Ambient working environment

The expansion of Western Australia's resource industry has brought with it an increased number of personnel required on site [9]. As these industrial sites tend to be located in remote areas exposed to hot and sometimes humid conditions, the exposure of more personnel to extreme environmental conditions is inevitable. For example, miners have experienced WBGT exposures of 29.1°C to 31.5°C [10, 11] and a Basic Effective Temperature ranging between 26.6°C and 29.4°C [12]. Within the mining industry, particularly underground mining, the geothermal gradient contributes to ambient heat. With current mining trends, mines are becoming increasingly deeper, and as a result, so too are the thermal gradients. For example, in a South African mine, a geothermal gradient of 10 – 22°C·km^{-1} has been recorded [13]. As such, a significant thermal environment is present thus requiring attention to improving the environmental strain experienced by personnel.

In addition to the heat gained by personnel in these hot environments, high metabolic heat loads associated with heavy working tasks have also been reported (Mate et al. 2007). For example, the task of shovelling has been measured to range from between 266 W·m^{-2} and 407 W·m^{-2} [14, 15], while drilling has been found to range from 217 W·m^{-2} to 290 W·m^{-2} [15, 16]. Shovelling at 266 W·m^{-2} for a 75 kg individual without the capacity to cool could increase core body temperature (T_c) by ~0.1°C·min^{-1}. According to the International Standards Organization 7243, such work intensities correspond to high and very high metabolic rates [17]. If heavy work intensities are performed during environmental conditions previously described, the onset of a heat-related illness can occur [18], causing symptoms ranging from central and/or peripheral fatigue [19-22], decreased focus/concentration, oedema of the periphery [23], up to a more serious and sometimes fatal heat stroke [23].

The beginning of the fly-in/fly-out (FIFO) work regime can be traced back to the middle of the last century where workers in the Gulf of Mexico were flown in long distances to work offshore on oil platforms [24]. Other industries began to use this FIFO method of labour for their work force requirements. Currently, approximately 49% of Western Australia's mining sites are operating on a FIFO basis [25]. This method of employment provides employers an opportunity to have personnel from all regions of Australia to fill vacancies. Having a diverse work force introduces unique heat stress concerns which would otherwise not be present in a traditional mining town scenario. For example, in the northern regions of Australia during the wet months (2010/2011), temperatures ranged on average from 33.0°C to 22.1°C while concurrently in Tasmania during the same season the hottest day time temperature was recorded to be 18.4°C with highs ranging from approximately 3.0 to 15.0°C to lows of -3.0 to 6.0°C [26].

If employees are flown in from such temperature extremes, the probabilities of experiencing heat stress injuries are more likely. It is not only the location of origin that is of concern, where workers go during the off phase of their swing and how long they stay there for could also cause problems. With swing shifts ranging anywhere between one week on and one week off up to four weeks on and two weeks off, the 'down' time is what is of interest. As will be discussed later in more detail in this chapter, the acclimation status of a worker influences their capacity to deal with occupational heat loads. Initially, at the start of the swing, workers may not be acclimated to the task and thus would be more susceptible to heat stress related injuries. As time on the swing progresses, physiological responses to the continuous heat insults enables a larger heat load to be tolerated. Once these insults are removed, such as during vacation to a cooler climate, the heat acclimated responses are less responsive and return the worker to a vulnerable state.

Usual physiological adaptations during heat acclimation, that occur irrespective of the acclimation modality, include: a reduction in resting heart rate in the heat [27], decreased resting core temperature [8], increase in plasma volume [28], decrease in rectal and skin temperature [29], change in sweat composition [30], reduction in the sweating threshold [31] and an increase in sweating efficiency [29].

The process of acclimation is dependent upon several variables such as duration and frequency of acclimating sessions, temperature, humidity and exercise intensity. For example, Yamazaki [27] used a 6 day acclimation protocol with participants exercising at 50% $\dot{V}O_{2max}$ in ambient conditions of 36°C and 50% RH. Buono et al. [8] had a protocol which required their participants to exercise for 7 consecutive days for four bouts of 25 min with a 5 min rest while treadmill walking (1.34 $m \cdot s^{-1}$ at a 3% grade) and cycling (75 W at 35°C at 75% RH). Shvartz and colleagues [29] used a bench step protocol which equated to a load equal to 85% $\dot{V}O_{2max}$ during ambient conditions of 21.5°C DB, 17.5°C WB, for 12 days. Two hour treadmill walks for 9 days in humid heat (37°C, 74% RH) was used by Garden et al. [32] for their acclimation protocol. Although there are many different acclimation protocols, there is a general consensus within literature that the greater the intensity of exercise during acclimation, the quicker observable responses will be elicited.

