American Journal of Infection Control 51 (2023) 1384–1391

Contents lists available at ScienceDirect

American Journal of Infection Control

journal homepage: www.ajicjournal.org

Major Article

Literature review of physiological strain of personal protective equipment on personnel in the high-consequence infectious disease isolation environment

Claire E. Figi BS [a,*], Jocelyn J. Herstein PhD, MPH [b], Elizabeth L. Beam PhD, RN [c], Aurora B. Le PhD, MPH, CSP, CPH [d], Angela L. Hewlett MD, MS [e,f], James V. Lawler MD, MPH [e], John J. Lowe PhD [b,e], Shawn G. Gibbs PhD, MBA, CIH [g]

[a] Department of Epidemiology and Biostatistics, School of Public Health, Texas A&M University, College Station, TX
[b] Department of Environmental, Agricultural, and Occupational Health, University of Nebraska Medical Center, College of Public Health, 985110 Nebraska Medical Center, Omaha, NE
[c] College of Nursing, University of Nebraska Medical Center, 985330 Nebraska Medical Center, Omaha, NE
[d] Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI
[e] Global Center for Health Security, University of Nebraska Medical Center, 986161 Nebraska Medical Center, Omaha, NE
[f] Department of Internal Medicine, Division of Infectious Diseases, University of Nebraska Medical Center, 983332 Nebraska Medical Center, Omaha, NE
[g] Department of Environmental and Occupational Health, School of Public Health, Texas A&M University, College Station, TX

Key Words:
Heat stress
Isolation

Background: Heat strain and dehydration can affect an individual's physical and mental performance. The purpose of this review was to examine the literature for the impact of heat strain on health care workers (HCWs) who care for patients with high-consequence infectious diseases (HCIDs) while wearing personal protective equipment (PPE), discuss the risks of impaired safety caused by heat strain and dehydration in HCID environments, identify attempts to combat PPE-related heat strain, recognize limitations, and provide suggestions for further research.
Methods: A literature search was performed in PubMed or MEDLINE and Google Scholar. Authors screened abstracts for inclusion criteria and reviewed articles if the abstracts were considered to include information relevant to the aim.
Results: The search terms yielded 30 articles that were sorted based on environment setting, physiological impact, and interventions.
Discussion: The safety of the HCWs and patients can be enhanced through the development and usage of cooler, more comfortable PPE materials and ensembles to help slow the rate of dehydration and support the regulation of core body temperature.
Conclusions: Heat strain caused by wearing PPE is an occupational health concern for HCWs in the high-risk environment, that is, HCID care. Future studies are needed to develop innovative PPE ensembles that can reduce heat strain and improve well-being.

BACKGROUND

Personal protective equipment (PPE) is designed to protect health care workers (HCWs) while caring for patients with high-consequence infectious diseases (HCIDs), such as Ebola virus disease (EVD) or other dangerous pathogen infections. However, PPE can contribute to physical and cognitive limiting factors such as heat stress, dehydration, and reduced psychomotor vigilance, which can

* Address correspondence to Claire E. Figi, BS, Texas A&M University, 1266 TAMU, College Station, TX 77843.
E-mail addresses: claire.figi@gmail.com (C.E. Figi), jocelyn.herstein@unmc.edu (J.J. Herstein), ebeam@unmc.edu (E.L. Beam), aurorale@umich.edu (A.B. Le), alhewlett@unmc.edu (A.L. Hewlett), james.lawler@unmc.edu (J.V. Lawler), jjlowe@unmc.edu (J.J. Lowe), sgibbs@tamu.edu (S.G. Gibbs).
Funding/support: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Conflicts of interest: One author reports a provisional patent. All other contributing authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

https://doi.org/10.1016/j.ajic.2023.05.005

lead to increased risk of occupational exposure, injury, and/or illness in HCID environments.[1] Controlling the ambient temperature (e.g. air conditioning) can reduce the severity at which these limiting factors are experienced. However, field environments, such as pre-hospital care, patient transfers from emergency medical services (EMS) at the hospital point of entry, or outdoor testing centers or patient care facilities in lower-resource environments, pose a particular challenge for HCW safety and comfort while using PPE because temperature, humidity, and air velocity cannot be regulated.

The routine PPE worn by HCWs while caring for patients with HCIDs tends to be restrictive and can include boot coverings, gloves, surgical hood, respiratory and eye protection (e.g. goggles or face shield, N95 respirator or powered air purifying respirator [PAPR]), and an impermeable gown or coveralls.[2] This in turn impairs the body's normal ability to regulate body temperature and puts personnel at a greater risk of fluid loss, heat strain, and degraded performance that can potentially result in accidental and avoidable contamination.[3] Attempts to combat heat stress on HCWs in PPE include the use of cooling vests and hyperhydration strategies; yet, each has their limitations such as cost, added weight, and availability of wearable technology. There is an increasing need for innovations and development within the field of PPE to better support HCWs as they treat patients with HCIDs in any environment.[4]

With an increase in the use of and need for PPE over the last years with the 2013-2016 Ebola virus disease (EVD) epidemic and the COVID-19 pandemic, the physiological effects of HCWs wearing PPE for long periods of time have been observed in both higher resource settings and austere environments.[5,6] HCW cognitive impairments resulting from PPE use include an increase in risk-taking behaviors, reduced speech intelligibility, and decreased psychomotor vigilance; confusion and fatigue can be extremely dangerous to both the patient and the HCW in the high-risk environment of caring for patients with HCIDs.[3,5,7,8] Poor decisions and slower reaction times can lead to injuries and accidents that could severely harm both HCWs and the patients for whom they are caring.[7,8]

