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REVIEW

Extreme Heat and Adverse Cardiovascular Outcomes in Australia and New Zealand: What Do We Know?

Georgia K. Chaseling, PhD [a,b,*,§], Nathan B. Morris, PhD [c,§], Nicholas Ravanelli, PhD [d,§]

[a]Engagement and Co-design Research Hub, School of Health Sciences, Faculty of Medicine and Health, The University of Sydney, Sydney, NSW, Australia
[b]SOLVE-CHD NHMRC Synergy Grant, School of Health Sciences, Faculty of Medicine and Health, The University of Sydney, Sydney, NSW, Australia
[c]Department of Human Physiology & Nutrition, University of Colorado, Colorado Springs, CO, USA
[d]School of Kinesiology, Lakehead University, Thunder Bay, ON, Canada

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Extreme heat events are a leading natural hazard risk to human health. Under all future climate change models, extreme heat events will continue to increase in frequency, duration, and intensity. Evidence from previous extreme heat events across the globe demonstrates that adverse cardiovascular events are the leading cause of morbidity and mortality, particularly amongst the elderly and those with pre-existing cardiovascular disease. However, less is understood about the adverse effects of extreme heat amongst specific cardiovascular diseases (i.e., heart failure, dysrhythmias) and demographics (sex, ethnicity, age) within Australia and New Zealand. Furthermore, although Australia has implemented regional and state heat warning systems, most personal heat–health protective advice available in public health policy documents is either insufficient, not grounded in scientific evidence, and/or does not consider clinical factors such as age or co-morbidities. Dissemination of evidence-based recommendations and enhancing community resilience to extreme heat disasters within Australia and New Zealand should be an area of critical focus to reduce the burden and negative health effects associated with extreme heat. This narrative review will focus on five key areas in relation to extreme heat events within Australia and New Zealand: 1) the potential physiological mechanisms that cause adverse cardiovascular outcomes during extreme heat events; 2) how big is the problem within Australia and New Zealand?; 3) what the heat–health response plans are; 4) research knowledge and translation; and, 5) knowledge gaps and areas for future research.

Keywords Heatwaves • Cardiovascular disease • Telehealth • Climate change • Ischaemic heart disease • Heat–health

Introduction

Extreme heat is a major natural hazard risk to human health [1]. Under all future climate change prediction models, extreme heat events will continue to become more frequent and intense [2]. In Australia, extreme heat events cause more deaths than all other natural disasters combined [1], with the effects of heat disproportionately impacting those living with low income, the elderly, and people with pre-existing medical conditions [3]. Paralleled with a growing and ageing Australian [4] and New Zealand [5] population, with a distinct increase in urbanisation [1], there is an insidious challenge of protecting the most vulnerable against the negative health effects of extreme heat.

Data generated from extreme heat disasters within Europe [6] and North America [7] demonstrate that the direct effects

*Corresponding author at: University of Sydney, Susan Wakil Health Building, Western Ave, Camperdown, NSW, 2050, Australia; Email: georgia.chaseling@sydney.edu.au; Twitter: @georgiakatec
§co-first authors.

of heat (e.g., heat stroke and dehydration), are not the main cause of morbidity and mortality. Instead, a common cause of death is cardiovascular in nature, often due to myocardial infarction [8], or ischaemic heart disease (IHD) [9], particularly in older adults and adults with pre-existing cardiovascular disease (CVD) [7]. Within Australia, some evidence exists for the effects of extreme heat on adverse cardiovascular outcomes [8,10–20]. In New Zealand, however, there is an alarming paucity of data that details the effects of extreme heat on morbidity and mortality [21] and New Zealand lacks scientifically backed, extreme heat risk management frameworks. Within Australia, heat warning systems have been developed by the Bureau of Meteorology (BoM), however, much of the individual heat–health advice publicly available is generic, not grounded by scientific evidence [22], and is not curated for specific 'at risk' populations, such as people with CVD. Because the projections of heat-related morbidity and mortality will depend on human adaptability, and our ability to provide adequate care [3], there is an urgent need to comprehensively understand vulnerability to extreme heat disasters amongst specific populations in Australia and New Zealand, and develop and disseminate scientifically supported public policy advice to mitigate the adverse health outcomes of extreme heat for vulnerable populations.

