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Abstract

Heat is a leading weather-related cause of death worldwide and heat waves are increasing globally in terms of frequency, duration, and intensity. Global heat-related deaths could quadruple by midcentury. As with many environmental hazards, numerous factors impact how heat might affect any given person and there are significant gaps in our understanding related to indoor heat and its effect on health. Despite growing interest in establishing standards and guidelines, there is currently no clear consensus on a safe maximum upper limit for indoor temperature. There is conclusive evidence of links between high outdoor temperatures and human health yet research on this correlation does not typically explicitly consider indoor heat exposure. Considerably more research has been completed on healthy, active individuals than for more heat-susceptible populations and the impacts of moderate heat stress on the health of large populations are not well understood.

We conducted a literature review on the impact of indoor thermal conditions on health, recognizing that air temperature alone cannot describe thermal exposure. We introduce the concept of a standardized maximum safe indoor temperature, defined for still air conditions, 50% relative humidity and mean radiant temperature equal to air temperature. Equivalent temperatures with respect to the thermal load on the body can then be calculated for various air velocities, humidities or mean radiant temperatures using the standard effective temperature (SET) model. For U.S. policymakers, we propose adopting a standardized maximum safe indoor temperature of 28 °C. We recognize that the adoption of standardized maximum safe indoor temperatures may vary around the world, but the framework we propose to adjust the standardized upper limit for humidity, air motion, and radiant temperature could be used globally. We also identify important knowledge gaps to guide future research on the relationships between heat and health that could support informed cost-benefit analyses.

Keywords

Overheating; Heat and health; Safe indoor temperature standards; Heat stress; Heat strain; Heatwaves

Introduction

Heat is the leading weather-related cause of death in the United States and heatwaves are increasing in frequency, duration, and intensity across the country. From 2000-2019, an average of 489,075 people died each year from heat-related causes (Zhao et al., 2021). Climate change will exacerbate heat-related risks of morbidity and mortality, with up to 74% of the world population exposed to climatic conditions exceeding a deadly threshold for 20 or more days per year (Basu & Samet, 2002; Dong et al., 2015; Kovats & Bickler, 2012; Li et al., 2020; Mora et al., 2017; Raymond et al., 2020). In Europe, a 3°C rise in global temperature has been projected to lead to a tripling of annual heat-related mortality to 30 deaths per 100,000. (García-León et al., 2024). Heat stress has been associated with increases in all-cause mortality (Vicedo-Cabrera et al., 2021), lower respiratory tract infection (Burkart et al., 2021), chronic respiratory disease (Burkart et al., 2021), cardiovascular disease (Burkart et al., 2021), chronic kidney disease (Burkart et al., 2021; Liu et al., 2021), diabetes (Burkart et al., 2021), adverse pregnancy outcomes (Chersich et al., 2020), and poor mental health (Noelke et al., 2016).

While there is considerable literature on the effects of heat on health, there is no clear consensus on a maximum safe indoor air temperature. As with many environmental hazards, there are numerous factors that impact how heat might affect any given person and there are significant gaps in our understanding. People adapt to heat through changes in their physiology and behavior, and we know there are both short-term and long-term impacts of heat health. All of these factors, along with the complexity of temperature being only one variable of the thermal environment affecting human response, complicates the determination of safe indoor air temperatures.

Exposure to elevated indoor air temperatures can pose health risks across all populations and the majority of fatal heat exposures in the developed world occur indoors (Quinn et al., 2014). While conditions that cause acute heat stress in healthy individuals have been studied extensively, the impacts of more moderate conditions on the health of heat-susceptible populations are not well understood. This knowledge gap poses a fundamental challenge to establishing maximum safe indoor air temperature guidelines. This paper provides a rationale for a maximum safe indoor air temperature; however, our recommendation is not based on a formal health risk assessment, due to insufficient data to support such an analysis. As the understanding of the relationship between indoor temperature and health improves over time, recommended maximum safe temperature limits should be reevaluated.

Our analysis and recommendations are aimed at the context of what might be appropriate for U.S. regulations but would be applicable to many other regions as well, noting that economic, cultural and climatic influences could sometimes be at play. We present a scenario in which we looked at heat impacts in our home state of California.

Methods

We reviewed hundreds of peer-reviewed articles, gray literature, guidelines and standards, laboratory studies, field studies, review papers and existing standards related to indoor thermal conditions. These materials were identified through citation searches and interviews with an international group of researchers in related fields. We extracted information on physiological effects of heat, health impacts of heat exposure, and thermal comfort standards with the objective of finding supporting data for establishing maximum safe indoor temperature guidelines.

