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Review Article

Health Impacts of Workplace Heat Exposure: An Epidemiological Review

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Abstract: With predicted increasing frequency and intensity of extremely hot weather due to changing climate, workplace heat exposure is presenting an increasing challenge to occupational health and safety. This article aims to review the characteristics of workplace heat exposure in selected relatively high risk occupations, to summarize findings from published studies, and ultimately to provide suggestions for workplace heat exposure reduction, adaptations, and further research directions. All published epidemiological studies in the field of health impacts of workplace heat exposure for the period of January 1997 to April 2012 were reviewed. Finally, 55 original articles were identified. Manual workers who are exposed to extreme heat or work in hot environments may be at risk of heat stress, especially those in low-middle income countries in tropical regions. At risk workers include farmers, construction workers, fire-fighters, miners, soldiers, and manufacturing workers working around process-generated heat. The potential impacts of workplace heat exposure are to some extent underestimated due to the underreporting of heat illnesses. More studies are needed to quantify the extent to which high-risk manual workers are physiologically and psychologically affected by or behaviourally adapt to workplace heat exposure exacerbated by climate change.

Key words: Climate change, Heat stress, Workplace heat exposure, Health and safety, Work-related injury

Introduction

Many ecological studies have revealed that extremely hot weather contributes to excess morbidity and mortality in the community[1)]. Most of the extreme heat-related research has traditionally focused on vulnerable populations including the elderly, children and patients with chronic diseases and those on certain medications[2)]. Extremely hot weather also places many types of indoor and outdoor manual workers at increasing risk of heat-related illnesses and injuries[3, 4)]. Increased concerns about the environmental heat-related impacts of climate change on population health have been raised since the late 1990s.

Heat gain can be a combination of external heat from the environment and internal body heat generated from metabolic processes. There are two types of external heat exposure sources in the workplace: weather-related and man-made heat exposure. With predicted increasing frequency and intensity of heatwaves, weather-related heat exposure is presenting a growing challenge to occupational health and safety. This article is intended to comprehensively review the characteristics of workplace heat exposure in selected relatively high risk occupations, to summarize findings of published studies, and ultimately to provide suggestions for heat exposure reduction, adaptations, and further research directions.

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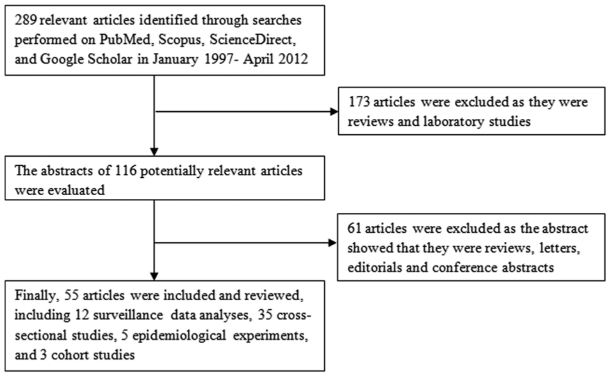

Fig. 1. Process of selection of articles for inclusion in the review.

Methods

All published epidemiological studies in the field of health impacts of workplace heat exposure for the period of January 1997 to April 2012 were reviewed, utilizing the searching strategy of random combination of the first keywords [tiab] AND the second keywords [tiab]. The field code 'tiab' is the abbreviation of 'title or abstract'. All academic articles containing search keywords in the title or abstract were retrieved. The first keywords included climate change, heat stress, heatwave, heat exposure, extreme heat. The second keywords included workplace, workers and occupational health and safety. Literature databases used for this review ranged from PubMed (biomedical sciences), Scopus, ScienceDirect and Google Scholar. Only original research articles published in English in peer-reviewed journals were included, whereas review articles, editorials, letters, conference abstracts, and government reports were excluded.

Results

Figure 1 shows the process of selection of articles for inclusion in the review. Out of 289 identified articles, 55 were finally included in the review, with 12 articles (22%) being surveillance data analyses (ecological studies), 35 articles (64%) being cross-sectional studies, 5 articles (9%) being epidemiological experiments, and 3 articles (5%) being cohort studies, as presented in Table 1 and 2 respectively.

