



BEYOND SPORT: SPORTS SCIENCE APPLICATIONS FOR LABORER ACUTE AND LONG-TERM HEALTH ISSUES AND CONSIDERATIONS IN A WARMER WORLD - PART 1

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KEY POINTS

- There is a lack of extensive research on the impact of heat exposure and effectiveness of heat stress prevention strategies in working populations. Findings from sports research cannot be directly applied to the occupational setting.
- Occupational heat exposure can lead to both acute and chronic health and safety consequences, including excessive fatigue, heat syncope, heat exhaustion, exertional heat stroke, increased accidents, kidney injury, cardiac mortality and the potential for a myriad of other health outcomes.
- There is an emerging understanding of an epidemic of chronic kidney disease of nontraditional etiology and occupational origin (CKDnT), which occurs in the absence of traditional risk factors. The prevalence is particularly high among young male workers in low-income countries.
- Early detection and intervention of heat-related health conditions is critical to improve health outcomes for workers exposed to heat stress.
- Work-related productivity losses due to heat exposure represent a significant economic burden, driven by reductions in physical work capacity, increased lost work time, lost wages and higher treatment and rehabilitation costs.

INTRODUCTION

Workers are frequently termed "industrial athletes" because of the physically strenuous tasks they undertake daily (Astrand et al., 1975; Binazzi et al., 2019; Flouris et al., 2018). In contrast to most athletes (Figure 1), workers face a combination of environmental heat exposure and high physical workloads with insulating personal protective equipment (PPE) over consecutive days without the adequate rest, recovery and resources that most athletes have available (Astrand et al., 1975). This combination significantly intensifies heat strain on the body, (Flouris et al. 2018; Ioannou et al., 2021a,b) placing workers at greater risk of succumbing to heat-related injuries, illnesses and fatalities. Every year, 2.41 billion workers are exposed to excessive heat, resulting in 22.85 million occupational injuries and 18,970 deaths worldwide (International Labour Organization (ILO), 2024). Alarming, 90% of worker exposure to excessive heat occurs outside of a heatwave (ILO, 2024). Occupational heat strain jeopardizes worker health and safety, resulting in adverse impacts on productivity. Heat-related productivity losses impose a significant strain on the economy, impairing both worker and organizational performance and success. By 2030, global economic losses from occupational heat stress are projected to reach \$2.4–2.5 trillion USD (Borg et al., 2021). As climate change progresses, the frequency, intensity and severity of heat events are expected to worsen (Gao et al., 2018), further amplifying the adverse impacts on health, safety and productivity (Morrissey et al., 2021b).

Although occupational heat exposure significantly affects workers, there is a lack of extensive research on the health and physiological impacts of working in heat, as well as effective heat mitigation

strategies to reduce heat strain. Furthermore, the diversity between occupations and within worksites presents additional challenges to applying general recommendations. In the United States, much of the existing heat physiology research has been concentrated on sports and military populations (8 and 1.3 million, respectively), while ~11 million documented workers are routinely exposed to hot work environments, which is likely an underestimate (Governing, 2013; ILO, 2024). While research in sports and military settings has made notable advancements in understanding and managing heat strain, these findings cannot be directly transferred to the occupational setting. For example, workers have a high prevalence of poor health conditions such as hypertension, cardiovascular disease, diabetes and obesity, which negatively impact physiological and thermoregulatory function under heat stress (Ali & Mohammadnezhad, 2019; Bamidele et al., 2024; Hertz et al., 2004; Kenny et al., 2013; Morrissey et al., 2021c; Notley et al., 2021). In some work settings, workers cannot miss work or change their schedule of work due to high heat conditions because of financial concerns. Also, in remote settings, there is limited access to medical care if a heat emergency were to occur. Therefore, it is critically important to expand our understanding on how occupational heat exposure acutely and chronically impacts worker health, safety and productivity.

This Sport Science Exchange (SSE) article will outline our current understanding of the acute and long-term issues associated with working in the heat. This article will serve as a "Part 1" of a two-part article series and "Part 2" will explore heat stress mitigation strategies to reduce occupational heat strain.