HEAT-SHIELD, a European Union-based project, was established to research, analyze, and report guidance and interventions regarding the thermal adaptation of European industry workers in hot environments.[9] This project investigated a variety of industries where workers may frequently encounter environments that increase the risk of heat exhaustion. Although HCWs were not included in this study, recommendations produced by HEAT-SHIELD, such as increased air flow, hydration strategies, and scheduled rest periods, may be applicable to reduce the heat stress experienced in and caused by PPE. Engineering and administrative controls may also be a target for increasing the comfort of HCWs in PPE, such as allowing HCWs to become acclimatized to the heat or environment they will be working in prior to their shifts through exercise and training in similar temperatures or using the lowest necessary level of PPE.[10] Other cooling interventions may include wearing a cooling vest during the shift or consuming cold beverages prior to donning PPE, but more research and innovations are needed to better allow HCWs to care for patients comfortably and safely in PPE.[4]

This review aims to examine the literature available on the physiological impacts of PPE on HCWs, identify the gaps and limitations of the identified studies, and discuss the recommendations for innovations needed to protect HCWs wearing PPE in HCID environments.

METHODS

A literature search was performed between September 2021 and January 2022 in PubMed or MEDLINE and Google Scholar with the terms: (1) "personal protective equipment" or "PPE" and "health care workers" or "health care professionals" or "nurses" or "doctors" and "core body temperature" or "heat stress" or "heat strain" or "physiological strain" or "dehydration" and "high level isolation" or "high consequence infectious disease" or "highly infectious disease" or "Ebola" or "COVID-19″ or "Lassa" or "Nipah" or "Marburg" or "MERS" or "SARS" or "Monkey Pox" or "Plague" or "Smallpox" (2) "personal protective equipment" or "PPE" and "health care workers" and "heat stress" or "heat exhaustion" or "heat illness" and "cognitive impairment" and "psychomotor vigilance" and "speech intelligibility." No filters and/or limits were used in the search. Authors screened abstracts for the following inclusion criteria: peer-reviewed articles written in English that describe the risk and effect of heat strain on HCWs wearing PPE while managing patients with HCIDs, such as EVD or COVID-19. Articles were further reviewed if the abstracts were considered to include applicable and appropriate information pertaining to the physiological impacts of PPE worn by HCWs in an HCID environment. Conference abstracts and dissertations were excluded. Heat strain was defined as the physiological response to heat stress with the onset of muscle cramps, exhaustion, dehydration, or severe cognitive impairment during or after exercise.[3,6] The cognitive impairment of heat strain was considered as impacting both the physical performance (psychomotor vigilance) and communicative ability (speech intelligibility) of the HCWs.

RESULTS

The search terms yielded 30 publications that were relevant to the topic of review and were included in this paper presented in the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) chart format (Fig 1). All articles published prior to 2019 were focused on PPE-related use during the care of patients with EVD, and those published from 2020 to the present were primarily focused on PPE ensembles worn during the care of patients with COVID-19. This review of PPE-focused literature is organized by environment setting, physiological impact, and interventions (Table 1).

Setting

The environmental settings in which the literature was grouped are divided into austere or field settings—encompassing studies conducted in or simulating conditions from the West Africa EVD epidemic of 2013-2016—and higher-resource clinical settings.[15–19] The term higher-resource clinical setting was decided upon by the authors, as it well described the settings that had more resources for ambient environment control (e.g. heating, ventilation, and air conditioning (HVAC) control of temperature, humidity, airflow controls, etc.) than those of an austere or field-based setting. However, the literature did not have consistent terminology nor definitions referring to either of these settings. It should also be noted that studies that were survey-based did not utilize a standardized survey or formatted scale for perceived exertion and heat.

Austere or field-based setting

Of the studies reviewed, 13 focused on austere or field-based settings, 4 were conducted on HCWs wearing PPE while treating patients with EVD in West Africa during the 2013–2016 epidemic, 4 were conducted in a controlled setting that simulated the conditions (e.g. hot, humid) of caring for patients with EVD in West Africa with PPE used in the hot zones of treatment centers, 2 studies addressed the treatment of COVID-19 patients in austere environments, and 3 papers focused on the treatment of other HCIDs within a simulated environment. Overheating and dehydration (measured by weight