Overview of published studies in 1997–2012

As shown in Table 1, all 12 surveillance data analysis articles were studies from high income countries with about half from the US, 3 from Australia, and 1 each from Germany and Italy. In terms of data sources, about 50% of studies were based on government surveillance data, and the remaining 50% were based on hospital or workplace daily records. Only 3 studies explored the relationship between temperatures and work-related illnesses and/or injuries, using Poisson regression analysis; however, others simply described the distribution of heat-related illnesses over time periods.

As shown in Table 2, of the 43 studies, there are 19 (44%) articles for outdoor workplaces, 20 (47%) for indoor workplaces, and 4 (9%) for mixed workplaces. Approximately 54% (23) studies involved process generated heat. In terms of region, most studies were carried out in the tropical zones, with 17 (40%) studies from South and Southeast Asia, 10 (23%) from America, 7 (16%) from the Middle East, 6 (14%) from Australia, and 3 (7%) from Europe. A range of heat indices were used with 25 (60%) studies using Wet Bulb Globe Temperature (WBGT), 7 (16%) using subjective heat stress and 6 (14%) using air temperature. Thirty four (79%) of studies indicated that participants were suffering from heat strain, with outdoor workplaces (90%) being much higher than indoor workplaces (65%). Workers' self-pacing (self-adjustment of work rate) has been reported in construction and mining industries in Australia, Germany, and the United Arab Emirates. In terms of gender, twenty one (49%) of studies focused on male worker only. In contrast, one study from India targeted only female workers. In addition, only 3 studies utilized qualitative research methods.

Overall, in terms of occupation classification, 20% of the 55 identified articles focused on manufacturing workers in steel and foundry industries, followed by miners (18%), mixed manual workers (16%), construction workers (13%), farmers (13%), and armed forces personnel (5%).

Impacts of Workplace Heat Exposure on Selected Susceptible Occupations

Without adequate heat dissipation, short-term acute extreme heat exposure can cause a rise in core body temperature and may result in direct heat illnesses. Adverse long-term health effects of chronic workplace heat exposure have also been reported such as cardiovascular diseases[42)], mental health problems[17, 36)], and chronic kidney diseases[18)]. In addition to work-related illnesses, workplace heat exposure can also increase the risk of occupational injuries and accidents. Core temperature elevation and dehydration have had negative behavioural effects such as physical

Table 1. Summary of findings from surveillance data analysis articles on workplace heat exposure published between in January 1997–April 2012

Data sources	Country	Data period	Target workers	Heat indices	Statistical analysis	Relationship between temp and occupational injuries/illnesses
The Australian Institute of Health and Welfare[5)]	Australia	2003–2004	Athletes	Not used	Descriptive analysis	Not analysed
Hospital discharge data, New South Wales, Australia[6)]	Australia	2001–2004	Athletes	Not used	Descriptive analysis	Not analysed
The medical centre of deep underground metal mine in Australia[7)]	Australia	1997–1998	Miners	Dry bulb temp and WBGT[1]	Descriptive analysis, U test	Not analysed
Hard coal mines in the Ruhr district, Germany[8)]	Germany	1995–1999	Miners	Basic effective temp	Multivariate linear regression	U-shaped curve
Admission records of 5 hospitals, Central Italy[9)]	Italy	1998–2003	All workers	Apparent temp	Poisson regression	Reversed U-shaped curve
The Washington State Department of Labour and Industries' State Fund, US[10)]	US	1995–2005	All workers	Not used	Descriptive analysis	Not analysed
The Agricultural Safety and Health Bureau of the North Carolina Department of Labour, US[11)]	US	1992–2006	Farmers	Not used	Descriptive analysis	Not analysed
The US Bureau of Labour Statistics (BLS) Census of Fatal Occupational Injuries (CFOI)[12)]	US	2003–2008	Farmers	Not used	Descriptive analysis	Not analysed
An aluminium smelting plant, US[13)]	US	1997–1999	Foundry workers	Dry bulb temp	Poisson regression	U-shaped curve
The US National Institute for Occupational Safety and Health Website[14)]	US	1983–2001	Miners	Not used	Descriptive analysis, U-test, z-test	Not analysed
Total Army Injury and Health Outcomes Database, the US Army Research Institute[15)]	US	1980–2002	Soldiers	Not used	Poisson regression	Not analysed
The Centre for Accession Research, US Army Accession Command[16)]	US	2005–2006	Soldiers	Not used	Multiple logistic regression	Not analysed