Results and Discussion

Existing temperature standards and codes

Minimum indoor air temperature thresholds in the range of 18-20 °C are well-established in existing regional, national, and international standards and codes (CA Title 24, 2022; IRC, 2018; World Health Organization, 2018). Maximum indoor air temperature standards do exist (see Table 1) but are much less common and their scientific basis is generally not well documented. The World Health Organization Housing and Health Guidelines (World Health Organization, 2018) identifies six priority areas to reduce the health burden due to unsafe and substandard housing conditions and provides guidelines for each area along with an assessment of the strength of the evidence supporting each recommendation. Four of these areas (crowding, minimum indoor temperatures, home safety and accessibility) receive a "strong" assessment with respect to the quality of supporting evidence. WHO makes only a conditional recommendation with respect to overheating guidelines, saying that "strategies to protect populations from excess heat should be developed and implemented," providing no specific temperature recommendation. WHO determined that "there are so few studies of the direct effect of high indoor temperature on health, the certainty of the evidence that reducing high indoor temperatures would reduce morbidity and mortality was assessed as low to very low."

Table 1. Maximum indoor air temperature limits in selected international standards

Country	Standard	Temperature	Reference
Finland	Finnish Society of Indoor Air Quality and Climate (FiSIAQ)	27 °C	(Ahola et al., 2019)
Germany	DIN 4108-2. Indoor environmental input parameters for design and assessment of energy performance of buildings	27 °C	(DIN 4108-2, 2013)
China	National Health Commission of the People's Republic of China, Standards for Indoor Air Quality, GB/T 18883-2022	28 °C	(National Health Commission of the People's Republic of China, 2022)
Japan	Building Environmental Sanitation Management Standards	28 °C	(Japanese Ministry of Health, Labor and Welfare, 2021)
UK	TM59. Overheating assessment in residential properties Mechanically ventilated houses Naturally ventilated housing: Bedrooms (10pm to 7am) Living areas	 26 °C 26 °C Adaptive model	(CIBSE TM59, 2017)

Review studies

A global systematic review of evidence on the direct impacts of high indoor temperature on health identified 22 articles including observational, cross-sectional and longitudinal cohort studies (Tham et al., 2020). They identified eight main health effects: respiratory, blood pressure, core temperature, blood glucose, mental health and cognition, heat-health symptoms, physical functioning and influenza transmission. Only five studies reported temperatures at which health outcomes worsened, ranging from 26 to 32 °C. They concluded that there was insufficient evidence to support a maximum indoor temperature threshold and suggested that 26 °C might be most suitable until more evidence can be accumulated.

Laboratory studies

Several laboratory studies have examined physiological responses to indoor heat by carefully controlling the thermal environment and monitoring a variety of physiological parameters, including body core temperature, heart rate, sweat rate, blood pressure and cardiac autonomic response (Cottle et al., 2022, Meade et al., 2024,) In the most relevant research found, a Canadian study of elderly adults exposed to four temperatures (22 °C, 26 °C, 31 °C and 36 °C) for 8-hour periods the authors found that core temperature and cardiovascular strain were not appreciably altered following exposure to 26°C compared to 22°C but increased significantly in the warmer two conditions of 31 °C and 36 °C (Meade et al., 2024). One limitation of this study is the lack of testing in conditions between 26 and 31°C, a range very common in residential buildings and of great interest with respect to establishing maximum safe indoor temperature standards.

Field Studies

Field studies on the relationship between indoor temperature and health in buildings are uncommon due to the lack of data on naturally occurring (rather than experimentally-induced) indoor temperature exposure. A case-control study reported that humidity exposure and indoor heat above 26°C non-significantly increased the proportion of emergency calls in New York due to cardiovascular and respiratory distress calls. Paramedics carried portable sensors into buildings where patients received care to passively monitor indoor temperature and humidity. The case–control study compared 338 respiratory cases, 291 cardiovascular cases, and 471 controls (Uejio et al., 2016).

One quasi-experimental study of 57 older people (age 62-92, average 73) before and after retrofits of a low-income senior housing complex in Phoenix, Arizona found that reductions in the number of days of indoor temperature above 27.2°C and reductions in mean and minimum indoor temperatures after the retrofits corresponded with improved reported occupant health and increased hours of sleep (Ahrentzen et al., 2016).

In a study of 40 households in New York City over two summers and two winters, the authors found no associations between indoor temperatures and reports of respiratory viral infection or heat illness, but found a significant relationship between sleep problems and the preceding daytime indoor temperature in the warm season (Quinn & Shaman, 2017).