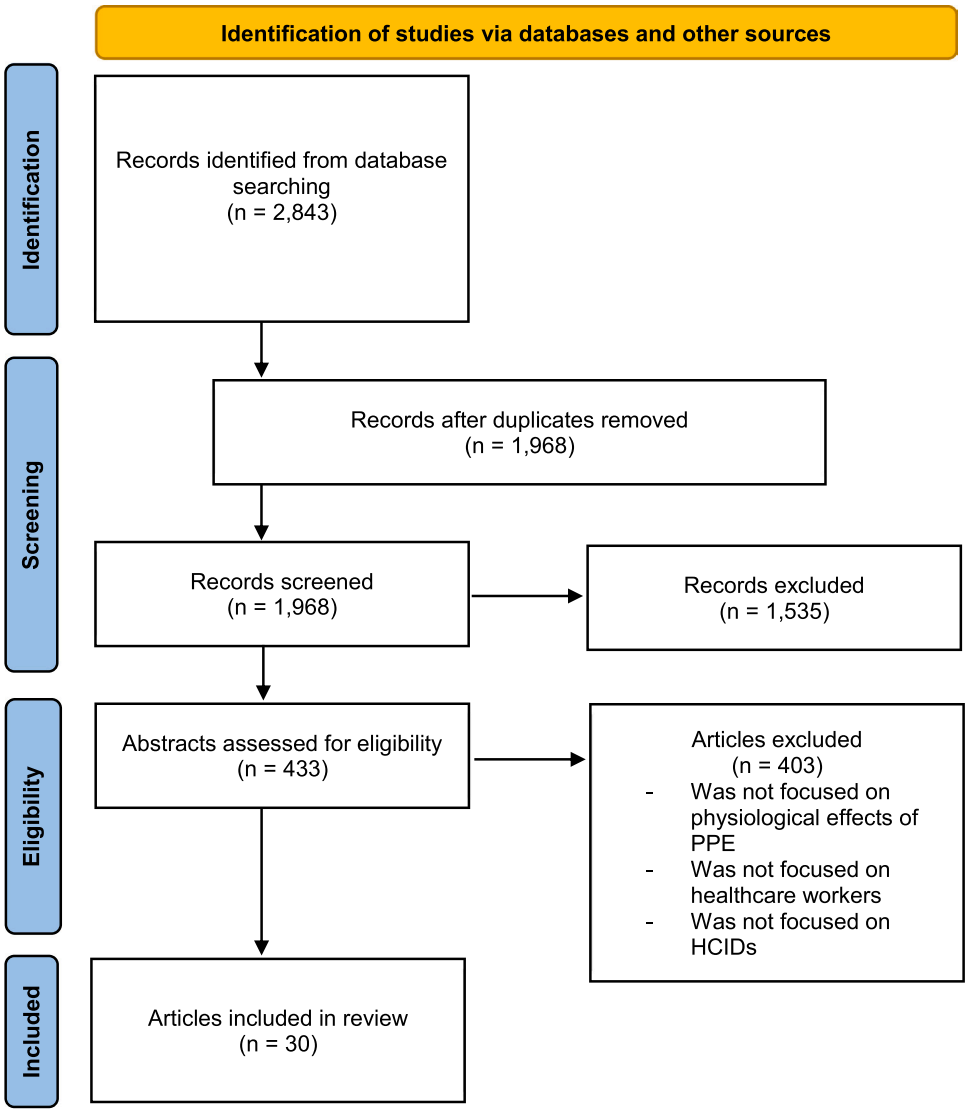

Fig. 1. PRISMA chart. Publications that were relevant to the physiological strain of personal protective equipment on personnel in the high-consequence infectious disease isolation environment. HCID, high-consequence infectious disease; PPE, personal protective equipment; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses.

loss) were the 2 most common issues for HCWs wearing PPE in field environments.[6,15–17] Studies conducted in controlled environments had participants performing tasks or exercising in a laboratory setting with temperature and humidity regulated to simulate the high-heat and high-humidity field-based working environments experienced in West Africa. The PPE ensembles discussed in the literature varied by name but generally consisted of a full-body Tyvek (DuPont), rubber boots, 2 layers of nitrile gloves, a full respirator hood with PAPR or N-95 level respirator with goggles or a face shield, along with any nuances utilized by each study, such as a rubber apron, a surgical cap, or an extra pair of gloves.[6,18,19] Six of the 13 articles conducted in austere or field-based conditions included a PPE ensemble with a surgical or isolation gown rather than a full-body Tyvek.

Higher core body temperatures were experienced during the hottest times of the day and were correlated to increased dehydration (weight loss) and increased perceived exertion of the HCWs.[6,15,16,19–22] Maynard and colleagues utilized the 15-point Borg Exertion scale to measure HCWs' perceived energy exertion during patient care in an EVD treatment unit in West Africa. Perceived exertion was highest for clinical activities during the middle of the day (11:00-14:59; 12 on the 15-point scale) and also the hours of highest temperatures, which coincided with a significant rate of weight loss per minute spent within the patient care area. In their study on 25 HCWs providing care in an EVD treatment unit in Guinea, Grelot and colleagues found limited thermal strain among HCWs performing treatment and care activities for approximately 1 hour in PPE, measured by core body temperature; however, they postured that the thermal strain resulting during a shift wearing PPE could potentially be predicted by the HCW's core body temperature before performing clinical tasks or before donning PPE.[6] Furthermore, Grelot and colleagues found no correlation between the increase in core body temperature and participant characteristics (body mass index (BMI), age, sex) or environmental factors (relative humidity, ambient temperature), but reported that female participants experienced lower rates of body mass loss and dehydration than the male study participants.[6] Goggles and face shields were reported to decrease the visibility of HCWs due to fogging from sweat and increased body temperature.[16,21,22] The decrease in visibility is directly related to an increased risk for both the treating

