UNIVERSITY OF COPENHAGEN

Workers' health and productivity under occupational heat strain

a systematic review and meta-analysis

Flouris, Andreas D; Dinas, Petros C; Ioannou, Leonidas G; Nybo, Lars; Havenith, George; Kenny, Glen P; Kjellstrom, Tord

Published in:
The Lancet Planetary Health

DOI:
10.1016/S2542-5196(18)30237-7

Publication date:
2018

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Flouris, A. D., Dinas, P. C., Ioannou, L. G., Nybo, L., Havenith, G., Kenny, G. P., & Kjellstrom, T. (2018). Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *The Lancet Planetary Health*, *2*(12), e521-e531. https://doi.org/10.1016/S2542-5196(18)30237-7

Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis

Andreas D Flouris, Petros C Dinas, Leonidas G Ioannou, Lars Nybo, George Havenith, Glen P Kenny, Tord Kjellstrom

Summary

Background Occupational heat strain (ie, the effect of environmental heat stress on the body) directly threatens workers' ability to live healthy and productive lives. We estimated the effects of occupational heat strain on workers' health and productivity outcomes.

Methods Following PRISMA guidelines for this systematic review and meta-analysis, we searched PubMed and Embase from database inception to Feb 5, 2018, for relevant studies in any labour environment and at any level of occupational heat strain. No restrictions on language, workers' health status, or study design were applied. Occupational heat strain was defined using international health and safety guidelines and standards. We excluded studies that calculated effects using simulations or statistical models instead of actual measurements, and any grey literature. Risk of bias, data extraction, and sensitivity analysis were performed by two independent investigators. Six random-effects meta-analyses estimated the prevalence of occupational heat strain, kidney disease or acute kidney injury, productivity loss, core temperature, change in urine specific gravity, and odds of occupational heat strain occurring during or at the end of a work shift in heat stress conditions. The review protocol is available on PROSPERO, registration number CRD42017083271.

Findings Of 958 reports identified through our systematic search, 111 studies done in 30 countries, including 447 million workers from more than 40 different occupations, were eligible for analysis. Our meta-analyses showed that individuals working a single work shift under heat stress (defined as wet-bulb globe temperature beyond 22·0 or 24·8°C depending on work intensity) were 4·01 times (95% CI 2·45–6·58; nine studies with 11 582 workers) more likely to experience occupational heat strain than an individual working in thermoneutral conditions, while their core temperature was increased by 0·7°C (0·4–1·0; 17 studies with 1090 workers) and their urine specific gravity was increased by 14·5% (0·0031, 0·0014–0·0048; 14 studies with 691 workers). During or at the end of a work shift under heat stress, 35% (31–39; 33 studies with 13 088 workers) of workers experienced occupational heat strain, while 30% (21–39; 11 studies with 8076 workers) reported productivity losses. Finally, 15% (11–19; ten studies with 21 721 workers) of individuals who typically or frequently worked under heat stress (minimum of 6 h per day, 5 days per week, for 2 months of the year) experienced kidney disease or acute kidney injury. Overall, this analysis include a variety of populations, exposures, and occupations to comply with a wider adoption of evidence synthesis, but resulted in large heterogeneity in our meta-analyses. Grading of Recommendations, Assessment, Development and Evaluation analysis revealed moderate confidence for most results and very low confidence in two cases (average core temperature and change in urine specific gravity) due to studies being funded by industry.

Interpretation Occupational heat strain has important health and productivity outcomes and should be recognised as a public health problem. Concerted international action is needed to mitigate its effects in light of climate change and the anticipated rise in heat stress.

Funding EU Horizon 2020 research and innovation programme.