[1]WBGT denotes wet bulb globe temperature

fatigue, irritability, lethargy, impaired judgment, vigilance decrement, loss of dexterity, coordination and concentration[3)], potentially leading to a compromise of occupational safety.

The characteristics of workplace heat exposure may vary in different occupations. It was summarized as below. The impacts of heat exposure can be particularly harsh on outdoor workers such as those in the agriculture, construction, mining and manufacturing industries as well as the armed forced personnel and fire-fighters as discussed below.

Agricultural workers

Agriculture is one of the industries at highest risk of heat-related illness and injury. Farmers are often exposed to outdoor heat extremes for long periods of time, and often there is a lack of occupational health and safety programs. In the US, agricultural industries have the third highest rate of heat-related deaths among all industries, with a mortality rate approximately 20 times greater than for all civilian workers[12)]. In terms of heat-related morbidity, farm workers have been shown to be four times more likely than non-agricultural workers to suffer from heat-related illnesses in the US[60)].

Currently, published literature assessing farmers' heat stress status is limited. Mirabelli[61)] identified that 161 heat-related fatalities occurred from 1977 to 2001 in North Carolina US by reviewing medical records, and found that 45% occurred among farmers. In another study by the same author, it was found that approximately 94% of farmers reported working in extreme heat, among which 40% experienced heat stress related symptoms[30)]. At the

Table 2. Summary of epidemiological studies of workplace heat exposure published between January 1997–April 2012