Table 1
Summary of literature

First author, year, country	Disease influencing PPE choice			PPE ensemble		Setting		Physiological impact		Cooling interventions		
	Ebola virus disease	COVID-19	Other	PAPR-level PPE	Particulate respirator-level PPE	Austere or field setting	Higher-resource clinical setting	Heat strain	Cognitive impairment	Cooling vest or body suit	Ice slurry or overhydration	Engineering or administrative controls
Bonell, 2021, The Gambia		X		X			X	X	X	X	X	
Bongers, 2021, Australia, Denmark, The Netherlands		X			X		X	X		X	X	X
Brown,[11] 2019, United States	X		X	X	X		X	X				
Brown,[12] 2019, United States	X			X	X	X	X	X				
Chang, 2017, United States						X*		X	X			
Coca, 2017, United States	X				X	X*		X				
Daanen, 2020, Australia, Austria, Denmark, Germany, Singapore, Switzerland, The Netherlands, United States		X		X	X	X	X	X			X	X
Davey, 2021, United Kingdom		X			X		X	X	X			X
De Korte, 2021, Denmark, The Netherlands		X			X		X	X		X		
Den Boon, 2018, West Africa	X				X	X		X				
Foster, 2020, United Kingdom		X		X	X		X	X		X	X	X
Grélot, 2016, Guinea	X				X	X		X				
Hancock, 2020, United States		X		Level not specified			X	X	X			X
Herstein, 2021, United States	X	X	X	X			X	X				
Jegodka, 2020, Germany		X		Level not specified			X	X	X	X	X	X
Kiiza, 2017, Canada	X				X	X*		X	X			
Lee, 2020, India, Singapore		X			X	X	X	X			X	
Lee, 2021, United States	X	X	X		X		X	X				
Loibner, 2019, Austria		X	X	X			X	X	X			
Lou, 2021, China		X			X		X	X				X
Maley, 2020, Australia, United Kingdom			X			X*		X		X	X	
Maynard, 2015, Sierra Leone	X				X	X		X				X
Messeri, 2021, Italy		X			X		X	X	X			
Parush, 2020, Israel, Portugal		X			X		X		X			
Potter, 2015, United States	X				X	X*		X		X		
Quinn,[13] 2018, United States	X				X	X*		X		X		
Quinn,[14] 2018, United States			X	X		X*		X	X			
Rojo-Rojo, 2022, Spain		X		X	X		X	X	X			
Ruskin, 2021, United States		X			X		X	X	X			X
Yuan, 2021, China		X			X		X	X				

NOTE. The table gives a review of PPE-focused literature organized by environment setting, physiological impact, and interventions.
PAPR, powered air purifying respirator; PPE, personal protective equipment.
*Simulated environment.

HCW as well as the patient due to potential exposure to pathogens and general safety issues associated with impaired vision, such as slipping, tripping, and potential falls for the HCW, as well as difficulty with performing clinical procedures and potential medication or documentation errors. In 2018, Den Boon and colleagues took the results from a PPE-focused survey of HCWs who had treated patients with EVD in West Africa to develop PPE rapid advice guidelines for HCWs deployed in emergency situations involving HCIDs, specifically EVD. These guidelines helped HCWs assess their environment and determine the best ensemble of PPE to use to mitigate heat stress and protect themselves from exposure to disease-causing pathogens. The importance of safety and protection was acknowledged in most of the literature, but few interventions were suggested to increase comfort for the HCWs. Of the articles included in this review, 14 addressed the need for cooling interventions or reduction in shift length to prevent heat illness and cognitive impairment. However, reducing the time spent in PPE and finding affordable cooling interventions are not always realistic for field operations.[4]

Higher-resource clinical settings

Of the 20 studies concentrated on high-resource clinical settings, 18 dealt with PPE involved in caring for patients with COVID-19 during the pandemic, with only 2 focusing on another high-consequence infectious disease such as EVD. Again, PPE ensembles were not referred to with consistent terms. The ensembles did consist of similar basic items such as a disposable fluid-repellent surgical gown, a face shield, gloves, and respiratory or facial splash protection (filtering facepiece respirators [e.g. N95] or surgical mask).[1,3,4,21–25] Only 7 articles reviewed the PAPR-level PPE ensemble within a higher resource setting.[1] Heat stress and discomfort in PPE within a clinical setting was a common experience across the literature. Cooling interventions within a controlled clinical ward, such as utilizing air conditioning to achieve lower temperatures than normal, cooling vests, and ingestion of ice slurries or other cold beverages prior to donning, were suggested because these interventions were more readily available and feasible in this setting.[4,21,22,26,27] Davey and colleagues stated that in a survey of UK HCWs within the National Health Service, almost 90% of the survey respondents felt very uncomfortable during their COVID-19 patient care shifts in PPE, with about 76% of respondents sharing that PPE compromised their physical and attentional performance during patient care. HCWs requested that hospital policy be updated regarding time spent in PPE and improving administrative controls, such as hydration breaks or strategies.[21] Many other survey-based studies produced similar results, with most HCWs agreeing that PPE reduces the evaporation of sweat and leads to a decrease in physical performance during patient care.[21,28–30]

Physiological impact

We found a shared concern among reviewed articles that HCWs wearing PPE while caring for patients with HCIDs will experience heat strain to the point of physical and cognitive exhaustion that jeopardizes the safety of both the HCW and the patient.[4,5,21,23,31] Whether the HCW experiences physical or cognitive impairment or both, the increased chance of making a decision that increases the risks to both the HCW and the patient for infection or injury is enough for requiring improvement in PPE ensembles and administrative and engineering controls. In the following sections, we describe the physical and cognitive impairments resulting from heat strain described in the literature.