Lancet Planet Health 2018; 2: e521–31

FAME Laboratory, Department of Exercise Science, University of Thessaly, Trikala, Greece (A D Flouris PhD, P C Dinas PhD, L G Ioannou MSc); **Human and Environmental Physiological Research Unit, Faculty of Health Sciences, University of Ottawa, Ottowa, ON, Canada** (A D Flouris, Prof G P Kenny PhD); **Department of Nutrition, Exercise and Sports, August Krogh Building, University of Copenhagen, Copenhagen, Denmark** (L G Ioannou, Prof L Nybo PhD); **Centre for Technology Research and Innovation, Lemesos, Cyprus** (L G Ioannou, Prof T Kjellstrom PhD); **Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Loughborough, UK** (Prof G Havenith PhD); and **Clinical Epidemiology Program, Ottawa Hospital Research Institute, Ottawa, ON, Canada** (Prof G P Kenny)

Correspondence to: Dr Andreas D Flouris, FAME Laboratory, Department of Exercise Science, University of Thessaly, Trikala 42100, Greece **andreasflouris@gmail.com**

Introduction

Nearly a third of the world's population is regularly exposed to climate conditions that exceed human thermoregulatory capacity, leading to major increases in morbidity and mortality.[1–3] Even if aggressive mitigation measures were to be adopted, estimates suggest that half of the world's population will be exposed to such conditions by 2100,[1] and several studies[4–7] report that the resulting occupational heat strain will directly threaten workers' health, with corresponding negative effects on productivity, poverty, and socioeconomic inequality. Occupational heat strain refers to the physiological effect of environmental heat stress on the body and it has a major impact on the ability of workers to live healthy and productive lives; nearly 1 million work life-years are projected to be lost by 2030 due to occupational heat stroke fatalities, with 70 million work life-years lost because of reduced labour productivity.[8,9] Warning systems for extreme weather events have been piloted in some countries, but they are designed for the general

Research in context

Evidence before this study

Occupational heat strain directly threatens workers' ability to live healthy and productive lives. To date, the magnitude of this problem has not been systematically investigated. To fill this knowledge gap, we completed the first systematic review and meta-analysis to estimate the effects of occupational heat strain on workers' health and productivity outcomes. We searched PubMed and Embase from the date of their inception to Feb 5, 2018, for studies in any labour environment, with no restrictions on language, workers' health status, or study design. We did six random-effects meta-analyses to estimate the effect of occupational heat strain on different health and productivity outcomes. In total, 111 studies done in 30 countries, including more than 447 million workers from over 40 different occupations, were eligible for analysis.

Added value of this study

This study estimated that individuals working a single work shift under heat stress are four times more likely to experience occupational heat strain, while their core temperature is increased by 0·7°C and their urine specific gravity is increased by 14·5%. Of those individuals who work under heat stress, 35% experience occupational heat strain, while 30% report productivity losses. Finally, 15% of individuals who typically work under heat stress experience kidney disease or acute kidney injury.

Implications of all the available evidence

Occupational heat strain has important effects on health and productivity outcomes and should be recognised globally as a public health problem. Concerted international action is needed to mitigate its effects in light of the occurring climate change and the anticipated rise in heat stress. Efforts should be made towards establishing a surveillance system, which will provide a basis for public health policy, health-care planning, and resource allocation for occupational heat strain prevention initiatives.

population whose needs and exposure to heat are vastly different from those of workers. For instance, these warning systems typically advise individuals to stay indoors throughout the day or to remain in cooling shelters at public buildings.[10] Such strategies are not compatible with the need to stay productive, regardless of the prevailing environmental conditions.

See Online for appendix

Considering that climate change will aggravate workplace conditions for billions of workers,[1] initiatives to mitigate occupational heat strain have been launched by, among others, WHO,[11] the World Meteorological Association, and the European Commission (Heat Shield)[12] to develop solutions and identify the best practices available. However, the magnitude of the effects of occupational heat strain has not been systematically investigated to date, primarily because the results are too complex to interpret by examining single studies or trials in specific occupational settings. Therefore, we did a systematic review and meta-analysis to systematically assess the available evidence on the effects of occupational heat strain on workers' health and productivity outcomes. This work contributes to the foundation needed to develop relevant policies and programmes, to assess their effect on health, economic, and social benefits, and to evaluate their effectiveness for reducing inequalities.