A study in Slovenia focused on symptoms in elderly subjects with and without cardio-vascular disease (CVD) related to high indoor temperatures during two heatwaves where mean indoor temperature ranged between 29 and 31 °C. The authors found cardiovascular symptoms were associated with higher indoor temperatures and lower indoor air quality and the subgroup with CVD showed greater sensitivity. The authors recommended using both heat and air quality indexes to evaluate the burden on health, because during heat waves, indoor air quality is likely poor because windows are more likely to be closed (Fink et al., 2017).

Sleep Studies

Sleep quality has direct and important impacts on health. A large UK (n = 591) study on residential buildings during the 2018 UK heatwave resulted in a recommendation of 28 °C as an 8-hour average night-time indoor air temperature threshold for most healthy persons and 26 °C for vulnerable people (Lomas & Li, 2023).

Thermal comfort standards

Thermal comfort in indoor environments has been studied extensively over the past century in laboratory and field studies. Although thermal comfort is not a direct measure of health, it does indicate a state of low heat stress on the body which would be unlikely to significantly contribute to health-related illness. ASHRAE Standard 55-2023 (ASHRAE 55, 2023) and ISO 7730 (ISO 7730, 2005) define in detail the environmental conditions required for human thermal comfort. Figure 1 shows the comfort zone as defined by ASHRAE 55 for a person wearing light summer clothing (0.4 clo) and seated quietly (1 met) in still air conditions. The upper limit of comfort under these assumptions and 50% RH is 28 °C.

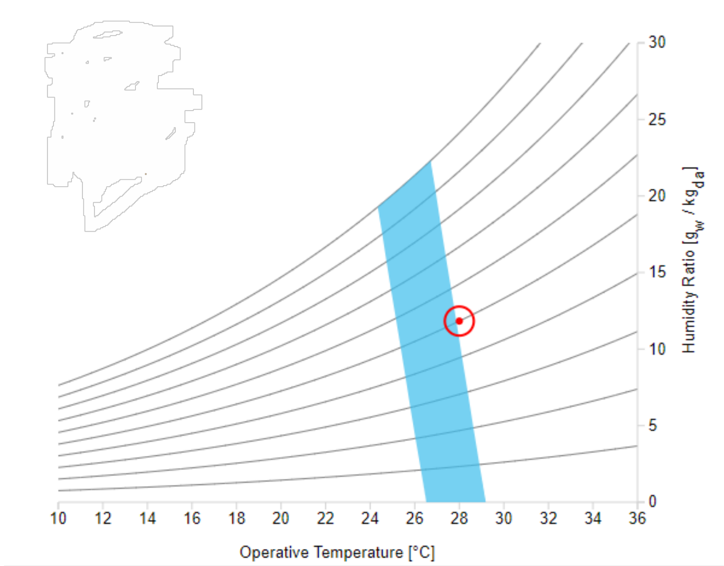

Figure 1. ASHRAE 55 thermal comfort zone for a person at rest (1 met) wearing summer clothing (0.4 clo) in still air. The marker shows the upper limit of thermal comfort for 50% RH.

Susceptible populations

While maximum safe indoor air temperature standards should apply to a broad range of the population, certain individuals are at higher risk for heat-related health impacts. Conditions associated with increased heat susceptibility include, but are not limited to, cardiovascular disease, respiratory disease, kidney disease, and poor thermoregulation. Several medications may reduce the ability to thermoregulate (Wee 2023). Currently, we have insufficient information to establish maximum safe temperatures for specific population groups and policies should acknowledge that individuals who require lower temperatures should have agency to make accommodations to meet their needs.

Adaptation to heat

Many authors agree that there are three levels of adaptive ability: behavioral, psychological and physiological (Brager & de Dear, 1998; Pallubinsky et al., 2023; Rahif et al., 2021). People living in hotter climates tend to cope better with extreme heat, and temperature thresholds for heat-related mortality are higher in warmer climates (Kenny et al., 2019). Such adaptation could be used as an argument to consider regional climate as a factor when establishing safe upper temperature standards.

Exposure time

The duration of heat exposure is clearly important; successive days of exposure can lower the threshold for heat-related mortality. Some standards specify maximum lengths of time that the maximum temperature can be exceeded before a building is out of compliance. Others combine time and temperature using the concept of degree-hours, where exposure to a temperature 2 degrees above a threshold for 1 hour is considered equivalent to a 1 degree above the threshold for 2 hours. Other standards acknowledge that temperatures can occasionally be above a specified threshold without specific quantitative guidance on the duration of exceedance (Title 42 Section 483).

Standardized maximum safe indoor temperature

When defining low safe indoor environmental conditions for health, ambient temperature alone is often used (WHO 2018). However, ambient temperature alone is not sufficient because air movement, humidity, and mean radiant temperature (MRT) can affect heat stress significantly. Not considering these additional environmental factors in guidelines and standards can have important consequences. For example, air movement can be a low-cost, energy-efficient means of reducing heat risk without lowering air temperature but a standard that specified only an upper air temperature limit would not reflect the potential benefits of air movement.