WORKER		vs.	ATHLETE	
Structural Factors				
Environmental Heat Exposure	✓		✓	
High Physical Work Loads	✓		✓	
Work Loads Sustained Over Consecutive Hours and Days	✓	Higher prevalence of prolonged heat exposure compared to training or a competition.	✗	
Appropriate Rest & Recovery	✓ / ✗	Due to the nature of certain jobs, rest breaks are not always feasible.	✓	
Insulating Textiles	✓	Personal Protective Gear (PPE) is often heavier and may be composed of flame retardant materials to withstand high temperatures. Removal of PPE must comply with safety regulation to avoid exposure to other hazards.	✓ / ✗	Personal Protective Gear (PPE) is often not as cumbersome and may be removed more frequently.
Flexibility in Schedule	✗	Work shifts are unlikely to be cancelled due to environmental conditions (e.g., at job sites operating 24-hours a day). Company productivity targets typically take precedence. Workers cannot miss work or change their work schedule in some settings.	✓ / ✗	Practice can generally be adjusted.
Phase-In Period	✓ / ✗	Gradual entry to an extreme environment or novel job is not always possible, particularly during excessive heat periods. Some companies utilize heat acclimatization, while many do not.	✓	Various state policies require gradual integration to a season, allowing for heat acclimatization to occur.
Accessibility of Medical Care	✓ / ✗	Medical treatment and care are not always available in remote settings, and organizational resources may be scarce. Remote worksites also present challenges with supplying fluid and cooling resources.	✓	
Prevalence of Additional Hazards	✓	Various occupational hazards (e.g., chemical, physical) are often present.	✗	
Individual Factors				
Health and Fitness Status	⚠	May or may not be healthy with co-morbidities (e.g., hypertension, obesity, diabetes) with varying levels of fitness status and age.	👍	Generally healthy with above-average fitness. Generally younger.
Quality of Diet	⚠	Generally below-average diet consistent with the standard American diet (e.g., high sodium, high sugar, excessive caffeine intake) commonly accompanied with dehydrated. Minimal support from key stakeholders, particularly during work in remote settings.	👍	Generally above-average with guidance and support from key stakeholders (e.g., RD, MD, coach).
Medication Use	⚠	Likely multiple to treat co-morbidities (e.g., hypertension, obesity, diabetes).	👍	Likely minimal use. Unlikely to impact athletic performance.
Situational Factors				
Pay Structure	⚠	Workers may be less likely to speak up about unsafe working conditions and medical concerns due to payment incentives and company targets.	N/A	Various
Classification	⚠	Unionization and immigration status create unique challenges for many workers, in addition to organizational structure (e.g., stakeholders).	N/A	Various

Figure 1: Differences in heat-related structural, individual and situational factors between workers and athletes.

ACUTE AND LONG-TERM HEALTH AND SAFETY EFFECTS

Workers often engage in physically demanding work in hot environments and are often required to wear PPE to avoid other workplace hazards (Bernard & Ashley 2009; Gao et al., 2018). This can result in many adverse health and safety outcomes (Crowe et al., 2023). When humans undergo physical work in the heat, the body maintains its temperature through thermoregulatory mechanisms, which includes skin vasodilation and eccrine sweating (Périard et al., 2021). It is the body's natural response to experience a rise in core temperature while engaging in physical work, however, when the metabolic heat generated by the body outweighs its ability to dissipate heat, this can result in continuous and a potentially dangerous rise in core temperature (Foster et al., 2020). High core temperatures have serious implications for the health and safety of workers exposed to heat, which range from discomfort, heat syncope, heat exhaustion, to life-threatening medical conditions such as exertional heat stroke (EHS) (Figure 2) (Casa et al., 2015). EHS is considered a medical emergency and is characterized as a core temperature over $>40^{\circ}\text{C}$ and presents with

central nervous system dysfunction (Casa et al., 2015). While reported occupational EHS cases are low, if left untreated, EHS can result in permanent complications or even death (US Department of Labor, 2020). For example, the Bureau of Labor Statistics reported an average of 34 deaths/year between 1992-2022 (Bureau of Labor Statistics, 2025). However, it's important to recognize that these cases are only reported instances and may not reflect the actual number of heat-related illnesses in the workplace. EHS and other heat-related illnesses might not always be correctly categorized or identified as such, and unfortunately, many employers may fail to report EHS-related fatalities, especially among undocumented workers (Morrissey et al., 2023). Moreover, occupational health and safety agencies may only require the proximal cause of death to be reported. This limits our understanding of the full impact of heat in the workplace, as heat can lead to cognitive impairments and neuromuscular dysfunction, both of which contribute to an increased risk of accidents (Mazlomi et al., 2017; Thompson et al., 2023).