The effectiveness of acclimation is dependent upon the acclimating conditions. Ideally, individuals should be acclimated in environmental conditions and workloads similar to those they would typically experience [33]. For example, individuals who work in desert type conditions should be acclimated in hot and dry conditions whereas those who work in tropical conditions should be acclimated in hot and humid conditions [32, 34]. A study on working capacity under dry and humid heat loads was performed by Nag et al. [35]. One group of subjects were acclimated to dry and hot conditions (41.3 ± 0.6°C and 40 – 50% RH) while another group was acclimated to humid and hot conditions (39.2 ± 0.6°C and 70 – 80% RH) for 9 days. It was found that those individuals who were acclimated in humid conditions were able to perform more work in similar conditions than those who were acclimated under dry conditions. Regardless of the acclimation protocol, both groups increased their work performance compared to the unacclimated state.

The benefits of acclimation were eloquently demonstrated by Wyndham and colleagues [36] when they calculated the quantity of work that could be performed between acclimated and unacclimated men in a laboratory setting. It was concluded that unacclimated individuals would reach a critical body temperature (a $\overline{T}_b$ where voluntary cessation of exercise occurs) quicker (600 min) than acclimated individuals (750 min) at the same ambient T_{wb}, particularly when initial core temperature was already elevated. These changes in sensitivity by the various thermolytic responses facilitate a reduction in the net rate of net heat gain.

The process of acclimating requires between several days to weeks of continual exposure to specific environmental and working conditions. Resources such as heat chambers may not necessarily be available on work sites which may make the process difficult. Consideration must also be made for the decay in heat acclimation status, which can range from between 6 days to 4 weeks [33, 37].

Despite the physiological advantage of a lower resting rectal temperature (T_{re}), increased sweat rate, reduced sweating threshold, reduction in resting heart rate, and increased blood volume, the commitment to induce these physiological responses in acclimation is both time and labour intensive. Even though miners have a good level of acclimatization, as previously described, heat stress related illnesses are still experienced despite currently implemented heat stress interventions. This supports the need for further cooling methods to be employed in heat stressful occupations.

Work-related injuries related to fatigue may be caused by dehydration [38], physical exertion (due to intensity and/or duration) and/or an elevated body temperature [19]. The deleterious effect of dehydration on running memory and perceptual motor coordination functions was found to occur beyond 2% dehydration [39]. When observing the effects of 2% body dehydration on word recognition, serial addition and trail marking tests, performance was found to decrease with increases in dehydration [38]. Performing prolonged activities in the heat can result in altered brain activity. During prolonged exercise (such as during a 12 h work shift), fatigue is thought to occur in the synapses due to excessive use, decreased spinal excitability to inputs and reductions in motoneural output from the spine resulting in a reduction in peripheral feedback [21]. Associated with elevated body temperatures are alterations in the central nervous system to drive working muscles [40-42]. With a reduction in working musculature, the ability to perform tasks may increase the risk of injury. Additionally, visual acuity is impaired during elevated body temperatures [43] while a reduction in mental and simple tasks occurs between a temperature of 30 – 33°C WBGT [44]. It was also identified by Nielsen et al. [45] through alterations in electroencephalogram measurements in the frontal cortex during hyperthermia, that the ability to exercise was reduced. These findings indicate that there are some neurological perturbations occurring while body temperatures are elevated, which could explain the commonly observed reduction in work and coordination.

3. Physiology of heat stress

As core body temperature increases, blood circulating through the core of the body picks up heat energy and the warmer blood flows to the skin where the blood is cooled and heat is exchanged with the environment. The rate of heat loss through the skin depends upon the temperature differences between the skin and the environment. Furthermore, the skin secrets sweat that evaporates thus removing additional heat energy from the skin. This process is influenced by humidity and air movement over the skin. Clothing can hamper heat loss through this process. If the net heat gain is equal to heat loss then the storage rate of heat is 0 and the body is in equilibrium.

There are 3 key factors that influence thermal balance, these are; climatic conditions, work demands and clothing. Heat induced illnesses are related to and exacerbated by a combination of environmental work and clothing factors as well as sub-normal tolerance, alcohol and drugs abuse, dehydration (excessive sweating, diarrhoea and vomiting) being un-acclimatised and electrolyte imbalance [46].

The risk and severity of excessive heat strain varies widely among people. In an occupational context heat strain is normally identified by various measures, including heart rate, core body temperature and the sudden onset of severe fatigue, nausea, dizziness and light headedness. Generally people are at greater risk if they have experienced profuse sweating sustained over a number of hours, their net weight loss exceeds 3% of body weight and their 24 hr urinary sodium excretion exceeds more than 50mmoles [47].

3.1 Heat stress indices introduction

Thermoregulation of mean body temperature ($\overline{T}_b$) is continually in a state of adjustment as a result of metabolic processes and interactions with the environment [48]. The regulatory centre for $\overline{T}$ b is located in the brain; more specifically, the preoptic anterior hypothalamus (PO/AH). In response to afferent signals from thermal receptors located throughout the body, the PO/AH integrates these signals and effector responses are initiated (sweating and/or increased skin blood perfusion during warm conditions) to restore $\overline{T}$ b or body heat content (Hb). These thermolytic mechanisms will continue until a thermal homeostasis is restored, as seen by an absence of a rising $\overline{T}$ b or core temperature (T_c).

