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Commentary

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Occupational Heat Stress and Practical Cooling Solutions for Healthcare and Industry Workers During the COVID-19 Pandemic

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Abstract

Treatment and management of severe acute respiratory syndrome coronavirus-2, which causes coronavirus disease (COVID-19), requires increased adoption of personal protective equipment (PPE) to be worn by workers in healthcare and industry. In warm occupational settings, the added burden of PPE threatens worker health and productivity, a major lesson learned during the West-African Ebola outbreak which ultimately constrained disease control. In this paper, we comment on the link between COVID-19 PPE and occupational heat strain, cooling solutions available to mitigate occupational heat stress, and practical considerations surrounding their effectiveness and feasibility. While the choice of cooling solution depends on the context of the work and what is practical, mitigating occupational heat stress benefits workers in the healthcare and industrial sectors during the COVID-19 disease outbreak.

Keywords: cooling; coronavirus; COVID-19; heat; occupational heat strain; PPE; protective clothing; respirators

Introduction

Treatment and management of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), which causes coronavirus disease (COVID-19), requires extensive personal protective equipment (PPE) to be worn by healthcare workers. Moreover, there is expected to be increased adoption of PPE for those returning to work in industry, in-particular face masks/respirators, which have been shown to induce thermal discomfort and in some cases physiological strain (Jones, 1991). In the healthcare sector, COVID-19 PPE for work involving potential aerosol generating procedures (AGPs) has, by design, almost no ventilation, which is causing healthcare workers to report high sweat rates and fatigue even in the absence of hot weather (Liu *et al.*, 2020). Standard medical scrubs are still adopted for non-AGPs as normal, but with increased use of face masks and gloves as per recommendations from Public Health England (Public Health England, 2020). Compared with standard medical scrubs, PPE relevant for work with moderate to high risk of SARS-CoV-2 transmission has approximately double the evaporative resistance, but this resistance can increase over 10-fold with added layers and with full encapsulation of the head and neck (Potter *et al.*, 2015). While high risk PPE designs successfully limit *incoming* fluid and airborne pathogens entering the human body, it also limits the *outgoing* removal of metabolic body heat. With limited heat loss combined with potentially high sweat rates, hyperthermia, dehydration, and fatigue can ensue rapidly. High sweat rates have been reported in healthcare workers adopting COVID-19 PPE, increasing thermal discomfort and fatigue (Liu *et al.*, 2020). Importantly, liquid protective, impermeable PPE can aggravate the heat stress response even in thermoneutral conditions close to 22°C (White *et al.*, 1989, 1991). If the resulting occupational heat stress is not mitigated in some way, literature demonstrates a clear risk of increased health risks associated with hyperthermia (Leon and Bouchama, 2015) and dehydration (Tawatsupa *et al.*, 2012; Flouris *et al.*, 2018), increased workplace accidents through poor decision making (Tawatsupa *et al.*, 2013; Taylor *et al.*, 2015; Spector *et al.*, 2019), and the need for more frequent rest breaks, which can impact productivity (Ioannou *et al.*, 2017; Flouris *et al.*, 2018).

COVID-19 is a global issue, but similarly to the Ebola outbreak, the effects of climatic heat will impact the hottest and poorest regions the most (WHO, 2014). We therefore wish to comment on the link between COVID-19 PPE and occupational heat stress, leading into discussion on the solutions available to help mitigate occupational heat strain and their practicality. The latter can contribute to improved management of the disease, wellbeing of workers in healthcare and industry, and mitigated productivity loss.