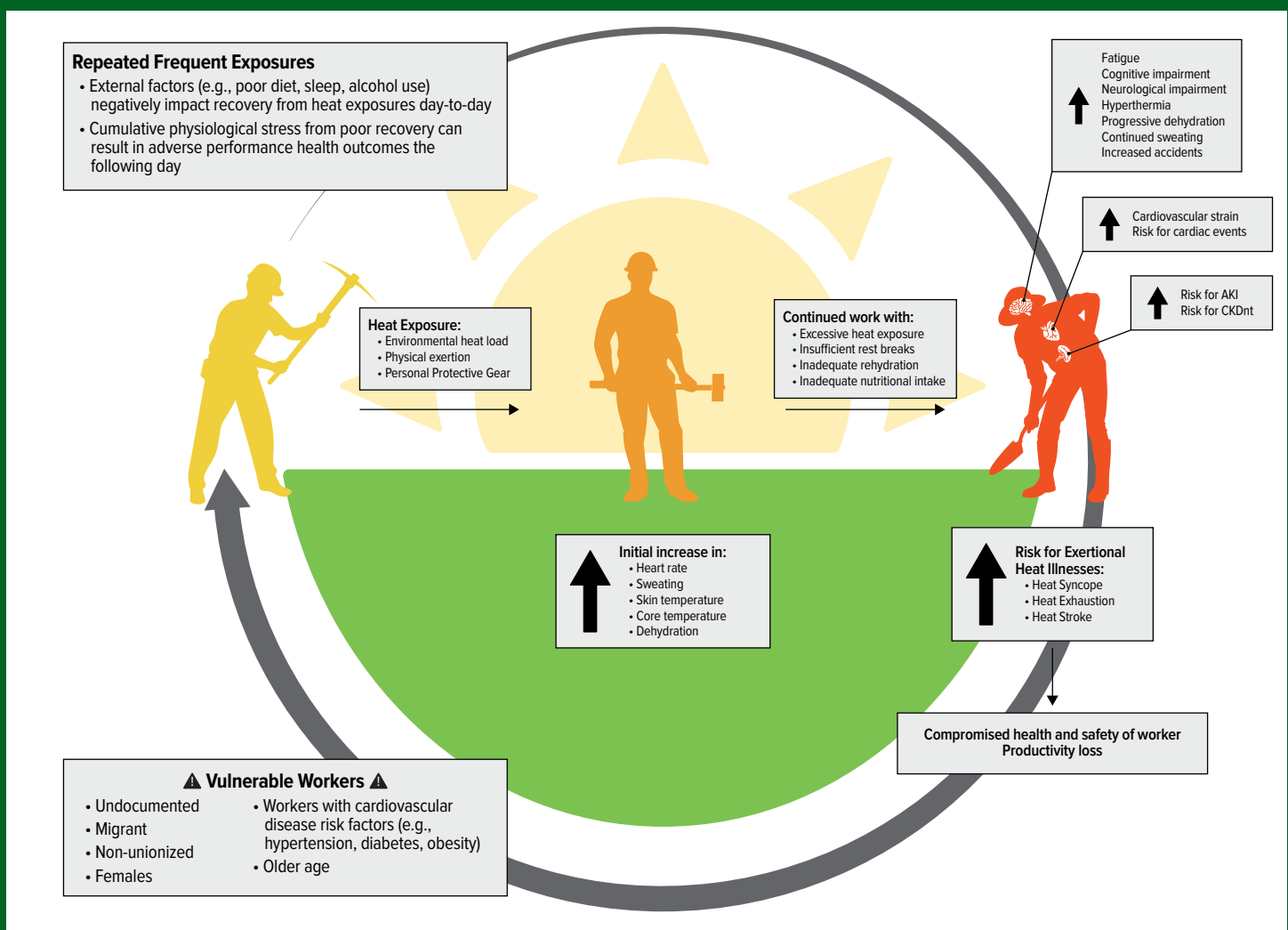


Figure 2: The influence of repeated and excessive heat exposure on workers. AKI, acute kidney injury; CKDnt, chronic kidney injury of nontraditional etiology and occupational origin.