Heat strain

Although the impermeability of PPE is often perceived as critical for the protection and safety of HCWs, it exacerbates heat strain by preventing sweat from adequately evaporating and cooling the core body temperature.[3–5,8,15,19,21,30] When heat cannot evaporate away from the body properly, the individual in PPE can experience muscle fatigue, exhaustion, and/or dehydration, which can severely impact their ability to safely care for their patient.[4] Excessive sweating combined with respirators and face shields, or goggles, can negatively impact breathing, vision, and communication of the HCW with patients and coworkers, which can intensify the onset and severity of heat strain if PPE is not removed. However, the removal of PPE during a shift due to feeling hot and uncomfortable may increase the risk of infection.[8,23] If not prevented or improved with timely intervention, heat strain can lead to impaired cognitive functioning and a decreased level of safety.

Heat strain is investigated in studies by measuring core body temperatures through either an ingestible sensor or a rectal thermometer, heart rate, skin temperature, breathing rate, dehydration measured by weight loss, and HCW perceived exertion.[1,3,6,13] Quinn and colleagues recently conducted a study investigating the role of trunk posture in monitoring the heat strain during the working shift and found that there is a relation between trunk posture and core body temperature. The authors suggest that visual examination of trunk posture during shifts could give insight into reducing the level of heat strain experienced.[14] Although not every article found the impact of heat strain of PPE on HCWs to be statistically significant, a majority of the literature found HCW's perception of heat and exertion to be increased while wearing PPE in all settings but not in all PPE ensembles. The measured factors of heat strain (i.e. core body temperature, heart rate, weight loss, etc.) varied in results on the significant impact of heat strain on HCWs, which suggests that further study is necessary to continue to determine the ultimate physiological effect of PPE on HCWs and the resulting heat strain.[5,6,13–16,18–24,30–33] Reduction in shift time, cooling vests, or ingesting ice slurries are examples of interventions to combat overheating and increase the comfortability of working in PPE; however, none are a fix-all and come with limitations.[4,14,22]

Cognitive impairment

Excessive heat from working in PPE can not only cause heat strain but also contribute to cognitive impairments that can severely inhibit the HCW's ability to make necessary decisions and safely care for patients.[4,25] Heat strain has been seen to impact risk perception of decision-making and may increase risky behaviors that could lead to avoidable accidents and injuries in patient care.[8,32] Any decrease in psychomotor vigilance of a HCW, which may also be impacted by fogged face shields or goggles, can create a potentially hazardous environment within the patient care room; if a HCW cannot respond to visual stimuli in a timely manner, the safety of both the HCW and the patient is at risk.[1,25] Speech intelligibility can also be affected and can be experienced through slurred words or the inability to comprehend instructions given by fellow HCWs or even the patient. These variables of cognitive impairment can together cause a degradation of situational awareness and increase the possibility of a HCW's mistakes or errors.[1,8,23,25] Hancock demonstrated that self-monitored vigilance might be most susceptible to heat strain, followed by dual-task performance and psychomotor performance.[4] Cognitive impairment from heat strain caused by wearing PPE can lead to mistakes in doffing PPE due to exhaustion, reduced dexterity, and/or decreased psychomotor vigilance and may lead to errors that could potentially expose HCWs to the HCID the PPE was protecting

them from.[3,8,23] Once again, cooling methods and interventions must be properly implemented to decrease cognitive impairment and avoid risky decision-making and errors in the patient care room.

Cooling interventions

There are several cooling methods that have been suggested throughout the literature, but the most appropriate cooling intervention may not always be realistic for the environment.[4,26] Cooling vests are a wearable technology that utilizes ice or a non-ice cooling method that HCWs can wear before, during, or after their shift to reduce heat.[34] Although this option may work well in a higher resource setting, it may not be feasible in a field or austere environment due to the need of a freezer or refrigerator to keep the vests cold; it may also become a burden if the vest does not stay cool for the duration of the shift and once the cooling impact is depleted, it becomes an added weight that increases the level of heat.[31,32] The environment and feasibility should also be considered with a water-perfused suit as well because it adds a significant amount of additional weight to carry.

Pre-cooling before a shift is typically done by ingesting an ice slurry or ice slushy that both hydrates and lowers the core body temperature prior to donning PPE and performing patient care.[26,35] Other options to reduce the impact of heat on HCWs are to implement engineering and administrative controls that lower the ambient working temperature, decrease the amount of time spent in PPE by cutting shift hours, or include small wearable devices to monitor the vitals of HCWs.[4,23,36] PPE and respirator matrices may be helpful in determining the lightest weight of PPE needed to keep HCWs comfortable while still protecting them.[11,12] It may be beneficial to consider cooling innovations or interventions utilized by other industries, such as those who wear bulletproof vests, stab-resistant armor, or any of the industries analyzed by the HEATSHIELD project. Many of the recommendations include utilizing cooling vests (while acknowledging the shortcomings) and improving engineering and administrative controls to allow for lighter clothing, cooler ambient temperatures, and more frequent hydration breaks.[9,37,38] The recent COVID-19 pandemic further highlights the need for new innovations and interventions to allow for cooler, more comfortable PPE for HCWs who care for patients with HCIDs.[4,39] Additionally, it is clear that innovation and development of new PPE that provide the same level of protection while reducing physiological strain is needed.