Under conditions of thermal neutrality, the net change in Hb approximates zero. During conditions of uncompensable heat loads (conditions where heat gain is greater than heat loss), a rise in Tc is observed. Ultimately, it is the thermal gradient between the Tc and skin, and the skin and environment which determines the rate and direction of net heat gain or loss; this relationship is illustrated in Figure 1. This thermal heat exchange can be expressed by the following heat balance equation as adapted from [49]:

$$S = M \pm (R + C) \pm W - E \tag{1}$$

Where S = rate of net heat storage (either positive or negative)

M = metabolic heat production (always positive)

E = evaporative heat loss (always negative)

R = radiative heat exchange,

C = conductive heat exchange

W = mechanical work

Note: In cold environments negative (–) values could be used instead of the (+) that indicates heat gain (especially relevant for R and C). R,C,K and C(rsep) can be in either direction [46].

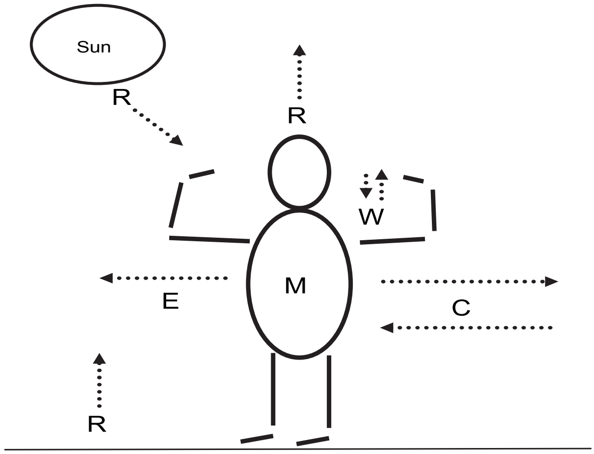

Fig. 1. Schematic representation of heat transfer where R = radiation, M = metabolism, E = evaporation, C = conduction, W = mechanical work

In addition to the heat gained by personnel in these hot environments, high metabolic heat loads associated with heavy working tasks have also been reported [50]. For example, the task of shovelling has been measured to range from between 266 $W{\cdot}m^{-2}$ and 407 $W{\cdot}m^{-2}$ [14, 15], while drilling has been found to range from 217 $W{\cdot}m^{-2}$ to 290 $W{\cdot}m^{-2}$ [15, 16]. Shovelling at 266 $W{\cdot}m^{-2}$ for a 75 kg individual without the capacity to cool could increase T_c by ~0.1°$C{\cdot}min^{-1}$. According to the International Standards Organization 7243, such work intensities correspond to high and very high metabolic rates [17]. If heavy work intensities are performed during environmental conditions previously described, the onset of a heat-related illness can occur [18], causing symptoms ranging from central and/or peripheral fatigue [19-22], decreased focus/concentration, oedema of the periphery [23], up to a more serious and sometimes fatal heat stroke [23].

International Standards Organization (ISO), World Health Organization (WHO), National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) are some of the governing bodies that have developed/implemented heat stress guidelines and/or indices to allow for safe repeated bouts of heat exposure by industrial personnel. There are several criteria deemed as a safe upper limit of T_c. These limits which have been developed by industrial governing bodies are: (1) a 1°C increase above resting T_c values [51], (2) a maximum T_c of 38.0°C [51], and (3) a T_c of 38.5°C if workers have been medically screened [51]. Despite these conservative limits, the incidence of heat stress related illnesses remains high, particularly in an Australian mine during the summer months (43/million-man hours on average throughout the year versus 147/million-man hours during February) [18]. Higher cases of heat illness during the summer months (May and September (88%)) were also observed among US marine corps [52]. With higher cases being reported during hotter months, one could suggest that workers and their managers are violating these imposed thermal limits and that improved heat stress interventions are required.

Thus, it seems important for occupational hygienists and managers to be aware of the severe consequences of a hot working environment and the potential risk for heat-related injuries. Some of the currently implemented interventions involve, establishing maximal exposure durations to stressful environments through heat stress indices [53-56], educating workers on hydration [57], and modification of the ambient working environment [50, 58]. By complementing these heat stress strategies with newer approaches, the incidence of heat related injuries in industry may be reduced. Therefore, the purpose of this review is to identify some approaches already taken to reduce heat stress in industry-highlighting some restrictions these interventions may have, and to provide an alternative solution which may compliment currently implemented heat stress interventions.