Target workers	Country	Sample size	Gender	Study design	Indoors or outdoors	Heat stress indices
All workers[17]	Thailand	40,913	Both	Cohort	Both	Subjective symptoms
All workers[18]	Thailand	37,816	Both	Cohort	Both	Subjective symptoms
Airport ground servicers[19]	Saudi Arabia	-	-	Cross-sectional	Outdoor	WBGT
Construction workers[20]	Japan	319	Male	Cross-sectional	Outdoor	WBGT
Construction workers[21]	UAE[1]	150	Male	Cross-sectional	Outdoor	TWL[2]
Construction workers[22]	India	11	Female	Cross-sectional	Outdoor	WBGT
Construction workers[23]	Thailand	108	Both	Cross-sectional	Outdoor	WBGT
Construction workers[24]	UAE[1]	22	Male	Cross-sectional	Outdoor	TWL[2], dry bulb temp
Construction workers[25]	Japan	12	Male	Cross-sectional	Outdoor	WBGT
Construction workers[26]	UAE[1]	44	Male	Cross-sectional	Outdoor	-
Cooks[27]	Japan	12	Male	Cross-sectional	Indoor	WBGT
Cooks[28]	Japan	809	Both	Cross-sectional	Indoor	WBGT
Cooks[29]	Japan	16	Male	Cross-sectional	Indoor	WBGT
Farmers[30]	US	300	Both	Cross-sectional	Outdoor	Subjective symptoms
Farmers[31]	Costa Rica	42	Male	Cross-sectional	Outdoor	Dry bulb temp
Farmers[32]	India	26	Male	Cross-sectional	Outdoor	WBGT
Farmers[33]	Costa Rica	17	Not indicated	Cross-sectional	Outdoor	Subjective symptoms
Fire fighters[34]	Canada	37	Both	Experimental	Outdoor	Dry bulb temp
Fire fighters[35]	Canada	40	Both	Experimental	Outdoor	Dry bulb temp
Fire fighters[36]	US	16	Male	Experimental	Outdoor	Dry bulb temp
Forestry workers[37]	Japan	125	Both	Cross-sectional	Outdoor	Subjective symptoms
Manufacturing workers[38]	UAE[1]	275	Not indicated	Cross-sectional	Indoor	WBGT
Foundry workers[39]	US	31	Not indicated	Cross-sectional	Indoor	WBGT
Manufacturing workers[40]	India	-	-	Cross-sectional	Indoor	WBGT
Manufacturing workers[41]	India	-	-	Cross-sectional	Indoor	WBGT
Manufacturing workers[42]	Bulgaria	102	Male	Cohort	Indoor	WBGT
Manufacturing workers[43]	India	-	-	Cross-sectional	Indoor	WBGT
Manufacturing workers[44]	India	242	Not indicated	Cross-sectional	Indoor	Subjective symptoms
Mine rescue workers[45]	US	-	-	Cross-sectional	Indoor	WBGT
Mine rescue workers[46]	Germany	52	Male	Cross-sectional	Indoor	Basic effective temp
Miners[47]	Germany	38	Male	Cross-sectional	Indoor	Basic effective temp
Miners[48]	Australia	362	Not indicated	Cross-sectional	Indoor	WBGT, TWL[2]
Miners[49]	Australia	39	Male	Cross-sectional	Indoor	WBGT, TWL[2]
Miners[50]	Australia	36	Male	Cross-sectional	Indoor	WBGT, TWL[2]
Miners[51]	Australia	45	Male	Cross-sectional	Indoor	WBGT, TWL[2]
Mixed manual workers[52]	South Africa	151	Both	Cross-sectional	Outdoor	Subjective symptoms
Mixed manual workers[53]	Thailand	21	Both	Cross-sectional	Both	WBGT
Mixed manual workers[54]	UAE[1]	186	Male	Cross-sectional	Both	Urine gravity
Mixed manual workers[55]	Australia	29	Male	Cross-sectional	Outdoor	Dry bulb temp
Soldiers[56]	Australia	64	Male	Experimental	Outdoor	WBGT
Steel workers[57]	Israel	3,507	Both	Cross-sectional	Indoor	Dry bulb temp
Steel workers[58]	Taiwan, ROC	55	Male	Cross-sectional	Indoor	WBGT
Steel workers[59]	Brazil	8	Male	Experimental	Indoor	WBGT

[1]UAE: United Arab Emirates, [2]TWL: thermal work limit

time no regulations and prevention measures were available for preventing heat exposure. A study of 124 Japanese forestry workers showed that 32.3% had reported symptoms of heat illness[37]. With low levels of mechanized farming and motivation by payment based on work output, agricultural workers in low-middle income countries may be at relatively higher risk of heat exposure[31, 52].

Construction workers

In the building industry, several contributing factors increase the risk of heat-related illness and injury. These include the constant use of machinery and powered tools, working on elevated surfaces, heavy workload, simple accommodation conditions near work sites, being temporarily employed by a sub-contractor on a daily payment basis, and constant and direct exposure to sunlight. From 2003 to 2008, the US Census of Fatal Occupational Injuries recorded 196 heat-related mortalities, and construction workers occupied the greatest proportion (36%)[12]. A self-administered questionnaire among 115 Japanese male construction workers in summer demonstrated that in terms of heat-related subjective symptoms, up to 63.7% of workers reported 'feeling thirst' at work, followed by 42.2% reporting it was 'easy to get fatigued', 41.2% reported 'waking up early due to hot conditions', 31.9% reported 'impatience', 13.2% 'headache', and 11.8% 'dizziness'[20]. Those symptoms are consistent with the hypothesis that heat exposure may increase the risk of occupational accidents and injuries. In Taiwan[62] and Thailand[23], temporarily self-employed construction workers reported suffering from severe heat strain because of physically demanding work and hot accommodation conditions in dormitories near construction sites.