Accordingly, this review will provide a summary on key areas relating to extreme heat events and adverse cardiovascular outcomes in Australia and New Zealand. We will describe potential physiological mechanisms that predispose an individual to adverse cardiovascular events and our current understanding of negative cardiovascular outcomes associated with extreme heat exposure. We will discuss the current heat response plans and how we can effectively work towards knowledge translation. Lastly, we will discuss the gaps in knowledge and areas for future research. We aim to update the reader on the present state of knowledge in this area and call on researchers to address the areas that need greater attention.

What Are Potential Physiological Mechanisms That Cause Adverse Cardiovascular Outcomes During Extreme Heat Events?

Cardiovascular Response to Heat Exposure

Previous research has discussed the cardiovascular responses to heat exposure in young and older healthy [23,24] adults and older adults with CVD [24]. We will briefly describe these responses below. It is important to consider that while heat stroke undoubtedly leads to cardiovascular challenges, heat stroke does not account for most morbidity and mortality during extreme heat events. Instead, an increase in adverse cardiovascular events, in the absence of heat stroke are commonly reported. The effects of heat stroke on cardiovascular failure have been reviewed in detail elsewhere [25], and will not be discussed in this review.

Heat exposure elicits an increase in core and skin temperature which stimulates cutaneous vasodilation and sweating to promote heat loss from the body to the environment. An increased cutaneous vasodilation results in reduced peripheral vascular resistance whereas sweating that is not compensated by fluid intake reduces central blood volume. These responses lead to an increase in cardiac output of 7–8 L/min with mild to moderate increases in core temperature (~37.5–38.0°C) but can reach 10–13 L/min with greater increases in core temperature (≥38.5°C) [26]. This increase in cardiac output is mostly met through an increase in heart rate as stroke volume remains relatively stable during passive heat exposure. In older adults (60–80 yrs), this increase in cardiac output with heat exposure is blunted by ~50% [26], which is predominantly attributed to a blunted heart rate response as stroke volume remains relatively stable during passive heat exposure [26].

Research investigating the influence of CVD on the cardiovascular response to heat exposure is severely lacking and has predominantly been conducted in heart failure patients. Heart failure patients have reduced cutaneous vasodilation compared to age-matched healthy controls during heat exposure [27,28]. Heart rate mostly [27,29], though not always [28], increases to the same extent as age-matched healthy controls during heat exposure, suggesting this blunted cutaneous vasodilation is unlikely due to chronotropic incompetence. Beyond this, only one study (to our knowledge) has examined the impact of heat exposure on IHD patients [30], demonstrating a greater core temperature (~0.2°C) and heart rate (~5 beats/min) at the end of a 3-hour exposure to a warm environment (between 25°C and 29°C), compared to a control condition (between 20°C and 24°C).

Extreme Heat and Myocardial Ischaemia

An understanding of potential pathophysiological mechanisms that predispose a person to adverse cardiovascular events is needed. A recent review published by our research group provides an in-depth outline on some potential physiological mechanisms that increase this risk [24].

The heart is an aerobic organ, whose metabolism relies almost exclusively on the oxidation of substrates for energy generation [31]. Oxygen consumption of the heart's muscle, the myocardium, is determined by the intraparietal pressure of the ventricle, contractility of the myocardium and heart rate [31]. Exposure to hot environments results in an increased heart rate and contractility, and should therefore increase myocardial oxygen consumption. At rest, oxygen extraction of the left ventricle is ~60–80%, reducing its ability to increase myocardial metabolism due to the limited capacity to increase oxygen extraction [32]. Therefore, increases in myocardial metabolism mainly depend on a proportional increase in coronary blood flow to increase oxygen supply to the cardiomyocytes. Coronary blood flow depends on the perfusion pressure gradient and the vasomotor properties of the coronary arterioles [33]. Considering the dilation capacity of the coronary arteries is impaired in people with IHD, insufficient vasodilation could limit the increase in myocardial blood flow that is required to sustain the greater metabolic need of the myocardium during exposure to a hot environment. If so, insufficient myocardial blood flow could lead to myocardial ischaemia, a trigger for cardiovascular events such as arrhythmia or myocardial infarction. However, the extent to which myocardial blood flow increases during heat exposure for people with CVD is unknown.

Extreme Heat and Inflammation

Chronic heat exposure may induce an inflammatory response that predisposes a hypercoagulable state, increasing the risk of thrombosis [34]. Some studies have shown that moderate increases in core temperature (∼38–38.5°C) during hot water immersion elicits an increase in systemic circulating concentrations of interleukin 6 and increases neutrophil counts [35,36]. The few human studies investigating haemostasis in response to mild/moderate increases in core temperature report mixed findings. Some studies employing hot water immersion (core temperature ∼38°C) have observed minimal activation of coagulation [37], whereas another study using the water-perfused suit model (core temperature 37.5–38°C) observed evidence that heat exposure activates the coagulation system through a decrease in time to initial fibrin formation and activated partial thromboplastin time [38]. Importantly, evidence regarding inflammatory and haemostatic responses to heat exposure comes from young healthy adults. It remains unknown how mild to moderate levels of hyperthermia affect inflammatory and/or haemostatic responses in older adults with or without CVD.