Environmental conditions in industry, as previously described, can place high and sometimes uncompensatable heat loads on workers. In order to help protect workers from heat stress related illnesses, heat stress indices or measurements have been created. These indices can be classed into three general categories; direct, rational and empirical indices. Direct indices involve the use of standard ambient measuring equipment. The more popular direct index used in industry is the ISO 7243 – WBGT [17]. Rational indices are measurements based more on physiological parameters such as sweating, T_c, heart rate, and metabolic work. Examples of rational indices include but are not limited to: predicted heat strain [59], heat stress index [56], and ISO 7933. Empirically based indices are those measurements which are based on meteorological parameters such as temperature, humidity and wind speed. Examples of empirically based indices are: effective temperature [60], corrected effective temperature and the predicted four hour sweat rate (P_4SR) [54].

Some approaches in addressing the issue of heat stress range from monitoring and manipulation of the ambient working environment (heat stress indices and ventilation practices), altering work practices and work schedules (mechanical equipment and rest to work ratios), primary care (acclimation of workers), implementation of safety equipment (cooling garments), to education of workers (hydration practices). Some challenges in creating a universal heat stress index are the multitude of variables which exist in the working environment. Such variability includes the identification of metabolic demands for tasks between workers, phenotype of workers, health status of the worker, tolerance to heat, heat sources (natural and artificial), mechanisation of occupation, interference of thermolytic mechanisms, level of intermittent work, and the ambient environment. Accounting for each variable in a single heat stress index may not be feasible for industrial applications. As a result, several indices have been developed to assist with protecting the worker and predicting heat loads. Regardless of its type, as summarized by Epstein and Moran [61], an index should: (1) be feasible and accurate through a range of conditions, (2) integrate important variables, (3) represent the workers exposure and (4) reflect increased physiological and psychological safety and health.

Described below are several heat stress indices and other heat stress interventions used in industry with a brief review of their function and in some cases, the variables measured and limitations.

4. Heat stress indices

Thermal Work Limit (TWL) – This index is defined as the limiting or maximal sustainable metabolic rate that a euhydrated, acclimatized individual can maintain in a specific thermal environment within safe limits of both deep body core temperature (38.2°C) and sweat rate (< 1.2 $kg \cdot hr^{-1}$) [62]. This index has been reported to be more appropriate and realistic than the WBGT during a field study performed by Miller and Bates [63]. The index incorporates various physiological limits in thermolysis to define its scale. From these physiological limits and environmental variables (WB, DB, barometric pressure and wind speed), a portable electronic device then determines a limit value. This value is compared to a table which then determines a safe sustainable metabolic level. Although this index may provide better accuracy in determining a safe working limit, the use of this index is difficult without the aid of the calculating device.

ISO 7243 - Wet Bulb Glob Temperature (WBGT) – An empirical index which is a compromise between an easy to use measure of ambient conditions and a reduced precision index for industrial environments. It is regarded as an exploratory method [17] to determine heat stress through the calculation of radiative, dry bulb, and wet bulb values.

The WBGT has been generally accepted amongst governing bodies upon which their recommendations and standards are founded [64]. This index allows for a maximal rectal temperature (Tre) of 38.0°C. The WBGT is calculated and then referenced against a table for tolerable exposure times, metabolic intensities and work ratios. Weighting for spatial variation in temperature accounts for the temperature at the head (having a weighting factor of two), abdomen and ankles divided by four. Also, there is a time weighting factor which is based on the work to rest ratio. The measurement is averaged over each work period. The simplicity of this index makes it an easy field assessment tool as it requires minimal equipment and training. In addition to the averaging of body segments and time, this index has two variations; the inclusion of radiative or solar heat loads. Typically they are used indoors or outdoors:

Indoors:

$$WBGT = 0.7\ t_{nw} + 0.3\ t_g \quad (2)$$

Outdoors:

$$WBGT = 0.7\ t_{nw} + 0.2\ t_g + 0.1\ t_a \quad (3)$$

t_{nw} = natural wet bulb

t_g = globe temperature

t_a = air temperature (dry bulb temperature)

In conjunction with WBGT values, estimated metabolic rates are given in five broad categories. This index also provides work/rest ratios adjusting for ambient conditions. The reference values provided are for a normally clothed individual (0.6 Clo), physically fit for the activity being considered and in good health and both acclimated and non-acclimated individuals [17].

While the usability of this index is easy, dry bulb measurements towards the top end of the scale may be over emphasised [30]. Further, the index may not adequately consider air flow during hot and humid conditions, and is insensitive to air flows above 1.5 $m{\cdot}s^{-1}$ [30]. This index is unable to accommodate for differences in metabolic rates; however, concomitantly using another ISO standard can correct for this shortcoming. The insulative component of clothing is not accounted for during the calculation of this index; although, another ISO standard can be used to correct for insulation. Despite the correction factors available from other indices, constantly referring to them may make this index cumbersome to use.

ISO 7933 – Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain - Predicting sweat rates and T_c are described by ISO 7933. The objectives of ISO 7933 are twofold; (1) to evaluate the working environment where rises in T_c or excessive water loss typically occur, and (2) determine exposure times where physiological strain is acceptable.