DISCUSSION

The literature shows that heat strain often impacts HCWs who care for patients within HCID environments while wearing varying ensembles of PPE. Of the studies included in this review, 18 articles mentioned COVID-19 being the disease of focus for determining the level of PPE to be used by HCWs. The authors acknowledge that COVID-19 is no longer considered a special or emerging pathogen in most nations; however, the initial COVID-19 response was bolstered in many US hospitals with emerging special pathogen programs by safely caring for the initial cases while the hospital prepared full units to provide the necessary isolation care with more typical transmission-based airborne and contact precautions.[40] Biocontainment patient care has been, from its beginnings, focused on reducing the impact of outbreaks and pandemics by early response to prevent the spread of outbreaks or to bolster HCWs voluntarily entering outbreak zones with the knowledge that they could be repatriated for care.[41] The safety of HCWs and patients during the whole of the COVID-19 pandemic, and especially in the beginning stages with so many unknowns of the emerging pathogen, has been sustained through the use of PPE. Supply chain issues became a major issue as manufacturers could not keep up with the high demand for PPE ensemble components. Although the supply chain has improved over time, it remains vulnerable if cases of respiratory illness or another emerging pathogen would spike again.

Impaired safety due to risky decision-making and physical exhaustion impacted by heat strain is detrimental to the safety of both HCWs and patients under care. Selecting or developing PPE that allows heat to evaporate off the body but still protects HCWs from infection can be difficult; however, there are other ways to support HCWs to mitigate heat strain that do not involve PPE. Special support considerations for HCWs, such as meal support during breaks or before and after shifts, lightweight undergarments, and overhydrating before shifts with cold electrolyte drinks and water as a form of hyperhydration strategy, can help improve the physical and cognitive readiness for the care environment and reduce the impact of heat strain on HCWs while caring for HCID patients. It is also ideal to implement limits on time spent in PPE, decreasing the shift length, which may require greater staffing for care teams or more frequent shift changes. Cooling vests and cooling suits offer a potential heat stress mitigation measure, but once the cooling material is no longer cold, HCWs carrying the extra weight of the cooling apparatus will produce extra heat for the remainder of their shift. If shifts are short, cooling vests may be ideal in environments in which they are available.

Another important aspect to consider is the level or amount of education HCWs receive on the PPE in which they will be expected to perform patient care, including how to identify their own symptoms of heat stress and cognitive impairment before they become critical. A higher level of education and knowledge of PPE donning and doffing procedures and selection matrices based on disease and exposure risks may reduce incorrect donning of PPE that can lead to higher levels of heat strain and increase awareness of when and how to safely doff PPE when heat strain is hindering safe patient care. Industry-wide studies of the effects of heat have long included firefighters, landscapers, police officers, and construction workers; however, HCWs are severely underrepresented and understudied in this area. HCWs are on duty daily to treat and care for ill patients around the world, yet they are rarely included in reputable studies that address the effects of heat on the physical and cognitive abilities to safely perform patient care in all environments, not just those involving HCIDs. Scenario-based studies focusing on the HCWs performing patient care tasks in PPE and the resulting heat strain would be ideal to better identify best practices and ensembles. Even without inclusion in previous studies, it may still be beneficial to utilize the results and identify ways to implement the considerations based on other industries for HCWs who wear PPE in HCID environments.

Prioritizing the investments in developing new PPE or reconfiguration of existing PPE ensembles that improve upon safety and comfort in the short term presents a difficult challenge. As noted above, available options to mitigate heat stress (such as cooling vests) all come with trade-offs in safety, cost, and practicality. In the meantime, and when possible, leaders in HCID response may be better served by focusing on engineering solutions—particularly climate mitigation or control measures to create more hospitable ambient environmental temperature and humidity to lower heat stress and increase HCW endurance. These engineering controls have the added benefit of reducing the heat stress on patients who may have difficulty with temperature regulation in acute illness and may offer lower overall costs compared to other interventions.

The resources available in the environments of care where HCWs are caring for HCID patients vary considerably and are not always consistently supplied. Higher-resource settings have an advantage of better accessibility to the necessary components of PPE to fit the

ensemble needed for the HCID in question; lower-resource or field-based settings may be severely limited as to what is available to compose a PPE ensemble that meets a necessary standard of safety and protection for the HCWs. The studies included in this review mention the utilization of PPE selection matrices and the evaluation of common ensembles, but nothing addresses adaptation to situations or environments in which resources are limited but the risk is high. For example, an austere HCID situation with extremely limited resources may result in HCWs having to utilize garbage bags instead of surgical isolation gowns for their PPE ensemble.[42] Although addressing the possibility of a potential event such as this is beyond the scope of this paper, further study on these potentially extreme events, whether in a high-resource environment or lower-resource, is warranted because heat strain could be further exacerbated due to lack of proper PPE.

LIMITATIONS

This study is not without limitations. First, this was not a formal, registered systematic literature review, so there was not a library scientist on the team to help navigate the literature. Consistent terms referring to clinical settings, both austere and higher resource, were not found or used. Similarly, PPE ensembles of different levels did not have consistency in names or references across the literature. It should also be noted that studies that were survey-based did not utilize a standardized survey or formatted scale for perceived exertion and heat, nor were core body temperatures measured with the same tools or technology. These limitations could be the cause of variation in findings. Standardization of names of PPE ensembles and clinical settings, as well as using standardized tools for measuring body temperature and perceived exertion, could help reduce discrepancies in future studies. This study was also subject to the limitations of available literature.