For more on **Heat Shield** see https://www.heat-shield.eu

Methods

Search strategy and selection criteria

Following PRISMA guidelines,[13] for our systematic review and meta-analysis we searched the PubMed and Embase databases from inception to Nov 30, 2017, for studies that assessed the effect of occupational heat strain on workers' health or productivity outcomes. A search update, via alerts, was done up until Feb 5, 2018. Studies done in any labour environment and published in any language were included. No restrictions on workers' health status or study design were applied. The search algorithms used are provided in the appendix. We excluded reviews, conference proceedings, editorials, and magazine articles, but we screened the reference lists of such publications and of the retrieved articles for relevant papers. We supplemented the electronic database searches with manual searches for published studies in international trial registers and websites of international agencies (eg, WHO). Across all searches, we included articles if they consisted of original quantitative research published in a peer-reviewed journal or scholarly report, while we excluded studies that calculated effects with simulations or statistical models instead of actual measurements in humans.

The screening of the titles, abstracts, and full texts for eligibility, and the selection of studies to be included, were done independently by two investigators (PCD and LGI). Any conflicts were resolved by a referee investigator (ADF). We included studies that involved any individuals working in any kind of conditions and at any level of heat exposure. We also included measurements that were done during working hours, either as an intervention using working modes or as epidemiological measurements. We included all methodological designs that had any kind of control-group (ie, non-workers) or crossover design (ie, different working and non-working conditions); no sample size criterion was applied for the included studies. The list of included and excluded papers is available in the appendix.

When necessary, additional information was requested from the journals or the study authors via email. For all studies, we extracted the author names, year of publication, and data on the participant numbers, age, sex, occupation, environmental conditions, intervention (if any), and adverse primary outcome (symptom, incidence). For epidemiological studies, we extracted incidence rate ratio for heat-related illness. For occupational health field studies, we extracted information for indices measured to calculate occupational heat strain: prevalence and SE, incidence rate ratio, risk ratio and odds ratio (OR), mean and SD, and confidence intervals. For the productivity-related field studies, we extracted the amount of work done, and the percentage of work time lost and reported productivity loss by the workers to calculate productivity loss for each included study. No transformations were applied to the extracted data.

To reduce bias and the likelihood of duplication, and to maximise the validity of the procedures used, we registered our systematic review in the international prospective register for systematic reviews (PROSPERO) database (number CRD42017083271) and reported our study in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist (appendix).[13] Because all included studies used an observational design, two independent investigators (PCD and LGI) assessed the risk of bias via the 13-item Research Triangle Institute item bank,[14] which is designed for observational studies and has previously shown median inter-rater agreement of 75%[15] and 93·5%.[16] The PROSPERO study protocol can be found online.

Data analysis

We did six random-effect model meta-analyses. Specifically, for meta-analysis one, we estimated the prevalence of occupational heat strain (ie, the physiological consequences of environmental heat stress) that occurred during or at the end of a work shift in heat stress conditions (wet-bulb globe temperature [WBGT], 21·2–52·0°C; air temperature, 33·0–38·7°C). Occupational heat strain was defined as present if one or more criteria were met: (1) core body temperature higher than 38°C, according to international occupational health and safety standards;[17–19] (2) at least one occupational heat strain symptom, as defined by international health and safety guidelines[17,19–22] (ie, serum creatinine concentration of >1·2 mg/dL [indicating acute kidney injury],[23,24] diagnosed urinary lithiasis [indicating acute kidney injury],[23,24] urine specific gravity ≥1·020 [indicating dehydration],[21] heat-associated self-reported nausea or vomiting [indicating heatstroke],[20] painful muscular spasms [indicating heat cramps],[20] confusion, dizziness, or fainting [indicating heat syncope, heat exhaustion, or heatstroke],[20] hot dry skin [indicating heatstroke],[20] and self-reported heat strain [indicating heat exhaustion]);[20] and (3) cholesterol concentration higher than 6·7 mmol/L or low-density lipoprotein concentration higher than 3·4 mmol/L (indicating heat-induced dyslipidaemia).[25,26]