As the ISO 7933 index estimates strain in Western populations, this specificity may discriminate against other ethnicities based on phenotype. McNeill and Parsons [65] investigated the accuracy of this heat stress index during a simulated tea leaf picking task in conditions similar to those found in India. They used Western participants in the study and observed differences in the accuracy of measured sweat rates, metabolic rates and insulative properties of clothing. The appropriateness of the index was found to be mainly directed towards Western countries as opposed to those regions where anthropometrically different people habituate. ISO 7933 states within its introduction that it is not applicable to cases where special protective clothing is worn [59], which include reflective clothing, active cooling and ventilation clothing, impermeable clothing and PPE.

ISO 8996 – Ergonomics of the thermal environment – Determination of metabolic rate – Here, the ISO 8996 specifies different methods for determining metabolic rates in assessment of working practices, jobs and activities. These estimates are based on an individual of 30 years of age, weighing 70 kg and standing 1.75 m tall (BSA 1.8 m^2) for men, and weighing 60 kg and standing 1.70 m tall (BSA of 1.6 m^2) for women [51].

The index is divided into four different assessment levels for metabolic estimates with each level having different levels of accuracy. Level 1; screening - this assessment quickly characterizes the mean workload of the occupation, but contains a high risk of error in estimation. Level 2; observation - a time motion analysis is performed for the occupation which includes workload estimates for body segments and postures. The accuracy of this level is ± 20%. Level 3; analysis - the estimation of metabolic rate is determined through heart rate. The accuracy of this level is ± 10%. Lastly, level 4; expertise - indirect calorimetry. Accuracy of this method is ± 5%, however it is limited by the measurement, duration or motion being evaluated.

Observer experience in the interpretation of task intensity, as defined by ISO 8996, plays a key role. Additionally, the grading of an activity can vary with the appraiser's level of fitness, age, experience and training level [66]. It was found that the difference between two groups of appraisers before visual training ranged between 18-60%. After training, the largest difference in a measurement was found to be 24%. These findings highlight the importance of intra-observer experience to accurately assess metabolic demands for heat stress purposes.

ISO 9886 – Ergonomics – Evaluation of thermal strain by physiological measurements – several methods are provided to measure physiological parameters which are to be used in conjunction with other ISO standards. The parameters included in this standard are: body temperature, skin temperature, heart rate and body mass loss. The index provides several methods to measure each parameter with an emphasis on body temperature. ISO 9886 provides limit values for the various physiological parameters.

Using heart rate as an indicator of thermal strain may be subjective as heart rate increases with work and heat. Physiological responses to heat may vary between individuals and setting an upper limit of an increase in HR of 33 bpm may be conservative. Nielsen and Meyer [67] attempted to calculate $\dot{V}O_2$ from measuring HR and observed both over and underestimation in $\dot{V}O_2$ due to differences in temperature, posture, and whether there were static or dynamic movements and non-steady state types of activities performed. Using HR as a factor to limit work may require further investigation.

Predicted 4 hour Sweat Rate (P_4SR) – developed by McArdle and colleagues [54], with the aim to create a simple index or method of assessing the physiological effects of any combination of temperature, humidity, radiation and air movement on personnel wearing different clothing types and working at various intensities. A nomograph encompasses these variables for ease of use. As with all indices, some limits were implemented in its derivation. This includes the dry bulb or globe temperature range, wet bulb, air movement speeds, metabolic rates and an upper sweat rate limit of 4.5 L in a four hour period. Once environmental variables have been obtained, lines are drawn on the nomograph and the required sweat rate can be determined along with the predicted rise in T_{re} at the end of a 4 hour period.

The inherent limitations are described within the index itself, however, the application of this index to acclimated individuals can be challenging since such individuals can easily achieve a sweat rate of 4.5 L in a period of four hours ($1.125\ L{\cdot}hr^{-1}$), and in fact, Wyndham et al. [68] showed acclimated individuals had a P_4SR range between 4.95 and 5.35 L. Therefore, a sweat rate of 4.5 L could be an overly conservative estimate. In as much as the investigators provide a nomograph for calculating sweat rates and rise in T_{re}, deciphering the graph provides a further challenge to the field use of the index. Furthermore, this index accounts for partial clothing to be worn by personnel, and therefore does not consider fully encapsulating garments, which could be problematic.

Physiological Strain Index (PSI) –an 11 point scale (0 to 10) is used to indicate the level of stress which is based on two physiological parameters; heart rate and T_{re} [69]. The PSI is simple to use and it does not discriminate between environmental conditions, nor the clothing worn by individuals; hence the functionality of the index. The evaluation of heat strain can be preformed instantaneously by a supervisor or the workers themselves at any time, which is advantageous; however, the social acceptance of T_{re} monitoring and its invasiveness are questionable.

$$PSI = 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \tag{4}$$

T_{ret} and HR_t are simultaneous measurements of rectal and heart rate

T_{re0} and HR_0 are the initial rectal and heart rate measurements

Conversely, the PSI could be considered a reactive rather than a proactive index. It is reactive in that, the workers would already have been or are currently being exposed to high heat loads. It is only when they stop work that their physiological responses are measured. These measurements could be a misrepresentation as a critical core temperature could have already been reached. It has been previously shown that modifications to work practices begin to occur as ambient conditions increase [11], reducing the effectiveness of this index.