How Big is the Problem in Australia and New Zealand?

Extreme Heat and Cardiovascular Outcomes in Australia

To perform an analysis on the effects of extreme heat on adverse cardiovascular outcomes, the existing literature was searched in PubMed to capture the risks associated with morbidity and mortality in Australia. Studies were excluded if they did not report a relative risk or percentage change in morbidity or mortality, and if they did not include CVD as an outcome measure. In total, 18 studies were included (Table 1) that demonstrate an increased risk in adverse cardiovascular events with extreme heat; 11 studies demonstrate the effect of hot weather on adverse cardiovascular morbidity (five studies) and mortality (six studies) using a multi-year analysis. Seven (7) studies demonstrate, retrospectively, the effect of specific historical extreme heat events on cardiovascular morbidity and mortality. Specific findings showed a greater risk of hospital admissions [8,39,42], and death [45,46] for IHD and acute myocardial infarction, and people with pre-existing heart conditions have an increased risk of adverse cardiovascular events [52].

First Nations Australian peoples have a greater incidence of chronic disease compared to non-Indigenous Australians. For example, IHD and heart failure are 2.1 and 1.7 times more prevalent, respectively, amongst First Nations Australians compared to non-Indigenous Australian people [53]. This increased disease risk potentially increases the relative risk of adverse cardiovascular outcomes during extreme heat events [42] in addition to climate change exacerbating the current economic, social and medical inequalities already faced by First Nations Australians [18]. To date, only one study has reported First Nations Australians having a 17% increased risk of IHD morbidity at temperatures >35°C [42].

Extreme Heat and Cardiovascular Outcomes in New Zealand

The Intergovernmental Panel on Climate Change have now declared it is 'virtually certain' New Zealand will experience more frequent heat extremes [54], yet New Zealand still lacks a formal definition of extreme heat. In fact, the only known definition of extreme heat in New Zealand provided by the National Institute of Water and Atmosphere (NIWA), defines a 'hot day' when temperatures equal or exceed 25°C [21]. Problematically, this definition stems from the idea that beef and dairy cattle experience heat stress at or above this 25°C threshold and ignores any importance for the impact of heat on human health. Furthermore, despite New Zealand public health agencies acknowledging the heat–health risks associated with extreme heat [55], very little evidence exists demonstrating the increased risk of morbidity and mortality within New Zealand. In fact, research has only demonstrated an increase in adverse cardiovascular events in New Zealand during colder months [56–58] and these studies were all conducted prior to 2012. Māori peoples also have a disproportionally greater prevalence of IHD [59] and are 1.5 times more likely to be hospitalised for CVD causes [60] compared to non-Indigenous New Zealanders. However, to the best of our knowledge, no evidence exists whatsoever demonstrating negative cardiovascular outcomes for Māori peoples during extreme heat events. Overall, the lack of data regarding mortality and morbidity during defined "hot days" in New Zealand suggests that while there is currently no strong evidence linking extreme heat with adverse cardiovascular outcomes, we have no idea how future extreme heat events will impact the health of their vulnerable populations at all.

What Are the Current Heat–Health Response Plans?

Heat response plans and strategies act as a first line of defence to prepare and protect communities against the negative health effects of extreme heat. New Zealand

Table 1 Studies reporting cardiovascular related hospital admissions and mortality associated with heat over several years or during a specific extreme heat event in Australia.