However, if preventive measures are sufficient in building sites, workers could avoid heat-related symptoms. A cross-sectional study has been conducted among 12 male workers in a Japanese hydroelectric power plant building site with WBGT often exceeding the recommended exposure limit values most of the time on a typical hot day in summer[25]. However, there was no significant change in subjective symptoms, serum electrolytes, blood pressures and heart rates before and after work, because preventive measures had been taken. These included temporary tents for rest, electric fans for ventilation, and automatic machines for cool drinks. But there should be caution in the interpretation of the results because of the small sample size and the fine weather conditions during the two days investigation period. Apart from common preventive measures, self-pacing can also be an effective way of reducing the risk of heat-related illness and injury as reported in a study of construction workers in the United Arab Emirates[24].

Miners

Hot working conditions in mines are very common and vary according to the type of mining. For opencut mines, heat exposure is similar to other outdoor workplaces. However, by far most problems of heat stress have been reported from underground mines as additional heat from virgin rock and mines increase with depth. Furthermore, air auto-compression for ventilation adds about 6°C dry bulb temperature per 1,000 m of vertical depth[49]. High humidity from water required for dust control also contributes markedly to the thermal load. The incidence of heat illness in underground mines has been reported to be higher for metal mining than for coal mining as underground metal mines are usually much deeper than coal mines in the US[14]. The incidence rate ratio of heat exhaustion for deep mines below 1,200 m compared with above 1,200 m was 3.17 in Australia[7].

According to the 1983–2001 data from the US National Institute for Occupational Safety and Health, most heat illness cases in mines occurred during dayshift hours rather than night shift hours[14]. This is to be expected for surface mining given the higher air temperatures during the day. But for underground mining, there is lack of convincing reasons for more heat illnesses during dayshift hours even after considering the greater proportion of dayshift workers than nightshift workers, because there is not significant change in temperatures in underground mines between day and night due to thermal damping effects. Brake and Bates[50] suggested that the normal diurnal variation of body internal temperature, which is relatively lower at night, may contribute to the lower risk of heat illness on night shift. The effects of seasonal change on underground temperatures decrease with the increase of mining depth. Hence, heat illnesses may occur throughout the year and with less incidence rate in non-warm seasons. Even so, most heat illnesses have been reported in summer seasons[7, 14]. Therefore, surface temperature forecasts can also be useful for warning miners and management about the risk of heat illnesses.

In some low-middle income countries miners with heat illness symptoms may still keep working in extremely hot environments due to relatively low perceptions of prevention strategies, lack of protective measures, and income incentives, which may result in the occurrence of life-threatening heat strokes. In South African deep underground gold mines, heat stroke has been an endemic hazard since before the 1970s. In recent years due to acclimatization and prevention measures, the incidence rate of heat stroke has been declining significantly[63]. The occurrence of heat stroke is reportedly relatively rare currently but still remains unresolved.

In high income countries heat stroke cases are seldom reported in mining industries. In an Australian deep underground mine with about 2,000 miners, no heat stroke cases had been reported to the 24-h on-site medical clinic during over 10 million work shifts in the period 1966–1997[50]. Similarly, there were no cases of heat strokes reported in 1983–2001 in the US mining industry[14]. Several reasons may contribute to the few occurrences of heat stroke cases in high income countries. Firstly, this may be attributed to a flexible management approach and the resistance of miners to continue strenuous labour in severe thermal conditions. Secondly, most miners are assumably well-trained about the effects of working in heat. Thirdly, in high income countries miners suffering heat-related illnesses generally report their conditions actively and cease mining[7]. Finally, it may result from self-pacing[47]. Miller *et al.* even suggest that self-pacing should be encouraged as a protective behaviour without productivity compromise in the mining industry[21], as nowadays many tasks in mining are highly mechanized and a reduction of work load may not necessarily result in productivity loss.

Armed forces personnel

Most epidemiological studies on military populations have focused on specific military bases for relatively short periods and with relatively small populations[16]. At present, heat-related morbidity and mortality analyses of military personnel data are based on consulting military hospital records[15, 64, 65]. Over time there has been a downward trend of heat illness hospitalization rates due to preventive measures in the US Army[15]. The total number of hospitalizations for heat illness reduced by 60% in the 22 yr period of 1980–2002[15]. However, heat stroke rates have markedly increased eightfold[15]. The possibility is that preventive measures might allow compromised soldiers to avoid minor heat illnesses and continue to exercise until more severe heat stroke occurs.