Heart rate – ISO 9886 [51] - includes equations to estimate heat strain in workers based on heart rate. These equations include a limit of heart rate (HR_L) that should not be exceeded:

$$HR_L = 185 - 0.65 \cdot age \tag{5}$$

or a sustained heart rate;

$$HR_{L,\ sustained} = 180 - age \tag{6}$$

It is suggested to set the upper limit for a change in heart rate of 33 bpm which is associated to a thermal strain being experienced by the worker (ΔHR_T). Despite these suggested limits, as with T_c, there are circumstances in which this limit can be exceeded, provided there is medical supervision. During these circumstances, the upper limit for HR would be 60 bpm.

4.1 Limitations to current heat stress interventions

Heat stress interventions typically do not consider individual variability. As such, individuals will respond differently to the same condition. Therefore, the accuracy of the index will vary. The development of a heat stress index is based on the statistical probability that most of the population will be protected and this probability will then either over protect or not protect at all. Those individuals who are considered to be at either one of the tail ends of the probability curve may not be adequately protected. Over the past century, there have been many indices developed that are aimed at protecting workers; however, the one major shortcoming of all indices is that they do not consider the unique characteristics of each individual during its prediction. In addition to the limitation of accuracy, a new index can be difficult to implement or regulate.

Creation of a new heat stress index could take years to accurately develop and trial. Manipulating the working environment can prove to be too costly and implementing cooling PPE would provide benefits when adhered to. As all workers are required to drink at rest breaks or during work, therefore supplying personnel with a specific type of drink could be an effective cooling intervention to implement. Drinking a solution which changes physical states, solid to liquid, has the potential to provide additional cooling to the worker during work.

4.2 Drinking a cold liquid as a heat stress intervention

The consumption of cold liquid water ($H_2O_{(aq)}$) results in an expansion of the body's natural heat sink. As the body warms the cooler consumed $H_2O_{(aq)}$, heat energy is exchanged between the body and the $H_2O_{(aq)}$ until a thermal gradient no longer exists. Therefore, the heat energy that would have been otherwise stored in the body is transferred to the $H_2O_{(aq)}$.

The consumption of cooler quantities of $H_2O_{(aq)}$ will theoretically allow even larger quantities of heat energy to be transferred from the body to the solution. In order to increase the temperature of $H_2O_{(aq)}$ by 1°C, approximately 4210 $J \cdot g^{-1} \cdot K^{-1}$ of heat energy is required to be transferred into the liquid. Thus, the specific heat equation 7 is used to calculate the quantity of heat transferred to 500 g (assuming the density of water is 1.000 ($kg \cdot m^{-3}$)) of 0°C $H_2O_{(aq)}$ consumed by an individual (body temperature of 37°C).

$$Q = m \cdot C_p \cdot \Delta T \quad (7)$$

Q is the quantity of heat gained or lost (kJ)

m is the mass of the substance (kg)

C_p is the specific heat capacity of the substance ($kJ \cdot kg^{-1} \cdot K^{-1}$)

ΔT is the change in temperature (°K)

Using this equation, it can be determined that approximately 77.9 kJ of energy is required to equilibrate the water to body temperature. In other words, by consuming 500 g of 0°C water, 77.9 kJ of cooling capacity is administered to the individual.

An ice slurry (combination of both solid ($H_2O_{(s)}$) and $H_2O_{(aq)}$ water; $H_2O_{(is)}$) results in an even greater thermodynamic potential for heat energy to be exchanged with the body. If left undisturbed, $H_2O_{(aq)}$ begins to change physical states from liquid to solid at a temperature of approximately 0°C. However, if $H_2O_{(aq)}$ is continuously stirred, the liquid forms small ice crystals and changes into an $H_2O_{(is)}$. By maintaining both physical states (solid and liquid), the $H_2O_{(is)}$ drink may provide a subtle, but significant advantage to reducing heat strain in thermally challenging conditions This advantage is due to the phase changing feature of the $H_2O_{(is)}$ when $H_2O_{(s)}$ is converted to $H_2O_{(aq)}$. $H_2O_{(s)}$ has a different specific heat capacity (C_p) (2108 $J \cdot g^{-1} \cdot K^{-1}$) to that of $H_2O_{(aq)}$. Comparing $H_2O_{(aq)}$ and $H_2O_{(is)}$, the $H_2O_{(is)}$ would have a greater C_p as a result of having both phases of water in its solution; this ultimately increases the solution's heat sink capacity. Therefore, if the C_p of $H_2O_{(s)}$ is used as a conservative approximation for $H_2O_{(is)}$ at temperatures below 0°C, and the C_p of $H_2O_{(aq)}$ is used for temperatures above 0°C, $H_2O_{(is)}$ results in a greater heat sink capacity than $H_2O_{(aq)}$ alone.