CONCLUSIONS

PPE, although necessary for the protection of HCWs while treating patients with HCIDs, limits the body's natural physiological cooling processes and can induce heat strain and cognitive impairment, and create potentially dangerous environments. Cooling interventions can help improve comfort and push back the onset of heat strain, but not all methods are realistic depending on the clinical setting. For this reason, innovation is needed in the engineering of PPE to create PPE and PPE ensembles that allow physiological cooling processes to take place while still having an impermeable barrier to infectious fluids or droplets. For example, improving respiratory protection to allow for a full view of the face for speech intelligibility would help reduce miscommunication in the patient care environment, or implementing special support for teams working in these HCID environments so that they have access to rest breaks, nutritional support, and trained observers if needed. Although HCWs have not been included in mass-industry studies of the effects of heat, such as the HEAT-SHIELD Project, intervention recommendations to other workers may be applicable to HCWs and PPE-induced heat strain. It is also true that engineering solutions for climate mitigation in HCID treatment units may be a practical and rapid solution to reduce heat stress among HCWs and patients. It is necessary for further studies to focus on HCWs and the burden of PPE while caring for patients with HCID, as the current paucity of information in the available literature falls short of the needed innovations and improvements.

References

1. Loibner M, Hagauer S, Schwantzer G, Berghold A, Zatloukal K. Limiting factors for wearing personal protective equipment (PPE) in a health care environment evaluated in a randomised study. *PloS One.* 2019;14:e0210775.
2. Beam EL, Schwedhelm S, Boulter K, et al. Personal protective equipment processes and rationale for the Nebraska Biocontainment Unit during the 2014 activations for Ebola virus disease. *Am J Infect Control.* 2016;44:340–342.
3. Herstein JJ, Abdoulaye AA, Jelden KC, et al. A pilot study of core body temperatures in healthcare workers wearing personal protective equipment in a high-level isolation unit. *J Occup Environ Hyg.* 2021;18:430.
4. Foster J, Hodder SG, Goodwin J, Havenith G. Occupational heat stress and practical cooling solutions for healthcare and industry workers during the COVID-19 pandemic. *Ann Work Expo Health.* 2020;64:915–922.
5. Hancock PA. Specifying and mitigating thermal stress effects on cognition during personal protective equipment use. *Hum Factors.* 2020;62:697–703.
6. Grélot L, Koulibaly F, Maugey N, et al. Moderate thermal strain in healthcare workers wearing personal protective equipment during treatment and care activities in the context of the 2014 Ebola virus disease outbreak. *J Infect Dis.* 2016;213:1462–1465.
7. Chang C, Bernard TE, Logan J. Effects of heat stress on risk perceptions and risk taking. *Appl Ergon.* 2017;62:150–157.
8. Ruskin KJ, Ruskin AC, Musselman BT, Harvey JR, Nesthus TE, Connor M. COVID-19, personal protective equipment, and human performance. *Anesthesiology.* 2021;134:518–525.
9. Integrated inter-sector framework to increase the thermal resilience of European workers in the context of global warming. CORDIS EU. Published July 28, 2021, Accessed on November 17, 2021. https://cordis.europa.eu/project/id/668786.
10. Brearley MB, Heaney MF, Norton IN. Physiological responses of medical team members to a simulated emergency in tropical field conditions. *Prehosp Disaster Med.* 2013;28:139–144.
11. Brown CK. Respiratory protection against emerging infectious diseases: face masks, respirators, and tools for choosing between them. *Health Secur.* 2019;17:133–139.
12. Brown CK, Matthews DL, Thomas RJ, Edens AL. Developing a personal protective equipment selection matrix for preventing occupational exposure to Ebola virus. *Health Secur.* 2019;17:213–228.
13. Quinn T, Kim J, Seo Y, Coca A. Comparison of thermal manikin modeling and human subjects' response during use of cooling devices under personal protective ensembles in the heat. *Prehosp Disaster Med.* 2018;33:279–287.
14. Quinn TD, Seo Y, Yorio PL, et al. Using trunk posture to monitor heat strain at work. *Ergonomics.* 2018;61:1560–1568.
15. Maynard SL, Kao R, Craig DG. Impact of personal protective equipment on clinical output and perceived exertion. *J R Army Med Corps.* 2015;162:180.
16. Den Boon S, Vallenas C, Norris SL. Incorporating health workers' perspectives into a WHO guideline on personal protective equipment developed during an Ebola virus disease outbreak [version 2; referees: 2 approved]. *F1000Research.* 2018;7:45. https://doi.org/10.12688/f1000research.12922.2 Published 2018 Jan 11.
17. Potter AW, Gonzalez JA, Xu X. Ebola response: modeling the risk of heat stress from personal protective clothing. *PLoS ONE.* 2015;10:e0143461.
18. Guidance on personal protective equipment (PPE). Centers for Disease Control and Prevention. Published August 30, 2018, Accessed September 23, 2021. https://www.cdc.gov/vhf/ebola/healthcare-us/ppe/guidance.html.
19. Coca A, Quinn T, Kim J, et al. Physiological evaluation of personal protective ensembles recommended for use in West Africa. *Disaster Med Pub Health Prep.* 2017;11:580–586.
20. Kiiza P, Mullin SI, Teo K, et al. Establishing healthcare worker performance and safety in providing critical care for patients in a simulated Ebola treatment unit: non-randomized pilot study. *Viruses.* 2021;13:2205.
21. Lee J, Venugopal V, Latha PK, et al. Heat stress and thermal perception amongst healthcare workers during the COVID-19 pandemic in India and Singapore. *IJERPH.* 2020;17(21):8100. https://doi.org/10.3390/ijerph17218100 Published 2020 Nov 3.
22. Daanen H, Bose-O'reilly S, Brearley M, et al. COVID-19 and thermoregulation-related problems: practical recommendations. *Temperature.* 2020;8:1.
23. Davey SL, Lee BJ, Robbins T, Randeva H, Thake CD. Heat stress and PPE during COVID-19: impact on healthcare workers' performance, safety and well-being in NHS settings. *J Hosp Infect.* 2021;108:185–188.
24. Lee Y, Salahuddin M, Gibson-Young L, Oliver GD. Assessing personal protective equipment needs for healthcare workers. *Health Sci Rep.* 2021;4:e370.
25. Parush A, Wacht O, Gomes R, Frenkel A. Human factor considerations in using personal protective equipment in the COVID-19 pandemic context: binational survey study. *J Med Internet Res.* 2020;22(6):e19947. https://doi.org/10.2196/19947 Published 2020 Jun 17.
26. Maley MJ, Minett GM, Bach AJE, Stewart KL, Stewart IB. Extending work tolerance time in the heat in protective ensembles with pre- and per-cooling methods. *Appl Ergon.* 2020;85:103064.
27. Bongers CC, De Korte JQ, Catoire M, et al. Infographic. cooling strategies to attenuate PPE-induced heat strain during the COVID-19 pandemic. *Br J Sports Med.* 2021;55:69.
28. Messeri A, Bonafede M, Pietrafesa E, et al. A web survey to evaluate the thermal stress associated with personal protective equipment among healthcare workers during the COVID-19 pandemic in Italy. *IJERPH.* 2021;18(8):3861. https://doi.org/10.3390/ijerph18083861 Published 2021 Apr 7.