COVID-19 PPE and occupational heat stress

The link between PPE and occupational heat strain is well established. Humans constantly generate heat through metabolism, which increases during physical work activity. The primary avenues for losing metabolic heat are through convective air movement over the skin and evaporation of sweat from the skin surface (Parsons, 2010). However, if the skin is not exposed, as with fluid resistant PPE, any convective or evaporative cooling becomes strongly limited (Havenith *et al.*, 1999; Holmér *et al.*, 1999; Potter *et al.*, 2015), causing body temperature to increase (Cheung *et al.*, 2000). Moreover, and particularly relevant to COVID-19 is the independent effect of facial protection and glove use. For example, filtering facepiece respirators (i.e. N95 FFR) can increase inspiratory breathing resistance, limit water ingestion, and increase skin temperature on the face (DuBois *et al.*, 1990; Laird *et al.*, 2002), one of the most thermosensitive regions on the body (Cotter and Taylor, 2005). In addition, respirators create a barrier between the skin and the environment for sweat evaporation, causing moisture accumulation and overall thermal discomfort (DuBois *et al.*, 1990; Jones, 1991). The associated perceptual response to wearing face masks without meaningful changes in internal body temperature is suggestive of a psychological component and/or regional changes in brain temperature (Roberge *et al.*, 2012). Despite minimal perceptual differences, powered air purifying respirators (PAPRs) minimize inspiratory breathing resistance and reduce facial skin temperature and humidity compared with filtering facepiece respirators (Powell *et al.*, 2017). Safety goggles/face shields are likely to have a similar effects, but we are not aware of data pertaining to their independent effect on worker heat strain and thermal comfort. Sweat accumulation is likely to increase fog in the goggles (Chia, 2020), which affects vision and may increase the risk of workers touching their face, which is not advised. The use of safety gloves will further reduce heat transfer from the skin to the environment (Romanovsky, 2014; Godsmark *et al.*, 2018), exacerbating thermal discomfort and likely decreasing willingness to wear such PPE if it is not considered absolutely essential (Laird *et al.*, 1993). The independent role of gloves was highlighted when their removal during physical activity in the heat substantially increased heat loss and extended work duration (Godsmark *et al.*, 2018). Taken together, increased adoption of PPE can have the negative side-effect of increasing occupational heat stress, even in mild thermal climates (White *et al.*, 1989, 1991).

For industry, the economic implications of occupational heat are well described (Zander *et al.*, 2015; Hsiang *et al.*, 2017), but the side-effects noted above will also lead to less efficient management of the COVID-19 outbreak. Learning from the Ebola outbreak in West-Africa, the World Health Organization stated '*Personal protective equipment is hot and cumbersome, especially in a tropical climate, and this severely limits the time that doctors and nurses can work in an isolation ward*' (WHO, 2014). For Ebola workers, a proposed solution published in this Journal was to increase ventilation in protective clothing (Kuklane *et al.*, 2015), but this is less applicable for COVID-19 due to its high transmission in air (unless the air is first PAPR filtered), as opposed to Ebola's transmission primarily through bodily fluids. Moreover, shortages in adequate PPE render it unlikely that clothing redesign to improve ventilation could be thoroughly researched, manufactured, and distributed in a timely manner. Alternative solutions are therefore required and are described below.

Solutions available to mitigate workplace heat stress

A task specific optimization of COVID-19 PPE, or improved design at the manufacturer level, is desirable to help maintain comfort and reduce the general requirement for cooling strategies. There exists limited data to comment on such optimization and redesign at this stage, and task specific optimization is often impractical if with wide variation in occupational tasks. Fortunately, there are simple methods to mitigate occupational heat strain while wearing such ensembles, without compromising safety. In fact, most of the research aimed at effective mitigation strategies during the 2013–2016 Western Africa Ebola Virus epidemic are relevant for the ongoing pandemic, aside from PPE redesign (Kuklane *et al.*, 2015). The solutions can be separated into strategic planning and practical cooling solutions.