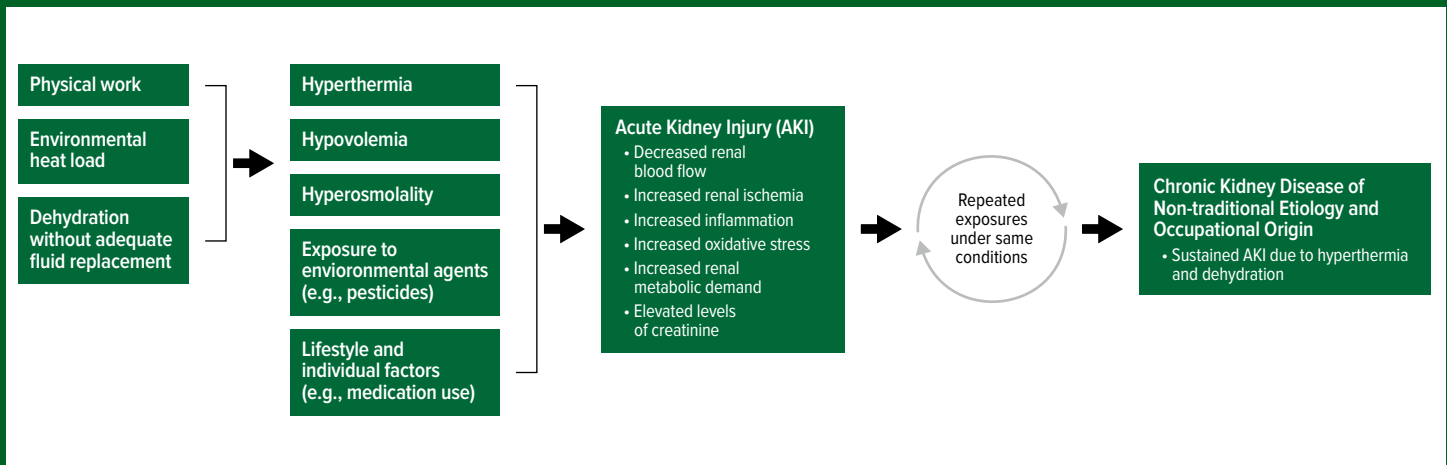


Figure 3: Etiology of chronic kidney disease of nontraditional etiology and occupational origin. AKI, acute kidney disease.

Working in the heat also has a profound effect on worker physiology, increasing skin temperature, heart rate, sweating and fatigue (Crowe et al., 2023; Périard et al., 2021). Increased sweating without adequate fluid replacement can further exacerbate a rise in heart rate (Cheuvront & Kenefick, 2014; Kenefick & Sawka, 2007; Adams et al., 2014), core temperature (Cheuvront & Kenefick, 2014; Cheuvront et al., 2010) and risk of acute kidney injury (AKI) (Chapman et al., 2020). AKI is characterized as a rapid reduction in kidney function and can be induced by increases in core temperature ($>38.5^{\circ}\text{C}$; hyperthermia) and dehydration without adequate fluid replacement (Chapman et al., 2020; Junglee et al., 2013; Schlader et al., 2017). Markers of AKI risk increase following physical work in the heat and are augmented as core temperatures rise and dehydration progresses (Chapman et al., 2020). Currently, there is an epidemic of chronic kidney disease (CKD) among laborers who perform heavy physical work in hot environments (Johnson et al., 2019). In 2020, 26.2 million workers were living with heat-related chronic kidney disease, classified as CKD of nontraditional etiology and occupational origin (CKDnt) (ILO, 2024). CKDnt is prevalent among laborers in agriculture, construction and mining, and tends to occur in the absence of traditional CKD risk factors such as age, hypertension, obesity or diabetes (Chapman et al., 2019; Gallo-Ruiz et al., 2019; Wesseling et al., 2020). Many individuals with CKDnt do not exhibit early clinical symptoms, which makes early detection and screening very difficult (Amorim & Schlader 2025; Chapman et al., 2019; Whaley-Connell et al., 2011). Elevated core temperature, dehydration, and exposure to environmental factors such as metals and pesticides, can lead to a reduction in renal blood flow, resulting in renal ischemia, inflammation and oxidative stress (Chapman et al., 2019; Gallo-Ruiz et al., 2019; Masoud et al., 2024; Venugopal et al., 2024). The kidneys are often required to increase their metabolic demand to regulate water and electrolyte balance which further exacerbates these effects (Chapman et al., 2021) (Figure 3). Unfortunately, clinical symptoms often become present when the disease has progressed, and substantial kidney damage has already occurred. There is a particularly high number of young male laborers in low-income countries who experience CKDnt (Stanifer et al., 2016). Young laborers in low-income

countries or those who migrate for work are also reported to have high risk of cardiac mortality during periods of high heat exposure (Pradhan et al., 2019). In conclusion, it is clear that occupational heat exposure can lead to substantial negative health outcomes in workers, both short and long term.