29. Jegodka Y, Lagally L, Mertes H, et al. Hot days and covid-19: online survey of nurses and nursing assistants to assess occupational heat stress in Germany during summer 2020. *J Clim Change Health.* 2021;3:100031.
30. Rojo-Rojo A, Pujalte-Jesús MJ, Hernández-Sánchez E, et al. Risk of dehydration due to sweating while wearing personal 2 protective equipment in COVID-19 clinical care: a pilot study. *Healthcare.* 2022;10(2):267. https://doi.org/10.3390/healthcare10020267 Published 2022 Jan 29.
31. Yuan N, Yang W, Lu J, Lv Z. Investigation of adverse reactions in healthcare personnel working in level 3 barrier protection PPE to treat COVID-19. *Postgrad Med J.* 2021;97:351–354.
32. Chang C, Bernard TE, Logan J. Effects of heat stress on risk perceptions and risk taking. *Appl Ergon.* 2017;62:150–157.
33. Grahn D, Makam M, Craig Heller H. A method to reduce heat strain while clad in encapsulating outerwear. *J Occup Environ Hyg.* 2018;15:573–579.
34. De Korte JQ, Bongers CCWG, Coen CWG, Catoire M, Kingma BRM, Eijsvogels TMH. Cooling vests alleviate perceptual heat strain perceived by COVID-19 nurses. *Temperature.* 2021;9(1):103–113. https://doi.org/10.1080/23328940.2020.1868386 Published 2021 Jan 20.
35. Bonell A, Nadjm B, Samateh T, et al. Impact of personal cooling on performance, comfort and heat strain of healthcare workers in PPE, a study from West Africa. *Front Pub Health.* 2021;9:712481.
36. Basodan RAM, Park B, Chung H. Smart personal protective equipment (PPE): current PPE needs, opportunities for nanotechnology and e-textiles. *Flex Print Electron.* 2021;6.
37. Lehmacher EJ, Jansing P, Küpper T. Thermophysiological responses caused by ballistic bullet-proof vests. *Ann Occup Hyg.* 2007;51:91–96.
38. Yuan M, Wei Y, An Q, Yang J. Effects of a liquid cooling vest on physiological and perceptual responses while wearing stab-resistant body armor in a hot environment. *Int J Occup Saf Ergon.* 2022;28(2):1025–1032. https://doi.org/10.1080/10803548.2020.1858618
39. Lou L, Chen K, Fan J. Advanced materials for personal thermal and moisture management of health care workers wearing PPE. *Mater Sci Eng R Rep: Rev J.* 2021;146:100639.
40. Vasa A, Pacino V, Vasistha S, ElRayes W, Lowe JJ. Covid-19 response among US hospitals with emerging special pathogen programs. *Health Secur.* 2022;20(S1):S31–S38. https://doi.org/10.1089/hs.2021.0193
41. Beam EL, Boulter KC, Freihaut F, Schwedhelm S, Smith PW. The Nebraska experience in biocontainment patient care. *Pub Health Nurs.* 2010;27:140–147.
42. Abramowitz SA, McLean KE, McKune SL, et al. Community-centered responses to Ebola in Urban Liberia: the view from below. *PLOS Negl Trop Dis.* 2015;9(4):e0003706. https://doi.org/10.1371/journal.pntd.0003706 Published 2015 Apr 9.