Strategic planning

As demonstrated above, scenarios involving potential AGPs present a moderate to high risk of SARS-CoV-2 transmission and therefore require encapsulating PPE. Using PPE with such low vapour permeability renders heat stress a *daily* consideration for workers during their shift, even in ambient temperatures ~22°C (White *et al.*, 1989, 1991). In tasks where less PPE is required (i.e. facemasks and gloves), the risk of heat stress is more dependent on the thermal environment. In these situations, a heat action plan is recommended for periods where hot weather is expected, particularly relevant to outdoor work (i.e. agriculture and construction). However, manufacturing plants with heat generating equipment are also at risk of high indoor temperatures (Pogačar *et al.*, 2018; Ciuha *et al.*, 2019). In Ghana, one of major barriers to workers adopting heat adaptation strategies is lack of training on this issue, management commitment, and heat related policy regulations (Nunfam *et al.*, 2020). Taken together, a strategic plan should aim to (i) identify a threshold ambient condition where the heat plan will be actioned, (ii) determine cooling options which can be implemented by workers during the day, and (iii) implement training to help workers adopt cooling solutions, and to learn the signs and symptoms of heat illness.

For situations where low level PPE is adopted (low transmission risk), the threshold ambient conditions for the adopting a heat action plan can be based on the Universal Thermal Climate Index (UTCI) (Bröde *et al.*, 2012; Jendritzky *et al.*, 2012). The UTCI provides a temperature which is adjusted based on air temperature, humidity, mean radiant temperature, and air movement. The UTCI can be calculated on the project website (www.utci.org) and linked with the severity indicators shown in Table 1. To protect most workers, a heat action plan can be implemented when UTCI ≥26°C, but this threshold may be too conservative in hot regions.

Specific cooling solutions are described below, and guidance on the signs and symptoms of heat illness are widely available from major public health agencies (i.e. https://www.cdc.gov/disasters/extremeheat/warning.html).

Cooling solutions

For indoor work, air conditioning is one of the most widely adopted cooling solutions worldwide. However, evidence suggests that air conditioning may contribute to the transmission of SARS-CoV-2 in poorly ventilated spaces (Lu *et al.*, 2020), and should therefore only be used based on updated regulatory guidelines. In operating theatres, temperatures can range from 14 to 27°C depending on the procedure (Balaras *et al.*, 2007), but generally are air conditioned to ~20°C for purposes of general infection control and thermal comfort of surgeons wearing full PPE (Wood and Carli, 1991). Such ambient conditions are likely to limit heat strain of the worker, but risk inducing cold discomfort for patients and staff who will not be wearing protective clothing (Wood and Carli, 1991). In large workspaces such as factory floors, air conditioning is seldom adopted due to its high energy use and financial burden. Taken together, air conditioning is not always feasible, especially given the uncertainty of its role in SARS-CoV-2 transmission. The EU funded project 'HEAT-SHIELD' (https://cordis.europa.eu/project/id/668786/results) provides in depth discussion on alternative, practical cooling solutions screened for their practicality and efficacy specific to the Manufacturing,

Table 1. UTCI equivalent temperatures categorized in terms of thermal stress.

UTCI range (°C)	Stress category
Above +46	Extreme thermal stress
+38 to +46	Very strong thermal stress
+32 to +38	Strong thermal stress
+26 to +32	Moderate thermal stress
+9 to +26	No thermal stress
+9 to 0	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
Below −40	Extreme cold stress

Source: Bröde *et al.* (2012).

Construction, Agricultural, Tourism, and Transportation sectors. We concisely address the primary solutions below and follow with discussion on their practicality.