Author/ Year	State/City	Time Point	Disease Outcome	Age	Findings
Multi-Year Analysis of Heat Effects on Hospital Admissions					
Nitschke, 2007 [39]	Adelaide	1993-2006	IHD	65-74 y	↑ IHD hospital admissions
				75+ y	↓ IHD hospital admissions
Loughnnan, 2010 [8]	Melbourne	1999-2004	AMI	All ages	↑ AMI hospital admissions
Khalaj, 2010 [40]	NSW	1998-2006	CVD	All ages	↑ CVD hospital admissions
Vaneckova, 2013 [41]	Sydney	1991-2006	CVD	All ages	↑ CVD hospital admissions
Webb, 2014 [42]	Northern Territory	1992-2011	IHD	All ages	↑ IHD hospital admissions ↓ Heart failure hospital admissions
Multi-Year Analysis of Heat Effects on Mortality					
Vaneckova, 2008 [10]	Sydney	1993-2001	CVD	65+ y	↑ Cardiovascular mortality
Yu, 2011 [43]	Brisbane	1996-2004	CVD	All ages	↑ Cardiovascular mortality
Yu, 2011 [44]	Brisbane	1996-2004	CVD	All ages	↑ Cardiovascular mortality
Wilson, 2013 [45]	Sydney	1997-2007	IHD	All ages	↑ Cardiovascular mortality
Doan, 2020 [13]	Brisbane	2007-2019	Cardiac arrest	All ages	↑ Out of hospital cardiac arrests
Cheng, 2021 [46]	Queensland	2013-2015	AMI	All ages	↑ AMI mortality
Effects of Specific Historical Extreme Heat Events					
Mayner, 2010 [47]	Adelaide	2009	CVD	All ages	↔ Cardiovascular emergency department visits
Tong, 2010 [48]	Brisbane	2004	CVD	All ages	↑ Cardiovascular mortality
Nitschke, 2011 [49]	Adelaide	2008	CVD	15-75 y	↑ Cardiovascular hospital admissions
Nitschke, 2011 [49]	Adelaide	2009	IHD	15-64 y	↑ IHD hospital admissions
Wang, 2012 [50]	Brisbane	2000, 2001, 2004	CVD	All ages	↑ Cardiovascular mortality
Herbst, 2014 [51]	Adelaide	2009	CVD	All ages	↑ Mortality with pre-existing IHD, cardiomegaly, myocardial fibrosis and hypertension
Zhang, 2017 [52]	Adelaide	2009	Heart disease	All ages	↑ Cardiovascular mortality with a pre-existing heart condition

Abbreviations: AMI, acute myocardial infarction; CVD, cardiovascular disease; IHD, ischaemic heart disease; y, years old.

currently has no formal heat–health plan in place [55]. Despite the New Zealand Ministry of Health publicising their intent to develop an early warning system for extreme heat disasters, New Zealand still has no formal definition of a heatwave, and there is a significant lack of evidence that would allow the development of a heat warning system [21]. Australia on the other hand, has implemented state and regional policies to prepare and mitigate community heat–health risks. Most state and regional heat response plans within Australia are activated based on predictions of heat extremes via the BoM and implement a top-down approach to inform businesses and communities about forecasted extreme heat events. For example, in New South Wales (NSW), NSW Health distributes heat–health alerts to health and welfare services, who will then distribute the same warning and heat–health advice to local stakeholders [61]. Problematically, within most heat response plans, tangible guidelines for how an individual can plan and respond to heat extremes are often vague, presented with catch-all blanket terms, lack supporting scientific evidence, and are not customised to vulnerable populations, such as people with CVD. For example, the Red Cross' 2019 Heatwave Guide for Cities contains less than two from 96 pages of information regarding how individuals can protect themselves from the heat; whereas Queensland's heatwave subplan includes generic advice such as 'have a plan' and 'keep cool'.

Of the recommendations regularly made that are supported by empirical evidence, visiting community cooling centres has been shown to decrease heat-related mortality [7]. However, where heat response plans suggest cooling centres, shopping malls, or libraries as a means of keeping cool, local authorities need to consider individual barriers such as poor mobility, proximity, lack of awareness of their existence, and other public health countermeasures (i.e., physical distancing to mitigate spread of contagious diseases). People may also avoid public facilities due to personal objections, including perceptions these facilities are not needed, or because they would rather not be surrounded by other vulnerable people [62]. An additional concern is ensuring that heat–health warnings and advice are delivered to and employed by the public. In Australia, it has been shown a greater proportion of people residing in metropolis areas are aware of the negative health effects of extreme heat [63]. Whereas people residing in rural areas perceive extreme heat as low to no risk for their health, and there is a low level of risk perception associated with the impact of medication use during extreme heat events [61]. Heat–health advice should not be generalised, yet readily accessible and designed to address the needs and priorities of the local community. Barriers such as, but not limited to, water security, socioeconomic status, literacy, infrastructure, and housing [3] can independently influence the efficacy or engagement in heat mitigation strategies and should be thoroughly considered when creating an accessible heat–health response plan. Collectively, in developing more effective heat–health recommendations, special attention is needed to effectively disseminate heat–health advice.