For meta-analysis two, we estimated the prevalence of kidney disease or acute kidney injury in individuals who frequently or typically work in heat stress conditions (minimum of 6 h per day, 5 days per week, for 2 months of the year for typical occupations, or minimum of 12 h per day, 2 days per week, for 12 months of the year for specialised occupations, such as mining; WBGT, 24·8–33·8°C; air temperature, 38·0–150·0°C). This evaluation was done given the well-established link between hydration and kidney function.[24] The occurrence of kidney disease was reported via self-reporting or a physician diagnosis. Acute kidney injury was defined according to international health guidelines[22,24] and included (appendix) estimated glomerular filtration rate, serum uric acid concentration, serum creatinine concentration, albumin creatinine ratio, diagnosed urinary lithiasis, and fulfilment of KDIGO (Kidney Disease: Improving Global Outcomes)[24] criteria (ie, increase in serum creatinine concentration by ≥0·3 mg/dL [≥26·5 μmol/L] within 48 h or increase in serum creatinine concentration to ≥1·5 times baseline, which is known or presumed to have occurred within the previous 7 days, or urine volume <0·5 mL/kg per h for 6 h) for self-reported acute kidney injury.

For meta-analysis three, we estimated the prevalence of productivity loss in individuals working in heat stress conditions (WBGT, 21·2–52·0°C; air temperature, 26·8–38·0°C), which in the included studies was either reported as loss of productivity or measured as loss of labour time, performance, or absence from work due to occupational heat strain (appendix).

For **study protocol** see https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=83271

In meta-analysis four, we estimated the OR of occupational heat strain that occurred during or at the end of a work shift performed under heat stress conditions (WBGT, 26·2–26·4°C; air temperature, 37·3–150·0°C). This assessment included comparing the occupational heat strain events (as defined in meta-analysis one and recorded by the study investigators) that occurred in heat stress conditions against the occupational heat strain events that occurred in thermoneutral conditions. Thus, the fourth meta-analysis complements the prevalence rate estimated in meta-analysis one by calculating the probability of an occupational heat strain event occurring when in hot workplace conditions.

For meta-analysis five, we estimated the average core temperature during a single work shift done in heat stress conditions (WBGT, 22·0–40·8°C; air temperature, 29·0–47·0°C). This average was calculated by comparing the core temperature measurements collected at preshift against postshift or by comparing those collected postshift from individuals working in heat stress conditions against individuals working in thermoneutral conditions.

For the final meta-analysis, we estimated the average percentage change in urine specific gravity due to completing a single work shift in heat stress conditions (WBGT, 24·8–48·9°C; air temperature, 32·7–38·0°C). This average was calculated by comparing the urine