Dehydration is a common consequence of heat stress and may be exacerbated with respirator use due to restricted water intake (Liu *et al.*, 2020). Up to 70% of European workers across different sectors arrive to work already dehydrated (Piil *et al.*, 2018), though through training and education on rehydration this can be alleviated by hydrating before and after work hours. During work, employees should have easy access to water during any breaks to limit the rate of dehydration. Of note, dehydration during physical work can exacerbate the increase in body temperature and in the long-term increase the risk of acute kidney injury or long-term kidney disease (Tawatsupa *et al.*, 2012; Flouris *et al.*, 2018). Second, in the case of makeshift tent-based treatment or assessment areas, shading solutions which limit the influx of solar radiation are desirable to mitigate occupational heat stress. Direct or indirect exposure to solar radiation (i.e. sunlight) can independently aggravate heat strain, reducing work output (Otani *et al.*, 2016), and thermal comfort (Hodder and Parsons, 2007). Third, the ingestion of ice slurry is a popular strategy to mitigate heat strain in occupational and sports settings. Ingestion of crushed ice is a more aggressive form of internal cooling compared with cold fluid ingestion because the ice undergoes a phase change from solid to liquid in the body. This process transfers a large amount of internal heat from the body to the ingested ice (latent heat of fusion), creating a more powerful cooling effect than cold fluid (Vanden Hoek *et al.*, 2004; Siegel *et al.*, 2010). For example, during walking exercise in mild (Maté *et al.*, 2016) and extreme heat (Watkins *et al.*, 2018) in full PPE, ingestion of ice slurry is shown to reduce core body temperature prior to and during activity. The positive effects of ice slurry seem to ease after ~20 min during activity, but reingestion prolonged its protective effect (Maté *et al.*, 2016; Watkins *et al.*, 2018). Fourth, cooling of the hands in running water or ice water buckets, even while wearing protective gloves, provides a meaningful cooling effect during recovery breaks (House and Tipton, 2005). Finally, cooling vests with phase change materials (PCMs) or ice can be included underneath the PPE. Such cooling vests absorb heat with a high storage density when the material changes from solid to liquid (Gao, 2014). The use of a PCM vest *underneath* nuclear, chemical and biological PPE has been shown to significantly reduced heat strain during physical activity and recovery in hot conditions (Chou *et al.*, 2008; McCullough *et al.*, 2011; House *et al.*, 2013; Bach *et al.*, 2019). Less researched but far more practical in the context of COVID-19 is the use of ice vests *on top* of the PPE layer, which has also been shown to reduce heat strain (Muir *et al.*, 1999). The effectiveness will vary depending on the clothing properties (i.e. thickness), and the general practicality compared with vests worn *underneath* PPE are discussed in the section 'Practical considerations'. The use of ice vests or PCMs requires freezers or cool areas for regeneration after use. If freezing access or power is unavailable, other types of PCM, e.g. Glauber's salt or organic hydrocarbons/wax, with melting/solidifying temperature at ~28°C are available (Gao, 2014; Kuklane *et al.*, 2015) that can be regenerated at higher temperature (fridge).

Interaction between SARS-CoV-2 transmission

The cooling solutions presented above should be considered for their potential role in transmission of SARS-CoV-2. We mention above the potential interaction of air conditioner use and increased transmission in poorly ventilated spaces (Lu *et al.*, 2020), yet the guidelines on air conditioning from major public health agencies is not completely clear. Guidelines are available from the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) concerning safe and optimal use of heating, ventilation, and air-conditioning in the context of COVID-19 (https://www.rehva.eu/activities/covid-19-guidance). REHVA advocate providing an '*even ventilation rate at low air velocity within all points in the room*'.

Also, highly relevant is the survival and transmission of SARS-CoV-2 in water, which is relevant for hydration, hand/forearm immersion, ice slurry ingestion, and cooling vests. Advice from the Royal Society of Chemistry would suggest that waste and drinking water *can* be contaminated with SARS-CoV-2 and potentially act as a vehicle for transmission (Naddeo and Liu, 2020). Importantly however, the US CDC suggest that conventional treatment methods should remove/inactivate COVID-19. Moreover, the CDC also state there is no evidence that COVID-19 can be contracted in pools of water, especially if that water is treated with chlorine. We advocate (i) no sharing of water bottles between workers, (ii) decontamination of bottles/cups used for ice slurry after each use, (iii) treating pools of water used for forearm/limb immersion with appropriate chlorine and checking for normal acidity, and (iv) decontamination of ice cooling vests after each use. Hand washing/sanitizer is also recommended after use of such cooling strategies. These views are based on guidelines available at the time of writing this commentary paper and are subject to change. Therefore, guidelines should be checked by employers before adoption of a given strategy.