To define safe maximum indoor temperature limits that consider these additional important environmental parameters, we define the term *standardized temperature* to refer to environmental conditions of still air, 50% relative humidity and MRT equal to the air temperature. We propose using the standard effective temperature model (SET) (ASHRAE 55, 2023) to calculate air temperatures for other air speeds, relative humidities and MRTs that represent an equivalent thermal load on the body as the standardized temperature. Our research group has a freely available online tool (https://comfort.cbe.berkeley.edu) that can be used for this purpose.

Proposed safe indoor upper temperature limits

Although our understanding of how indoor thermal environments affect health is incomplete, it is important to establish reasonable standards to address the increasing health risks associated with overheating in residential buildings. Following our review, we propose a standardized maximum safe indoor temperature limit of 28 °C for the U.S. Based on this limit, we can then calculate equivalent air temperatures under other air speeds, humidity and mean radiant conditions that represent the same thermal load based on the standard effective temperature (SET) model. Figure 2 shows these safe upper limits based on the proposed standardized maximum safe indoor temperature limit of 28 °C and three air speeds (still air, 0.4 m.s and 0.8 m.s). For example, with 0.4 and 0.8 m/s air speed, 50% RH, the indoor temperature limits are 30.1 °C and 31.2 °C respectively. When implementing regulations, if a different standardized maximum safe indoor temperature limit is chosen, the same method of accounting for air motion, humidity and mean radiant temperature can be applied.

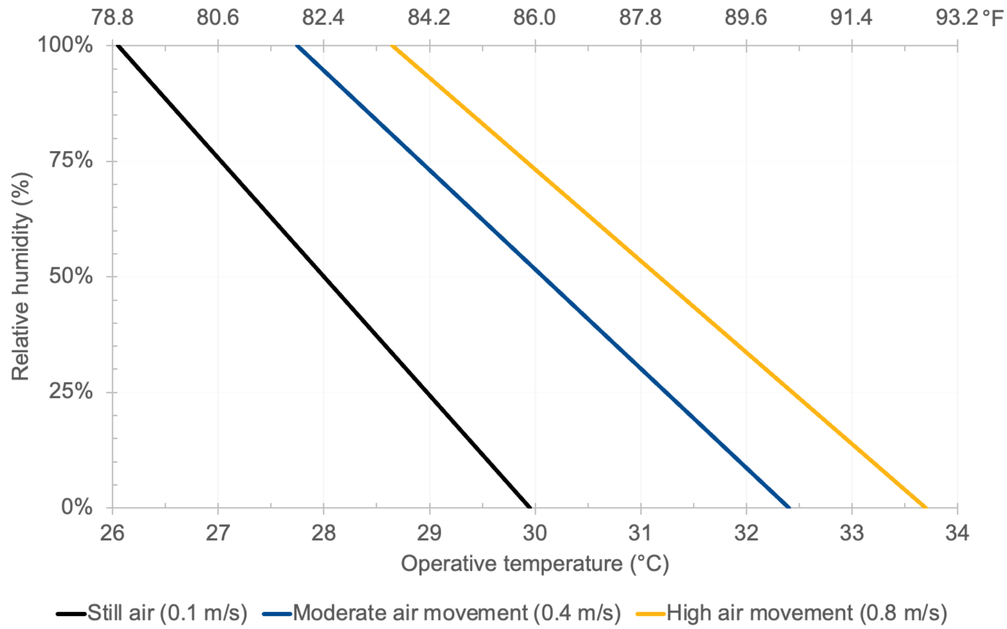

Figure 2. Proposed operative temperature limits corresponding to a standardized maximum safe indoor temperature limit of 28 °C (indicated with a black circle) as a function of humidity for still air, moderate air movement and high air movement. The lines represent equivalent thermal heat loads on the body.

Conclusions

Our literature review identified hundreds of papers related to heat and health, yet no clear consensus has been reached with respect to defining maximum safe indoor environmental conditions. Despite this lack of consensus, there is an obvious and growing interest internationally in establishing standards in the context of increasing intensity and duration of heatwaves. We propose that such standards, much like existing thermal comfort standards, must include the effects of air movement, humidity, and mean radiant temperature in addition to air temperature. We define the term standardized temperature as a means of specifying safe indoor temperature standards using the single parameter of air temperature yet acknowledging that all four environmental parameters are important. Finally, based on our research, we propose 28 °C as a reasonable candidate standardized temperature for such a standard in the U.S.

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