PRODUCTIVITY AND PERFORMANCE EFFECTS

Labor productivity and economic success are significantly impacted by occupational heat stress (Messieh, 2021; Borg et al., 2021; Park et al., 2017; Orlov et al., 2019). It is predicted that the global cost of lost worktime associated with occupational heat exposure will rise to \$2.4-2.5 trillion in 2030 ($>1\%$ of gross domestic product (GDP)) from 311 billion in 2010 ($\sim 0.5\%$ of GDP), which is a 557% increase (Borg et al., 2021). A meta-analysis in 11 studies of a total of 8076 workers estimated a 30% prevalence of productivity losses due to occupational heat stress (Flouris et al., 2018). Seven of the included studies reported a 2.6% decrease for every degree increase in wet bulb globe temperature above 24°C (Flouris et al., 2018). In the United States, occupational heat exposure could result in a loss of \$100 billion annually (Messieh, 2021). Without implementing effective occupational heat stress mitigation interventions, heat-related labor productivity losses could double to \$200 billion by 2030 and reach \$500 billion by 2050 (Messieh, 2021).

There are several factors that cause labor productivity losses induced by occupational heat stress. Machinery mechanical failures, infrastructure system failures and agricultural yield loss are mechanisms associated with labor productivity losses, however, these factors are not directly linked to worker health, safety and work capacity (Messieh, 2021). Worker-related labor productivity losses associated with heat stress include both presenteeism and absenteeism (Morrissey et al., 2021b) (Figure 4). Heat-related presenteeism can be defined as losses in productivity when workers are not fully functioning in their workplace, and therefore, have reductions in their physical work capacity (Morrissey, Brewer, et al. 2021). Reductions in physical

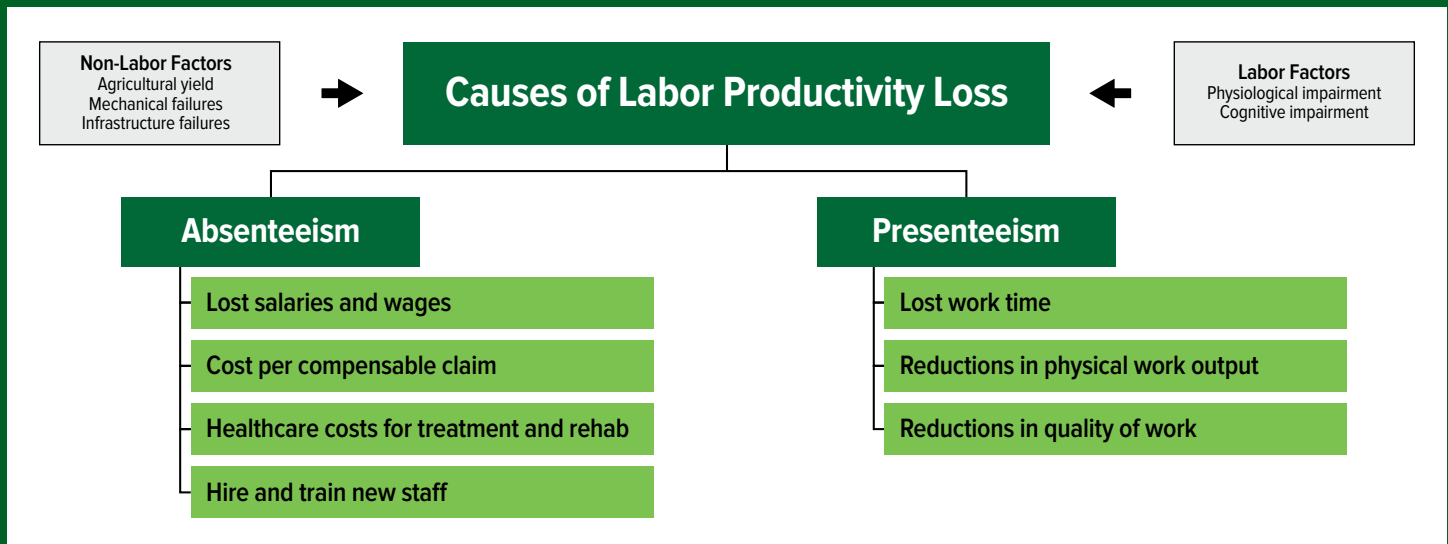


Figure 4: Mechanisms associated with heat-related labor productivity losses.