Practical considerations

While we describe several methods available to mitigate occupational heat strain, it is important to address some practical issues that may limit their use. Ultimately, the practicality of any cooling solution depends on the setting (indoor/outdoor), occupation, shift organization, geographical region, and the level of PPE used. The use of shading and air conditioning is clearly dependent on whether the work is undertaken indoors or outdoors. The opportunities for workers to doff PPE and adopt a cooling solution (i.e. ice slurry ingestion) is dependent on shift durations and what PPE is used by the workers. For example, it is easier to hydrate without wearing face protection, and if a cooling solution requires doffing of PPE (i.e. any limb immersion in cool water) it is less likely to be adopted. Finally, as alluded to in the discussion of strategic planning, the threshold UTCI equivalent temperature for triggering a heat action plan will likely depend on the geographical location. For example, regions with infrequent heat exposure (i.e. Northern Europe) may require protection from the heat at lower UTCI compared with regions where environmental heat is already commonplace and workers are adapted to the heat (i.e. the Persian Gulf) (Pal and Eltahir, 2016).

Many of the practical issues concerning the use of cooling solutions during heat stress arise when they are adopted *during* work time. As such, there may be hesitation from employers due to concerns that a cooling solution will detract workers from their primary activities and reduce productivity. The use of specialized rest areas (a cooling oasis) helps ensure that cooling does not interfere with productivity during work but instead *accelerates recovery* of workers during their pre-determined break times. Those break times will vary widely depending on the occupation, but findings from the EU funded HEAT-SHIELD project (https://cordis.europa.eu/project/id/668786/results) indicates that regular, planned breaks (~2 min every 30 min) can be beneficial for worker comfort and performance in the heat. If regular breaks are not implemented, workers will likely suffer a net loss of work time due to more irregular, unplanned rest/cooling breaks (Ioannou *et al.*, 2017). Outdoor cooling areas should be shielded from sunlight and have water readily available to maintain worker hydration. More aggressive cooling methods such as crushed ice drinks, and hand/forearm immersion will offer further benefit and generally do not require full removal of PPE, especially in industry. If adopting this strategy, a designated individual may be required to maintain water availability and general cleanliness of the cooling area, which will incur its own time and cost. Finally, it is preferable to have power available close to the cooling area to ensure ice slurry beverages can be generated ad hoc.

Maintaining hydration is challenging while wearing COVID-19 PPE. Workers may be reluctant to drink freely because it increases the rate of urination, and secondly, ingestion of water requires the removal of protective respirators, likely necessitating the worker to access a safe area before doing so. Each of these issues likely detract workers from their primary activities, decreasing productivity and willingness to hydrate adequately. Since approximately 70% of European's arrive to work already in a dehydrated state (Piil *et al.*, 2018), the primary hydration advice to workers should be to hydrate the night and morning *before* starting work. We also emphasize that the health and cognitive effects of acute and chronic dehydration are well established (Cheuvront and Kenefick, 2014; Flouris *et al.*, 2018), such that reluctance of workers to maintain hydration will have a net effect of decreasing worker health and wellbeing in the long term. As discussed more below, the second method to improve hydration without compromising productivity is to adopt a cooling oasis, for use specifically during recovery breaks. Importantly, most of the solutions become more practical if they are implemented as part of a designated cooling area to be used during breaks.

The adoption of ice or phase change vests may be most practical during rest breaks. While the benefit of such vests is that they can be worn underneath the PPE ensemble, their feasibility is particularly limited in healthcare settings. Firstly, the effect of cooling vests on body temperature has been typically assessed over short time periods (<1 h), not over a full working day. Once the vest warms up and no longer provides active cooling, the extra weight of the vest *at best* decreases comfort, and at worst increases metabolic heat production, potentially increasing heat strain (Dorman and Havenith, 2009). A recent survey from healthcare workers in Wuhan, China indicates that personnel can feel '*weighed down*' by the PPE, so the adoption of a cooling vest which adds extra weight should be carefully considered (Liu *et al.*, 2020). Furthermore, changing or removing cooling vests in the healthcare industry requires full removal and decontamination of PPE layers, which is time consuming, impractical, and requires a designated individual to manage that procedure across a group of workers. A less powerful but far more practical approach is to wear the vest over the PPE, which removes the need to remove clothing layers when the vest or ice packs are replaced. That method was shown to extend work time and decrease physiological and perceptual strain in warm environments (Muir *et al.*, 1999), but its effectiveness will clearly depend on the thickness of the initial clothing layer. Vests should be treated as contaminated after each use and therefore will require decontamination, incurring some added cost. Research in COVID-19 PPE redesign should consider that proposed by Muir *et al.* (1999), in which the PPE could accommodate external cooling packs. Phase change vests have been shown to be very effective for reducing core body temperature during rest periods, even if the rest takes place in a hot environment (House *et al.*, 2013). Thus, we recommend cooling vests be adopted during recovery if working time substantially exceeds the potential cooling time.