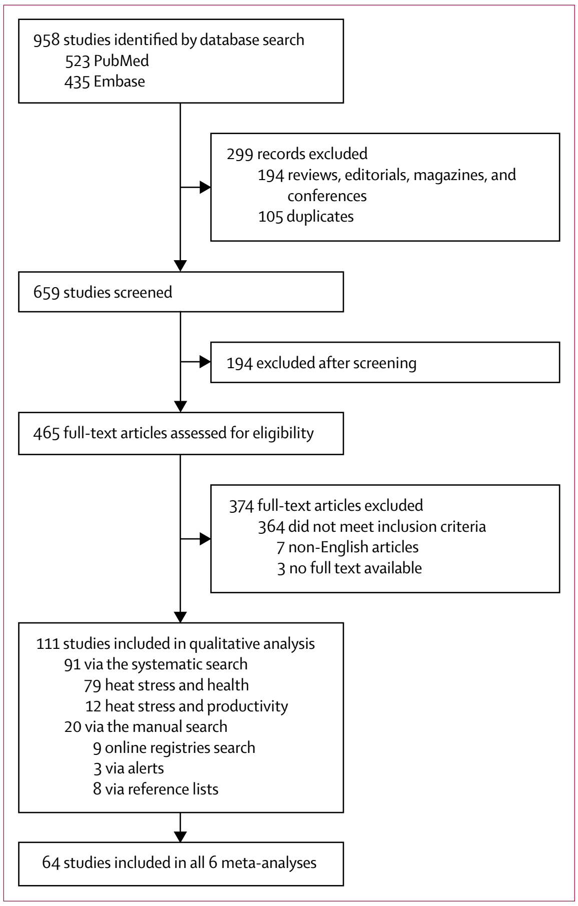

Figure 1: Study selection

specific gravity results obtained either preshift against postshift or by comparing those obtained postshift from individuals working in heat stress conditions against individuals working in thermoneutral conditions.

We manually did meta-analyses one, two, and three, which refer to prevalence, by dividing the incidence of occupational heat strain by the overall sample size of each study. We calculated SEs for these meta-analyses using the formula[2]

$$SE = \frac{\text{incidence}}{(\text{incidence} \times \text{sample size})}$$

We then used SEs for weighted proportions and the RevMan 5.3 software[27] to generate forest and funnel plots. We did meta-analysis four, which refers to OR, using a dichotomous, inverse variance, random-effect model via the RevMan 5.3 software. We used incidence of occupational heat strain in individuals exposed to heat stress conditions against the same incidence in non-exposed individuals, while we calculated weighted proportions based on each study's sample size. We did meta-analyses five and six, which refer to mean differences, using a continuous, inverse variance, random-effect model via the RevMan 5.3 software. We used means and SDs either preshift against postshift or postshift from individuals working in heat stress conditions against postshift, or only postshift in individuals working in non-heat stress conditions, while we calculated weighted proportions based on each study's sample size.[28]

If data for the same participants were presented in multiple publications, these data were only used once (ie, single outcome). We synthesised the study effect sizes using a random-effects meta-analysis model to account for heterogeneity due to differences in study populations, interventions, study duration, and other factors.

We evaluated the 95% CI and heterogeneity between studies using the I^2 statistic. We considered a significant result for heterogeneity when $p<0 \cdot 10$, while interpretation of I^2 index was made based on previous guidelines.[29] We assessed small study effects, potentially caused by publication bias, using funnel plots produced via RevMan. Given the large heterogeneity (I^2 >70%) in all six meta-analyses, a sensitivity analysis was done (Grading of Recommendations, Assessment, Development and Evaluation [GRADE]) for each meta-analysis.[28] GRADE assessed the quality of the meta-analysis results via methodological design, risk of bias, heterogeneity, indirectness, imprecision, publication bias, and effect sizes displayed in both the included studies in a meta-analysis and the meta-analysis itself. GRADE rates the quality of a meta-analysis as very low, low, moderate, and high, allowing for firmer conclusions to be made.[28]

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

A total of 958 records were identified through our systematic search, of which 105 were duplicates (figure 1). A further 194 records were excluded (reviews, editorials, or conference proceedings). Of the 465 full-text articles assessed for eligibility, three articles were excluded due to non-availability of full texts (despite contacting authors and journals) or due to non-English language used, while 364 were classified as non-eligible. A total of 91 studies assessing the effect of occupational heat strain on workers' health or productivity outcomes were included in the review. 20 additional studies were retrieved through manual searches or the reference lists of the retrieved articles.