An additional factor which contributes to the larger $H_2O_{(is)}$ heat sink capacity is the energy required to change the physical state of a solid to a liquid. That is, the energy required to change the physical state of $H_2O_{(s)}$ to $H_2O_{(aq)}$ without a change in temperature. This is termed the latent heat of melting or 'enthalpy of transformation'. For water, the energy required is 334 $kJ \cdot kg^{-1}$. To estimate the cooling capacity of $H_2O_{(is)}$ from equation 7 while incorporating both the enthalpy of transformation and the C_p of $H_2O_{(s)}$, the cooling capacity for 500 g of $H_2O_{(is)}$ at -1°C becomes 245.9 kJ. Again, using equation 7 to determine the change in T_c for a 75 kg individual drinking 500 ml of $H_2O_{(aq)}$ or $H_2O_{(is)}$, a change of 0.299°C and 0.945°C would occur, respectively.

While the thermodynamic effect of $H_2O_{(is)}$ consumption has been investigated in animals. Vanden Hoek et al. [70] infused a 50 ml $\cdot kg^{-1}$ solution of either saline slurry or saline water of equal temperature in 11 swine over a 1 hr period. Brain temperature was reduced by 5.3 ± 0.7°C with saline slurry compared with 3.4 ± 0.4°C using saline water. Another study by Merrick and co-workers [71] showed how phase changing cryotherapy modalities were able to produce colder superficial skin temperatures (ice bag; from 35.6 ± 0.9 to 27.8 ± 3.5°C at 1 cm, 36.3 ± 0.7 to 31.8 ± 2.2°C at 2 cm, wet-ice; from 35.7 ± 0.8 to 27.2 ± 3.4°C at 1 cm, 36.2 ± 0.7 to 30.6 ± 3.0°C, and gel pack; from 35.49 ± 0.8 to 29.5 ± 2.4°C at 1 cm, 36.1 ± 0.9 to 32.1 ± 1.5°C at 2 cm) at a depth of 1 and 2 cm compared with non-phase changing cryotherapies. Kennet and colleagues [72] investigated the cooling efficiency of four different cryotherapeutic agents and showed that crushed ice (19.6 ± 3.8°C) reduced skin temperatures more than a gel pack (13.2 ± 5.1°C), frozen peas (14.6 ± 4.2°C), and ice-water immersion (17.0 ± 2.8°C). Lee et al. [73], demonstrated that cold (4°C) versus warm (37°C) drinks administered prior to and during cycling exercise lowered mean T_{re} during exercise (37.3 ± 0.4°C versus 38.0 ± 0.4°C) and extended time to exhaustion (63.8 ± 4.3 vs. 52.0 ± 4.1 min; cold versus warm drink, respectively). More recently, Siegel et al. [74] showed that consuming 7.5 $ml{\cdot}kg^{-1}$ ice slurry resulted in a lower pre-exercise T_c, which remained lower for the first 30 min of treadmill running compared with ingesting cool liquid of the same composition. This supports the notion of ice slurry having a greater cooling capacity than cool liquids of equal volumes. Additionally, time to exhaustion was significantly (P = 0.001) increased in the ice slurry (50.2 ± 8.5 min) versus cold liquid (40.7 ± 7.2 min). While a thermodynamic advantage should theoretically be gained through the phase change properties of solid versus liquid water, the physiological effects of consuming such a mixed solution during exercise have only recently been reported [72, 74].

With a greater theoretical cooling capacity of an ice slurry over a liquid, ingesting this as an additional cooling source should aid in regulating heat during work. In addition to the cooling potential of an ice slurry, the capacity to hydrate also increases as the ice slurry provides a source of fluid replacement. Replacing fluids, as described below, with an ice slurry could theoretically better attenuate the rate of rise in body temperature and increase exercise performance compared to water alone.

5. Recent research

Recent heat stress research in the LNG industry by Maté et al. [75] focused on identifying which heat stress indices best attenuated heat stress in on and off shore workers. The authors measured the physiological responses to a typical work day, as deemed by personnel during March. Body temperature, skin temperature, heart rate, hydration status and estimated metabolic work were measured throughout the work day. The interesting findings from the study were, the P_4SR was most accurate for both cohorts, ISO 8996 did not accurate predict workloads and the majority of personnel were dehydrated upon the start and completion of their work shift. These findings question the appropriateness of specific heat stress indices to be used while dehydrated.

A subsequent study by the same authors [76] investigated a practical cooling intervention on an off shore oil platform. They compared the physiological responses to drinking a cold liquid to drinking ice slurry. The same physiological measurements were recorded as in the previous study. Results from the study indicated that complete replacement of fluid during working hours (excluding meal breaks) by ice slurry, although not statistically significant, can attenuate the heat load experienced by personnel. Interestingly, the hydration status of workers was similar between studies as well as ambient working conditions. It could therefore be concluded that the physiological attenuation of heat gain is attributed to the ingestion of ice slurry.