Conclusions

Decreasing occupational heat stress can prolong work time, improve decision making, and ultimately help contain the transmission of SARS-CoV-2. The decision to implement a specific heat mitigation strategy depends on the context of what is available. Hydration solutions should be strongly advocated and accessible all workers, possibly combined with more aggressive cooling (i.e. ice slurry, forearm water immersion) during rest breaks. The 'HEAT-SHIELD' provides detailed, industry specific guidelines to mitigate workplace heat in the Construction, Agriculture, Manufacturing, Transport, and Tourism sector (https://cordis.europa.eu/project/id/668786). Although the healthcare sector was not specifically addressed in that project, the practical guidance provided in this document may offer some beneficial effect.

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Conflict of interest

The authors declare no conflict of interest.

References

Bach AJE, Maley MJ, Minett GM *et al.* (2019) An evaluation of personal cooling systems for reducing thermal strain whilst working in chemical/biological protective clothing. *Front Physiol*; **10**: 424.

Balaras CA, Dascalaki E, Gaglia A. (2007) HVAC and indoor thermal conditions in hospital operating rooms. *Energy Build*; **39**: 454–70.

Bröde P, Fiala D, Błażejczyk K *et al.* (2012) Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *Int J Biometeorol*; **56**: 481–94.

Cheung SS, McLellan TM, Tenaglia S. (2000) The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. *Sports Med*; **29**: 329–59.

Cheuvront SN, Kenefick RW. (2014) Dehydration: physiology, assessment, and performance effects. *Compr Physiol*; **4**: 257–85.

Chia CLK. (2020) Leading a COVID-19 cohort ward without blades: a surgeon's perspectives. *Br J Surg*; **107**: 298–9. doi:10.1002/bjs.11735

Chou C, Tochihara Y, Kim T. (2008) Physiological and subjective responses to cooling devices on firefighting protective clothing. *Eur J Appl Physiol*; **104**: 369–74.

Ciuha U, Pogačar T, Bogataj LK *et al.* (2019) Interaction between indoor occupational heat stress and environmental temperature elevations during heat waves. *Weather Clim Soc*; **11**: 755–62.

Cotter JD, Taylor NA. (2005) The distribution of cutaneous sudomotor and alliesthesial thermosensitivity in mildly heat-stressed humans: an open-loop approach. *J Physiol*; **565** (Pt 1): 335–45.

Dorman LE, Havenith G. (2009) The effects of protective clothing on energy consumption during different activities. *Eur J Appl Physiol*; **105**: 463–70.

DuBois AB, Harb ZF, Fox SH. (1990) Thermal discomfort of respiratory protective devices. *Am Ind Hyg Assoc J*; **51**: 550–4.

Flouris AD, Dinas PC, Ioannou LG *et al.* (2018) Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health*; **2**: e521–31.

Gao C. (2014) Phase-change materials (PCMs) for warming or cooling in protective clothing. In Wang F, Gao C, editors. *Protective clothing: managing thermal stress*. Cambridge, UK: Woodhead Publishing Ltd. pp. 227–49.

Godsmark CN, Tipton MJ, Dennis MR *et al.* (2018) Moisture vapour permeable gloves extend thermal endurance and safe work time more than other similarly permeable chemical-biological ancillary protective items. *Ergonomics*; **61**: 1635–45.