The 111 studies included in the analysis were published between 1954 and 2018 and included 447 108 664 workers from more than 40 occupations. The studies were done across 30 countries covering all the continents, relevant

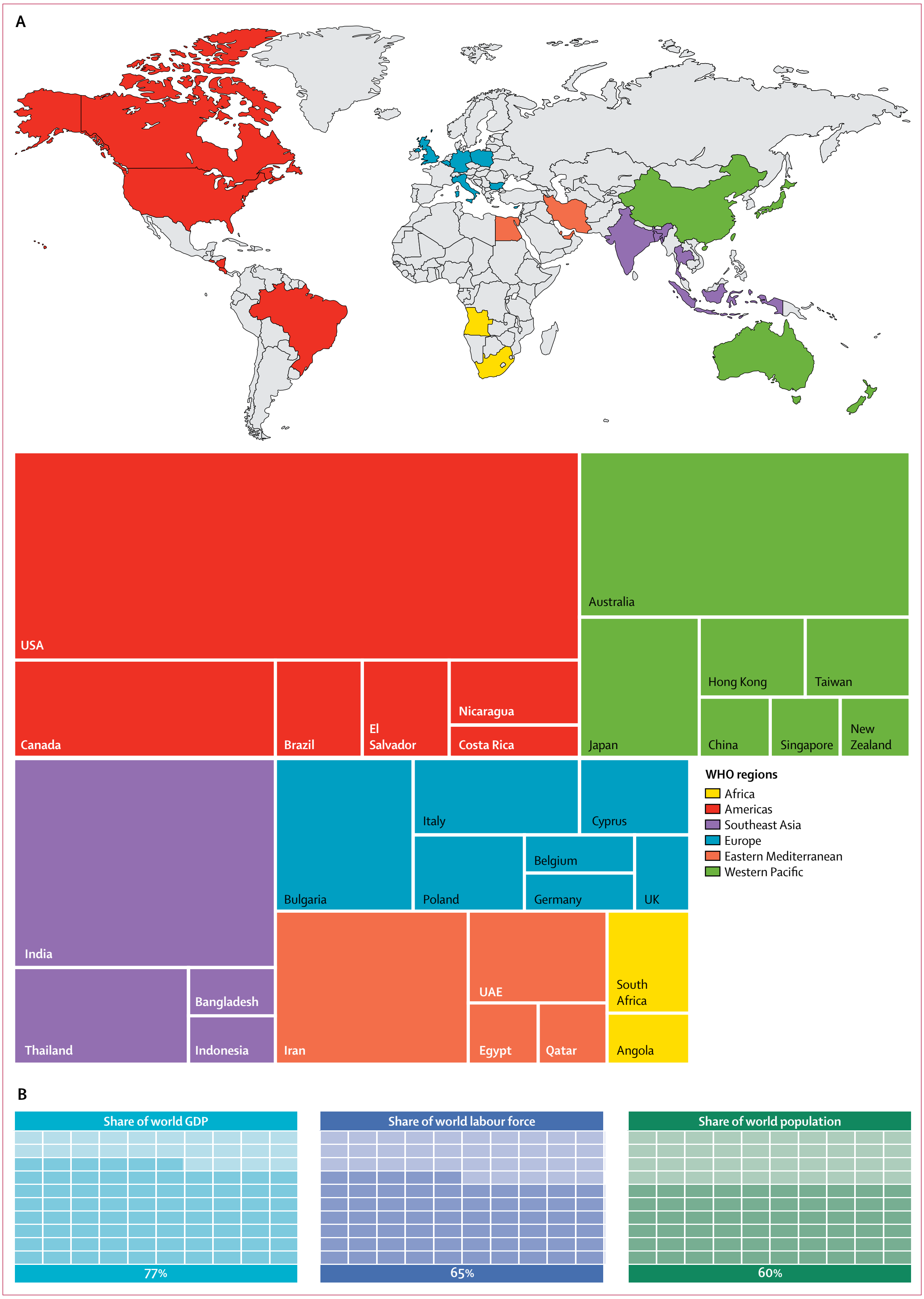

***Figure 2*: 30 countries where the 111 included studies took place**
(A) Area plot indicating the number of studies per country categorised by WHO region. (B) Key performance indicators for the 30 countries. Share of world GDP estimated based on data from the International Monetary Fund World Economic Outlook Database, 2017;[30] share of world labour force estimated based on the Central Intelligence Agency World Factbook, 2018;[31] share of world population estimated based on data from the World Population Prospects: The 2017 Revision by the UN, Department of Economic and Social Affairs, Population Division.[32] GDP=gross domestic product. UAE=United Arab Emirates.