Regarding the proportion of heat illness spectrums, almost 60–70% of heat illness cases were due to heat exhaustion and 13–18% for heat stroke[15, 66]. The percentage of mild heat illnesses is small as individuals may recover rapidly in the field without being hospitalized. Infantry soldiers had the greatest risk of heat illness in the US in the period 1980–2002[15], whereas soldiers in administrative and support jobs had the lowest risk. In addition, ethnicity, gender, fitness level, and geographical origin are related to heat illness occurrence in military populations. Caucasians are more vulnerable to heat illness than African Americans and Hispanic Americans[15]. Soldiers from northern US are more susceptible to heat illness that those from southern US, and female soldiers are at greater risk of heat illness than male soldiers[15].

Fire-fighters

Fire-fighters are required to wear fire-fighting protective clothing and self-contained breathing apparatus regardless of environmental temperatures. This personal protective equipment can reduce the effect of heat dissipation and increase the risk of heat stress. Recently, based on simulated trials among 70 volunteers recruited from the Toronto Fire Service, the replacement of the duty uniform long pants and shirt with shorts and T-shirt has been recommended by McLellan and Selkirk[34, 35], as it could significantly reduce heat strain and extend at least 10–15% heat exposure time. But it raises concerns about whether the replacement of long pants with shorts may put fire-fighters at greater risk of injury. Evidence from the New York City Fire Department proved that not only were the burn incidence and severity not affected, but also the days lost due to heat illnesses were significantly reduced[67].

In a simulated fire-fighting drill among 16 male fire-fighters from a Fire Service Institute in the US, higher blood lactate levels, longer recovery time, and significantly increased heart rate and core temperature were observed after performing tasks in a live fire environment than after performing the same tasks in a non-fire environment[36]. In the same study it was shown that psychological impacts of emergency conditions are also a problem for fire-fighters. A dramatic increase of anxiety level immediately following firefighting activities was found[36]. Elevated anxiety status may impact on cognitive performance, resulting in inappropriate decisions that might increase of risk of injury. Interestingly, the relationship between perceptions of heat illness and heat strain varies by thermal conditions. In non-hot conditions, the correlation coefficient was moderately positive (r=0.57–0.48), however, there was little relationship (r=0.01–0.18) in hot conditions. If perceived risk of heat illness is underestimated, fire-fighters may put themselves at greater risk. But there is a probability that it may result from information bias that participants were unwilling to report their real feelings because of peer pressure[36].

Manufacturing workers

Manufacturing workers in non-air conditioned indoor workplaces are also at risk of heat-related illness despite little or no direct sunlight radiation. The levels of heat stress can be very high in workplaces surrounding hot machines, furnaces, ovens, and molten metal. Even in winter, the temperatures near furnaces in a steel plant have ranged from 35.5 to 46.5°C when the outdoor temperature was only 14–18°C[58]. Increased hot days due to climate change may worsen the extent of heat stress for individuals working around heat generating sources. Hence, many epidemiological studies have focused on the impacts of workplace-generated heat on factory workers in steel plants[13, 59], foundries[42], automobile industries[43, 44], and glass manufacturing units[41].

Excessive industrial heat exposure is associated with dyslipidemia[42], cardiovascular and digestive diseases[68]. However, a cohort study in a French stainless steel producing plant showed that cardiovascular disease mortality was 10% lower for the workers exposed to heat than for a control group that was not exposed[69]. The negative relationship between heat exposure and mortality may result from the 'healthy worker effect' due to the stringent selection criteria when recruiting workers.