Individual Cooling Strategies

Heat–health action plans should also include effective at-home, evidence based, heat mitigation strategies, that are widely accessible for all communities. By far the most effective individual cooling strategy during heat extremes is air conditioning (AC) use. Yet, more than 25% of Australians don't have access to AC; paralleled with its high energy demand and surging electricity prices, AC use is limited for most vulnerable populations who are often at home during the hottest parts of the day [64]. In young healthy adults, fan use [65], skin wetting and/or cool water foot immersion [66] have been shown to mitigate thermal and cardiovascular strain during simulated heatwaves [22]. However, in older adults with or without CVD, less is understood about the efficacy of these cooling interventions. Indeed, fan use can be beneficial for older adults in temperatures up to 38°C [65], however the efficacy of fan use will depend on the environment, such that during very hot and dry heat extremes that are often experienced across Australia, alternative strategies such as skin wetting may be more beneficial.

Research Knowledge and Translation

Communication strategies will play a key role in mitigating the negative health effects of extreme heat events, particularly amongst vulnerable populations. Heat–health advice must include well defined communication goals, strategies, and messages to increase awareness amongst communities, stakeholders and caregivers of the potential health risks and protective measures to be used before, during and after extreme heat events [67]. People are more likely to have trouble during extreme heat events if they do not receive or understand heat warnings due to a lack of access to translation services, direct language barriers, social and economic disadvantages, disabilities, or computer illiteracy [68]. Despite best efforts from public health authorities, members of the public can often remain ignorant of upcoming extreme heat events and how best to respond. Australians currently rely on traditional media outlets to receive their health information regarding heat extremes, such as television (90%), radio (71%), newspapers (45%) and the internet (42%) [63]. Notably, although most heat–health advice suggests that people with medical conditions follow their doctor's recommendation on how to protect themselves, research has shown that only 1% of Australians receive heat–health information from their family doctor or general practitioner [69].

The Use of Telehealth to Build Community Resilience to Extreme Heat Events

There is a need to develop and utilise more publicly available tools to publicise heat–health advice and enhance community resilience to extreme heat events. With smartphone ownership proliferating, the use of apps, text messaging systems and telehealth can become a powerful tool that integrates all key scientific and clinical data that determine a person's specific heat–health risk. Smartphones can combine environmental and personal health monitors. Therefore, this small technology has incredible potential (Figure 1) to provide specific local temperature warnings, physiological response warnings and feedback as to whether a cooling intervention has been successful. In addition, the use of text messaging systems has the potential to help educate people through providing information on topics such as proper medication use and storage, or physical activity limitations during extreme heat events. Smart devices can also be used to broadcast automated distress signals, for example in response to elevated heart rates or falls—all without the need for conscious contribution of either clinician or patient [70]. The use of telehealth (i.e., being able to call a health practitioner) during extreme heat events might also increase access to heat–health advice, particularly for people living in remote areas. Despite the increased interest in telehealth and smartphone use for detecting negative health events and patient monitoring in chronic disease, telehealth has almost been ubiquitously underutilised for extreme heat events [71].

One example of how telehealth is already successfully being used for community outreach during heat extremes is the South Australian Red Cross Telecross REDi program [72]. This program developed from a fall-prevention program, where volunteers from the Red Cross call housebound elderly individuals daily. In the event an elderly person fails