Havenith G, Holmér I, den Hartog EA *et al.* (1999) Clothing evaporative heat resistance—proposal for improved representation in standards and models. *Ann Occup Hyg*; **43**: 339–46.

Hodder SG, Parsons K. (2007) The effects of solar radiation on thermal comfort. *Int J Biometeorol*; **51**: 233–50.

Holmér I, Nilsson H, Havenith G *et al.* (1999) Clothing convective heat exchange—proposal for improved prediction in standards and models. *Ann Occup Hyg*; **43**: 329–37.

House JR, Lunt HC, Taylor R *et al.* (2013) The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures. *Eur J Appl Physiol*; **113**: 1223–31.

House JR, Tipton MJ. (2005) Heat strain is reduced at different rates with hand, foot, forearm or lower leg cooling. *Elsevier Ergon Book Ser*; **3**: 91–5.

Hsiang S, Kopp R, Jina A *et al*. (2017) Estimating economic damage from climate change in the United States. *Science*; **356**: 1362–9.

Ioannou LG, Tsoutsoubi L, Samoutis G *et al*. (2017) Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers. *Temperature (Austin)*; **4**: 330–40.

Jendritzky G, de Dear R, Havenith G. (2012) UTCI—why another thermal index? *Int J Biometeorol*; **56**: 421–8.

Jones JG. (1991) The physiological cost of wearing a disposable respirator. *Am Ind Hyg Assoc J*; **52**: 219–25.

Kuklane K, Lundgren K, Gao C *et al*. (2015) Ebola: improving the design of protective clothing for emergency workers allows them to better cope with heat stress and help to contain the epidemic. *Ann Occup Hyg*; **59**: 258–61. doi:10.1093/annhyg/mev003

Laird IS, Goldsmith R, Pack RJ *et al*. (2002) The effect on heart rate and facial skin temperature of wearing respiratory protection at work. *Ann Occup Hyg*; **46**: 143–8.

Laird IS, Pack RJ, Carr DH. (1993) A survey on the use and non-use of respiratory protective equipment in workplaces in a provincial New Zealand city. *Ann Occup Hyg*; **37**: 367–76.

Leon LR, Bouchama A. (2015) Heat stroke. *Compr Physiol*; **5**: 611–47.

Liu Q, Luo D, Haase JE *et al*. (2020) The experiences of health-care providers during the COVID-19 crisis in China: a qualitative study. *Lancet Glob Health*; **8**: e790–8.

Lu J, Gu J, Li K *et al*. (2020) COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. *Emerg Infect Dis*; **26**: 1628–31. doi:10.3201/eid2607.200764

Maté J, Siegel R, Oosthuizen J *et al*. (2016) Effect of liquid versus ice slurry ingestion on core temperature during simulated mining conditions. *Open J Prev Med*; **06**: 21–30.

McCullough EA, Eckels S, Elson J. (2011) *Human subject evaluation of personal cooling systems for soldiers data for Steele PCS only project: evaluation of personal cooling systems (PCS) for soldiers introduction to overall project*. Manhattan, KS: Kansas State University.

Muir IH, Bishop PA, Ray P. (1999) Effects of a novel ice-cooling technique on work in protective clothing at 28 degrees C, 23 degrees C, and 18 degrees C WBGTs. *Am Ind Hyg Assoc J*; **60**: 96–104.

Naddeo V, Liu H. (2020) Editorial Perspectives: 2019 novel coronavirus (SARS-CoV-2): what is its fate in urban water cycle and how can the water research community respond? *Environ Sci Water Res Technol*; **6**: 1213–6.

Nunfam VF, Adusei-Asante K, Frimpong K *et al*. (2020) Barriers to occupational heat stress risk adaptation of mining workers in Ghana. *Int J Biometeorol*; **64**: 1085–101.

Otani H, Kaya M, Tamaki A *et al*. (2016) Effects of solar radiation on endurance exercise capacity in a hot environment. *Eur J Appl Physiol*; **116**: 769–79.