	Outcome	Studies included	Number of positive events in workers assessed*	Controls	Prevalence (95% CI)	Odds ratio (95% CI)	Mean difference (95% CI)	I^2	Risk of bias (%)†					
									A	B	C	D	E	F
1	Prevalence of occupational heat strain	33	2517/13 088	··	35% (31–39)	··	··	97%	77	100	13	0	90	59
2	Prevalence of kidney disease or acute kidney injury	10	80/21 721	··	15% (11–19)	··	··	96%	58	92	25	8	92	58
3	Prevalence of productivity loss	11	961/8076	··	30% (21–39)	··	··	98%	64	91	0	0	82	45
4	Occupational heat strain during or at end of a work shift	8	420/2009	217/9573	..	4·01 (2·45–6·58)	··	73%	78	100	0	0	100	56
5	Average core temperature during work shift in heat stress conditions	17	575	515	..	··	0·7°C (0·4–1·0)	99%	78	100	0	0	94	89
6	Change in urine specific gravity due to a work shift in heat stress conditions	14	679	684	..	··	0·003 (0·001–0·005)	71%	80	100	0	0	100	80

*For meta-analyses 5 and 6, number of workers assessed shown only. †Risk of bias estimates are the proportion of studies assessed as low risk in terms of selection bias (A), performance bias (B), detection bias (C), attrition bias (D), selective outcome bias (E), and confounding factors bias (F).

Table: **Six random-effects meta-analyses assessing the effects of occupational heat strain on workers' health and productivity outcomes**

climate zones, and WHO regions (figure 2). 56 (50%) of 111 studies did not report funding. The remaining studies were funded by government agencies (41 [40%]), industrial actors (six [5%]), or by government and industrial cofunding (8 [7%]). From the 88 included studies that examined health-related outcomes due to occupational heat strain, 62 (70%) reported ranges for WBGT of 19·3–52·0°C and air temperature of 21·2–150·0°C (this extreme value was recorded in a steel plant worksite). From the 14 included studies that examined productivity loss due to occupational heat strain, 10 (71%) reported ranges of WBGT (21·2–52·0°C) and air temperature (26·8–38·0°C). The main characteristics and outcomes are reported in the appendix.

We used data from 64 studies, which included a total of 55 791 workers, to do the meta-analyses. 22 studies provided sufficient information to be used in more than one analysis.[33–54] 33 studies including 13 088 workers were included in meta-analysis one. The pooled proportion of individuals experiencing occupational heat strain during or at the end of a work shift in heat stress conditions was 35% (95% CI 31–39; appendix). Ten studies with 21 721 workers were included in meta-analysis two. The pooled proportion of individuals who frequently work in heat stress conditions and experience kidney disease or acute kidney injury was 15% (11–19; appendix). 11 studies with 8076 workers were included in meta-analysis three. The pooled proportion of individuals showing productivity loss due to occupational heat strain during work in heat stress conditions was 30% (21–39; appendix). In addition to the prevalence of productivity loss, seven studies[4–6,38,55–57] reported precise changes in productivity as a function of environmental heat stress. These studies suggest an average 2·6% productivity decline (individual study estimates: 0·8%,[4] 1·4%,[5] 1·8%,[56] 2·2%,[38] 2·8%,[57] 4·4%,[55] 5·0%[6]) for every degree increase beyond 24°C WBGT. Nine studies with 11 582 workers were included in meta-analysis four. Individuals working in heat stress conditions were more likely to experience occupational heat strain during or at the end of a work shift compared with individuals working in thermoneutral conditions (OR 4·01 [2·45–6·58]; table; appendix). 17 studies with 633 workers were included in meta-analysis five. The average increase in core temperature during a single work shift due to working in heat stress conditions was 0·7°C (0·4–1·0°C; table). 14 studies of 691 workers were included in meta-analysis six. The average urine specific gravity during a work shift in thermoneutral conditions was 1·0214, in line with reference values of 1·013 to 1·029 for healthy adults.[58] The average increase due to working in heat stress conditions was 0·0031 (0·0014–0·0048; table; appendix), which is equal to a 14·5% (6·5–22·4) increase.