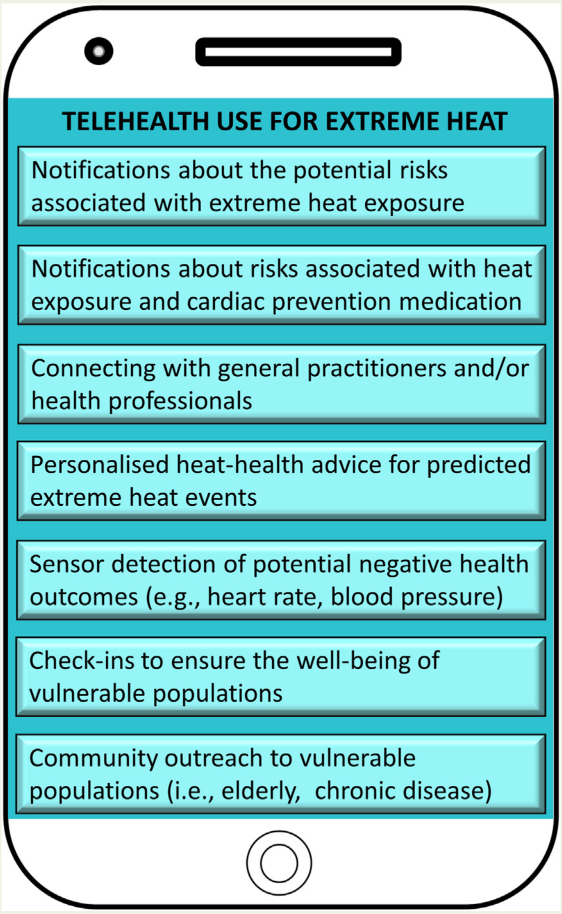

Figure 1 Examples of how telehealth can be used to mitigate negative health outcomes during extreme heat events.

to answer their phone, the Red Cross sends someone to that person. Although this program has yet to be independently evaluated for its effectiveness, it is part of a multi-front heat–health early warning system [73], and is only AUD$67,621 of a total $593,000 heat–health warning system which was found to be a net cost benefit compared to the costs associated with the increased health care expenses during heat extremes [74].

Knowledge Gaps and Future Research

Strengthening collaboration between researchers, key government stakeholders and the community will facilitate more translatable and evidence-based policies that can be used to protect communities against extreme heat events. A key research gap is the paucity of data on the effects of extreme heat on morbidity and mortality within New Zealand, and for First Nations Australian and Māori peoples. Although New Zealand demonstrates a more temperate climate, there is an urgent need to comprehensively understand: 1) the minimum temperature at which an increase in mortality is observed; 2) specific cardiovascular diseases that demonstrate a greater relative risk of morbidity and mortality during extreme heat events, and the impact of not only temperature, but the combination of temperature, humidity, wind speed and radiation on this increased risk; 3) implementation of successful heat protection advice that considers clinical factors such as age and co-morbidities, and medication use and storage; and, 4) application of evidence based cooling interventions that can be used to mitigate the negative effects of extreme heat.

A greater physiological understanding of the association between extreme heat and adverse cardiovascular events is needed, with the addition of understanding the modulating effects of cardiovascular medication. For example, statin use is associated with a reduced risk of all-cause mortality during extreme heat [75], whereas diuretics are associated with a greater risk of death from heatstroke [76]. Furthermore, extreme heat events may alter the pharmaceutical quality of prescribed medications which could have an indirect impact on human health. While medications such as statins may not degrade during extreme heat events [77] other medications such as nitro-glycerine [78] and angiotensin converting enzyme inhibitors [79] have been shown to degrade under extremely hot and/or wet conditions (~69°C, 74% humidity). Importantly, very little research has investigated the effects of ecologically valid doses of cardiovascular medication on the human thermal and cardiovascular responses to hot environments. While heat–health action plans should ensure proper education surrounding medication use and storage, there is an urgent need to support this advice with empirical evidence.

Although the BoM can effectively detect upcoming extreme heat events, an assumption of their methods used is that people will become acclimatised to heat throughout the summer. While partial heat acclimation may occur throughout summer [80] in healthy adults, this acclimation has not been demonstrated to occur in vulnerable populations, and more research is needed to establish this. Furthermore, a common reliance on temperature values reported in weather forecasts to judge heat stress risk, ignores the large influence of humidity, wind, and sun exposure on the human heat stress response. Within Australia, there is an urgent priority to increase community resilience to the heat through simple and affordable cooling solutions that mitigate the potentially devastating health impacts amongst vulnerable populations during extreme heat events. Lastly, despite exercise being recommended for people with CVD, particularly those undergoing cardiac rehabilitation, there is a lack of research defining environmental limits under which people with CVD can safely exercise. As such, there is a need to develop guidelines that prescribe safe environmental limits for exercise among CVD populations.

Conclusion

Extreme heat is consistently associated with a greater risk of cardiovascular morbidity and mortality. Relatively mild levels of hyperthermia are sufficient to place substantial strain on the cardiovascular system, which may explain the increased risk of cardiovascular mortality and morbidity during extreme heat events. Nonetheless, there is an urgent need to develop and disseminate evidence-based heat–health advice that is customised to vulnerable populations, such as people with CVD. Furthermore, advancements in telehealth will create opportunities for targeted heat–health advice that can be customised for specific vulnerable populations and provides a means of reaching vulnerable populations who reside in remote and/or low-income settings. Collaboration between researchers, clinicians, key government stakeholders and community members is needed to allow for optimal care for vulnerable populations during extreme heat events in Australia and New Zealand.

Conflicts of Interest

None to declare.

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