work capacity can be induced by factors such as impaired cognitive performance, dehydration, hyperthermia, increased discomfort and fatigue (Morrissey et al., 2021b). Occupational heat exposure can also impact the work environment. For example, safety goggles can fog, sweat can get in workers' eyes and sweaty hands can reduce grip on tools, leading to increased risk of accidents (Morrissey et al., 2021b). Ultimately, physiological, cognitive, perceptual and physical changes in the environment induced by occupational heat exposure can reduce the overall work output, the quality of work and increase time off task.

Heat stress can also impact productivity through heat-related absenteeism (Morrissey et al., 2021b). Heat-related absenteeism is characterized as a worker's absence from work due to the adverse effects of heat. Absenteeism associated with heat exposure can occur due to heat-related illnesses, workplace injuries and fatalities. When illnesses and injuries occur, employers are subjected to worker compensation claims insurance payouts, medical fees (i.e., healthcare costs related to treatment and rehabilitation), subsidies and additional expenses to hire and train new staff members (Borg et al., 2021; Martínez-Solanas et al., 2018; Morrissey et al., 2021b). Employers also face the risk of lawsuits related to long-term health issues and fatalities caused by heat exposure. Interventions to mitigate occupational heat exposure are typically low-cost, and heat-related deaths can be prevented through evidence-based heat stress management strategies and emergency procedures (Casa et al., 2015; Demartini et al., 2015). Workers are also susceptible to financial burdens as heat-related illnesses and injuries can result in lost salaries and wages. Borg et al. (2021) reported there was a greater cost for workers in low and middle-income countries, outdoor industries, medium-sized businesses and workers between 25-45 years old. In response to these productivity and economic concerns, effective and practical heat mitigation solutions are urgently needed to safeguard workers health and safety and limit threats to productivity (Morris et al., 2020; Morrissey et al., 2021a).

PRACTICAL APPLICATIONS

Understanding the health, safety and productivity impacts of occupational heat stress is the foundational step to creating the solutions to implement to protect workers. As such, the following practical applications are proposed and will be expanded upon in "Part 2":

- Do not directly apply heat physiology research from sport to the occupational setting (Figure 1).
- Understanding the substantial occupational health and safety effects of heat stress on workers is crucial to improve short-term and long-term health and safety outcomes and enhance productivity and economic success (Figure 2).
- Methods of early detection and intervention of health conditions, such as CKDnt, should be considered to better protect vulnerable workers.

SUMMARY

It is essential to enhance our understanding of the acute and chronic effects of occupational heat exposure on worker health, safety and productivity. While research in sports settings has advanced knowledge about the impact of heat, the differences between athletes and working populations demonstrate that these findings should not be directly applied to occupational environments. Occupational heat exposure can cause immediate health and safety issues, such as discomfort, fatigue, heat syncope and an increased risk of accidents. Excessive heat exposure can lead to exertional heat stroke, a life-threatening condition that requires immediate treatment to prevent permanent damage or death. Additionally, there are significant long-term health consequences, such as acute kidney injury resulting from hyperthermia and dehydration, which can lead to chronic kidney disease (CKD). In workers, particularly young males in low-income countries, there is

a rising epidemic of chronic kidney disease of non-traditional causes (CKDnt), often occurring in the absence of typical risk factors and without symptoms until the disease has advanced. Early detection and intervention for CKDnt and other heat-related conditions are critical. Moreover, occupational heat exposure negatively impacts productivity by reducing physical work capacity, increasing lost work time and leading to lost wages and higher healthcare costs for treatment and rehabilitation, resulting in a substantial economic burden. In response to health, safety and productivity decrements, effective heat stress mitigation strategies must be developed and implemented to adequately protect workers.

The views expressed are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

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