Discussion

If the predictions about likely future temperature increases prove reliable, weather-related extreme heat exposure is placing many types of indoor and outdoor workers at increasing high risk of heat-related illnesses and injuries. For acclimatised manual workers, a few degrees of climate change can make dangerous days increase to 15–26 d per year in 2070 compared to 1 day per year at present in Australia[70]. Outdoor workers, in particular those undertaking highly intensive and physical activity under the sun are susceptible to heat stress during heatwaves when preventive measures are not adequately adopted[20, 22, 25, 26, 30–33, 37]. Physical and strenuous activity generating internal body heat load with increasing metabolic rate, together with significant radiant heat load from direct sunlight may further worsen heat stress. Indoor workers, especially those working around furnaces, ovens, smelters and boilers, are at a higher heat stress risk on hot days[34–36, 57, 58]. Despite indoor workers not being exposed to direct solar radiation, they can be exposed to heat and humidity generated from work processes or equipment. Their working environment can also become very hot when a cooling system is not available or ventilation is insufficient during hot days[58].

This review of the health impacts of workplace heat exposure has examined 55 epidemiological studies published between January 1997 and April 2012. Due to the availability of occupational health and safety data, all surveillance data based articles have been from high income countries. Although the underreporting of work-related injuries may challenge the data quality and affect the reliability of results, it still provides a good overview of the characteristics of occupational health and safety in the workplace. About three quarters of the articles simply described the distribution of heat-related illness or injuries by industrial sectors, occupations, seasons, and months, etc. Undoubtedly, most of heat-related illnesses and injuries occurred in summer months and hottest parts of a day according to previous findings[10]. There is lack of further data analyses exploring the association between temperatures and heat/work-related injuries.

Theoretically, the number of work-related injuries is positively related to the increase of temperature. It has been characterized as U, V, and J-shaped curve relationship. Practically, however, preventive measures may be adopted in the workplace or workers may stop work or self-pace if the workplace temperature is extremely high. It can result in the unexpected decline in the number of work-related injuries, which is described as reversed U-shaped curve[9]. But if denominator information is available for calculating work-related injury rates, the relationship still appears to be U-shaped curve[47]. The relationship patterns between temperatures and work-related injuries may vary by industries, gender, and age group. For example, young workers aged less than 30-yr-old showed consistently higher injury rates than other age groups in all thermal categories[47], which may be related to the practice of assigning young workers with more physically demanding work.

More epidemiological analyses based on occupational injury surveillance data are needed to quantify the extent to which high-risk manual workers are affected by workplace heat exposure, and to identify risk factors for workplace heat prevention and adaptation, especially for low-middle income countries in tropical regions[3]. This is achievable if there is a routine occupational injury surveillance system and it may also provide epidemiology-based evidence for the decision of heat alert temperatures in the workplace. There are several points worth noting when analysing the temperature-occupational injury relationship, including the selection of appropriate regression models, the adjustment of confounding factors, and the handling of non-linear relationship. Among these reviewed articles, only three papers used Poisson regression suitable for count data[9, 13, 15]. However, none reported checking whether the distribution of work-related injuries was over-dispersed or not, in which case negative binominal regression is more appropriate. It also applies for the selection of family functions when using GEE (generalized estimating equation model). In terms of confounding factors, amongst the reviewed articles only Morabito[9] took public holiday, weekend, and time-lag effects into account, whereas the long-term variation trend and day of week were not adjusted. As to the problem of non-linearity, piecewise linear regression or linear spline function has been adopted by dividing temperature ranges into several pieces[9, 13].

Usually, the number of reported heat illness is very small. In Australia, statistics show there were 485 compensation claims due to exposure to environmental heat in the 11 yr period of 1997–2007[71]. Similarly, 480 heat-related compensation claims were identified during the 11 year period of 1995–2005 in Washington State, US[10]. If just based on the reported statistical figures, it is not surprising that heat stress is not listed as occupational health priority. But it should be noted that heat-related illnesses may be underreported largely due to following reasons. Firstly, many high income countries utilize workers' compensation claims to measure occupational health and safety performance. However, the compensation based data does not provide any information for groups not covered by workers' compensation schemes, such as some self-employed workers. Secondly, some workers with minor injuries may not apply for compensation claims. Most heat illnesses are mild and individuals recover rapidly through simple treatment or rest on site without hospitalization. Thirdly, because heat exposure can exacerbate existing medical conditions, illness or death due to heat exposure may be preceded by other diseases and reported as other diseases other than heat illness. Additionally, the criteria used to determine heat illness and death vary largely, resulting in misclassification. Overall, it should be realized that a huge potential risk of heat-related injury and accident may be disguised by the underestimated number of heat-related illness and death.