The results from both studies indicate the P_4SR and ingestion of ice slurry will mitigate heat stress in personnel, a *caveat* must be applied to each study. Sample sizes were small and the sample population were from one location and time of year. Although these limitations do exist, the findings hold promise for using ice slurry as a cooling modality. It is easily implementable, cost effective and personnel enjoyed drinking the new beverage. Future focus should be placed on educating the work force on the importance of hydrating. Once adherence to maintaining hydrated has been firmly implemented in the working culture, heat loads experienced by personnel can be accurately determined.

6. Recommendations for further research

Occupational heat stress is one issue which is most likely to remain within industry. In order to attenuate the effects of heat on personnel, a two pronged approach can be proposed. This consists of 1) better prediction of heat loads and 2) identifying those individuals whom are better suited physiologically to work in the hot environment. Irrespective of the approach, the task to effectively minimize heat stress related disorders in industry is monumental.

Predicting heat loads which personnel will experience can be further dissected into environmental and metabolic. Environmental considerations vary according to atmospheric conditions and the immediate working vicinity. Controlling the atmosphere is not probable; however, manipulating the immediate working environment is. This cost can be substantial; which suggests more research into better conditioning techniques and efficiently running and cooling machinery. Engineering examples for environmental modification can include but are not limited to more efficient machinery, better insulated components, and separation of heat producing sources and personnel.

In addition to conditioning of the environment, modification of the physicality of tasks can further attenuate heat loads. For example, rather than manually lifting boxes from point A to point B, have boxes delivered as close as possible to the destination and also at a height which is mechanically and spatially practical. This may be an area where ergonomist could provide better and more detailed evaluations of work space.

Heat stress indices attempt to predict heat loads experienced by personnel which are dependent on the environmental and metabolic loads. The accuracy and precision of the index is also dependent on the accuracy of the values entered into the various equations. Should an estimated temperature be entered into the equation, an estimated predicted heat load will be provided. The calculated value may or may not be a true reflection of the actual heat load experienced. That estimate may in turn over or under protect the worker. In the field, obtaining accurate environmental measurements are relatively easy and simple. Obtaining metabolic measurements of tasks are unfortunately not as simple. A similar type of error may occur as with an inaccurate temperature reading. If a task is assumed to be not as physically demanding than it is in reality, then the worker will be expected to work longer in unsafe conditions. This type of situation can jeopardize the safety and health of the worker. Therefore, investigating the metabolic costs associated with specific occupations or even tasks could increase the protectiveness of current heat stress indices.

Methods to identify physiologically suitable individuals for work are also required. Practically speaking, attainment of a thermal neutral working environment with minimal physical exertion is not likely for those industries where manual labour is the only method of production. Therefore, a closer inspection of those variables which allows one individual to work in a more heat stressful environment than another is warranted.

There may be some specific genotypical predisposition between individuals that determines the quantity of stress which can be tolerated. In addition to genotype, the tolerance developed by acute or chronic exposure to heat may also contribute to this tolerance. Changes in physiology which occur as a result of heat acclimation have been described above. As mentioned previously, this process attenuates heat stress related illnesses but does not eliminate the issue or susceptibility.

The precise physiological modifications which occur from acclimatization are not well understood; however, several hypotheses have been proposed. It is thought that a modification in the cellular functioning is what ultimately defines the capacity of one individual to do work over another. Recently, interest has grown into measuring cellular protein concentration levels as a defence to acute episodes to heat shock. It is this protein, called heat shock protein (HSP), which stabilises other cellular proteins. Further reading can be found at [77-82]. With the HSP safeguarding other protein structures within the cell, destruction as a result of heat exposure is attenuated. There is an abundant quantity of literature on plant and animal testing, however, limited research has been done in humans. Therefore, investigation in the cellular modifications which occur as a result of heat insult is an area of research which is growing and could possibly explain the physiological changes responsible for acclimation.

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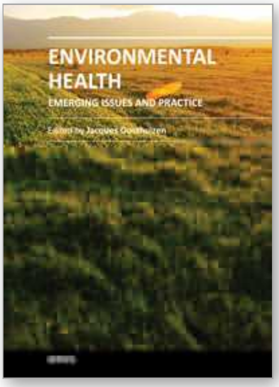

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Environmental health practitioners worldwide are frequently presented with issues that require further investigating and acting upon so that exposed populations can be protected from ill-health consequences. These environmental factors can be broadly classified according to their relation to air, water or food contamination. However, there are also work-related, occupational health exposures that need to be considered as a subset of this dynamic academic field. This book presents a review of the current practice and emerging research in the three broadly defined domains, but also provides reference for new emerging technologies, health effects associated with particular exposures and environmental justice issues. The contributing authors themselves display a range of backgrounds and they present a developing as well as a developed world perspective. This book will assist environmental health professionals to develop best practice protocols for monitoring a range of environmental exposure scenarios.

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