Pal JS, Eltahir EAB. (2016) Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nat Clim Change*; **6**: 197–200.

Parsons KC. (2010) *Human thermal environments*. 2nd edn. London, UK: Taylor & Francis.

Public Health England. (2020) COVID-19 personal protective equipment (PPE). *Summary of PPE recommendations for health and social care workers*. Avaialble at https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control/covid-19-personal-protective-equipment-ppe. Accessed 29 April 2020.

Piil JF, Lundbye-Jensen J, Christiansen L *et al*. (2018) High prevalence of hypohydration in occupations with heat stress—perspectives for performance in combined cognitive and motor tasks. *PLoS One*; **13**: e0205321.

Pogačar T, Casanueva A, Kozjek K *et al*. (2018) The effect of hot days on occupational heat stress in the manufacturing industry: implications for workers' well-being and productivity. *Int J Biometeorol*; **62**: 1251–64.

Potter AW, Gonzalez JA, Xu X. (2015) Ebola response: modeling the risk of heat stress from personal protective clothing. *PLoS One*; **10**: e0143461.

Powell JB, Kim JH, Roberge RJ. (2017) Powered air-purifying respirator use in healthcare: effects on thermal sensations and comfort. *J Occup Environ Hyg*; **14**: 947–54.

Roberge RJ, Kim JH, Coca A. (2012) Protective facemask impact on human thermoregulation: an overview. *Ann Occup Hyg*; **56**: 102–12.

Romanovsky AA. (2014) Skin temperature: its role in thermoregulation. *Acta Physiol (Oxf)*; **210**: 498–507.

Siegel R, Maté J, Brearley MB *et al*. (2010) Ice slurry ingestion increases core temperature capacity and running time in the heat. *Med Sci Sports Exerc*; **42**: 717–25.

Spector JT, Masuda YJ, Wolff NH *et al*. (2019) Heat exposure and occupational injuries: review of the literature and implications. *Curr Environ Health Rep*; **6**: 286–96.

Tawatsupa B, Lim LL-Y, Kjellstrom T *et al*. (2012) Association between occupational heat stress and kidney disease among 37,816 workers in the Thai Cohort Study (TCS). *J Epidemiol*; **22**: 251–60.

Tawatsupa B, Yiengprugsawan V, Kjellstrom T *et al*. (2013) Association between heat stress and occupational injury among Thai workers: findings of the Thai Cohort Study. *Ind Health*; **51**: 34–46.

Taylor L, Watkins SL, Marshall H *et al*. (2015) The impact of different environmental conditions on cognitive function: a focused review. *Front Physiol*; **6**: 372.

Vanden Hoek TL, Kasza KE, Beiser DG *et al*. (2004) Induced hypothermia by central venous infusion: saline ice slurry versus chilled saline. *Crit Care Med*; **32**: 425–31. doi:10.1097/01.ccm.0000134259.59793.b8

Watkins ER, Hayes M, Watt P *et al*. (2018) Practical pre-cooling methods for occupational heat exposure. *Appl Ergon*; **70**: 26–33.

White MK, Hodous TK, Vercruyssen M. (1991) Effects of thermal environment and chemical protective clothing on work tolerance, physiological responses, and subjective ratings. *Ergonomics*; **34**: 445–57.

White MK, Vercruyssen M, Hodous TK. (1989) Work tolerance and subjective responses to wearing protective clothing and respirators during physical work. *Ergonomics*; **32**: 1111–23.

WHO. (2014) Unprecedented number of medical staff infected with Ebola. Available at https://www.who.int/mediacentre/news/ebola/25-august-2014/en/. Accessed 29 April 2020.

Wood MLB, Carli F. (1991) Inadvertent hypothermia in the operating theatre. *Curr Anaesth Crit Care*; **2**: 222–31.

Zander K, Botzen W, Oppermann E. (2015) Heat stress causes substantial labour productivity loss in Australia. *Nat Clim Change*; **5**: 647–51.