In contrast to surveillance data analyses, most cross-sectional field surveys aiming to investigate heat stress status and workers' physiological responses to heat are from low-middle income countries in tropical regions[22, 31, 33, 41, 43, 44, 52, 53]. It is consistent with the regional maps proposed by Hyatt[72], predicting regions at high risk of occupational heat exposure. With global climate change trends, extreme workplace heat exposure situations may extend to large areas of the world apart from Australia, South Asia, Southern Africa, Central America, and southern US. A majority of the studies show that workplace heat stress exceeds the heat stress criteria of the American Conference of Governmental Industrial Hygienists and is presenting a threat to manual workers' health and safety. Usually, physiological responses and subjective symptoms of industrial workers exposed to heat include elevated blood pressure and urine gravity, increased recovery heart rates and body temperature, and increased fatigue symptoms[25, 34, 36, 47, 48, 51, 54, 58]. However, if effective prevention measures are taken in the workplace, risk of heat-related illness and injury can be significantly reduced[20, 24, 57, 59].

Workers' self-pacing has been found to reduce heat strain in construction and mining industries in Australia[50, 51], Germany[47], and the United Arab Emirates[21]. Currently, there is no consensus about whether self-pacing should be encouraged in the workplace. Positive self-adjustment of work pace to a safe level could be considered as a flexible management approach to maintain productivity without compromising workers' safety in hot environments[21]. This can be subject to the conditions that the task has no urgent character and does not involve work output based payment incentives, that workers should be well trained in their job, and that self-pacing may be associated with close supervisory surveillance[73]. On the contrary, if self-pacing is workers' passive physiological or/and psychological reactions to thermally stressful conditions by slowing work pace, it may be inefficient either in terms of productivity or in terms of heat strain reduction. Evidence from field studies in Australia has suggested that few workers will voluntarily work at a pace that requires an average heart rate over 110 bpm for any length of time[50], a level consistent with WHO recommendation[74]. Therefore, working in hot environment is not only a matter of occupational health and safety, but also an area involving all levels of society economically: individual, family, community, regional, and national levels[75]. In addition, there are few studies to investigate how decision makers, hygienists, employers, supervisors, workers and relevant stakeholders perceive the role of self-pacing for reducing the risk of heat-related illnesses and injuries in the workplace. This can be important for the formulation of self-pacing related guidelines and regulations and more studies in this area should be encouraged.

Regarding gender differences on workplace extreme heat exposure, more evidence is required. Women have a lower sweat rate than men, which is disadvantageous in hot-dry environments, but advantageous in hot-wet environments[76]. It was reported that there was higher risk of heat-related injury occurred in women performing National Guard duties during a Midwest flood rescue operation in the US in 1993[77]. One qualitative study from South Africa showed that women felt they could not cope with hot weather as well as men did, especially when they had to undertake labour intensive work[52]. However, if cardiovascular fitness level, aerobic capacity, surface area-to-mass ratio, and the extent of acclimation are standardized, the distinctions tend to disappear[78].

Conclusions

With predicted increasing frequency and intensity of extremely hot weather due to climate change, workplace heat exposure is presenting an increasing challenge to workers injuries and heat-related illnesses. Manual workers who are exposed to extreme heat or work in hot environments may be at risk of heat stress, especially for workers in low-middle income countries in tropical regions. Those workers include farmers, construction workers, fire-fighters, miners, soldiers, and manufacturing workers working around process-generated heat. If effective prevention measures are taken in the workplace, workers may not be physically challenged by heat stress. The potential impacts of workplace heat exposure are to some extent underestimated due to the underreporting of heat illnesses and the lack of awareness that heat exposure can increase the risk of work-related injuries.

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