The variety of populations, exposures, and occupations used in the six meta-analyses provided a wide adoption of evidence synthesis, but resulted in large heterogeneity with an average I^2 of 80% (table). For meta-analyses one to four, GRADE analysis (appendix) revealed that the true effect is likely to be close to the estimate of the effect, but it is possibly substantially different (moderate confidence). For meta-analyses five and six, GRADE analysis revealed that the true effect is likely to be substantially different from the estimate of effect (very low confidence). Most (68%)[4,6,26,33–35,39–43,45,46,50–55,56,57,59–104] of the included studies incorporated low risk for selection bias, with the remaining studies presenting selection bias that was non-applicable (10%),[36,105–126] unclear (16%),[37,47–49,118,127–132] or, in some cases, high risk (6%)[5,38,44,133] due to across-group variation in inclusion or exclusion criteria, and across-group differences in participant recruitment or selection. Most (61%) of the included studies incorporated low risk for confounding factors bias, with the remaining studies presenting confounding factor bias that was unclear (16%)[6,26,36,38,60,62,63,67,80,84,85,92,98–100,102,105,107–111,113,114,134–136] or high risk (23%)[33,35,37,44,45,47,49,59,66,74,83,86,89,91,94,96,118,127,128,132,137,138] due to non-reporting of limitations or no attempt to balance reallocation between groups or variables. However, most (85%) of the included studies incorporated unclear risk of detection bias since almost all included valid and reliable measures, but assessors in only one study[135] were masked to the measurements. Finally, attrition bias was not applicable in 97% of the included studies as most of them were cross-sectional.

Discussion

Our systematic evaluation shows that the effects of occupational heat strain on workers' health and productivity outcomes have been studied heavily across continents and in many different occupations for more than six decades. The quality of studies on this topic is high because most of the included studies incorporated low risk of bias for performance (97%) and selective outcome (93%). Two large-scale epidemiological studies on heat-related illness and mortality (which were not included in our meta-analyses) reported that workplace environmental heat stress is responsible for 13–36 deaths per year in the USA alone.[113,120] It is important to note that seven[67,74,85,87,94,132,135] of the 47 studies excluded in our meta-analyses showed no effect of workplace environmental heat stress on the prevalence of heat-related illness or health outcomes.

Most of the 111 studies included in this systematic review suggest that working in hot conditions (WGBT >22°C for very intense work; WBGT >25°C for most occupations) increases the likelihood of experiencing occupational heat strain, with significant detrimental effects on health and productivity. We attempted to quantify these effects by extracting data from 64 of these studies for use in six meta-analyses. Our results showed that individuals working in heat stress conditions were four times more likely to experience occupational heat strain during or at the end of a work shift compared with individuals working in thermoneutral conditions. Indeed, working a shift in thermoneutral conditions did not lead to physiological or clinical effects on core temperature, which, on average, remained at 36·9°C (SD 0·3). However, individuals who worked a single shift in heat stress conditions showed average core temperature values of 37·6°C (SD 0·4), while 35% of them experienced occupational heat strain. This occupational heat strain is also associated with dehydration; our analyses show that people who worked a single shift in heat stress conditions had an increase of 14·5% in urine specific gravity compared with those who worked a shift in thermoneutral conditions. Given the well-established links between hydration and kidney function,[24] we were not surprised to find that 15% of individuals who typically or frequently (minimum of 6 h per day, 5 days per week, for 2 months of the year for most occupations) worked in heat stress conditions had kidney disease or acute kidney injury. Finally, in our analyses, 30% of individuals working in heat stress conditions had losses in productivity. These losses increased by 2·6% for every degree increase beyond 24°C WBGT.

Possible effect modifiers should be considered when interpreting the present results. The analysed studies did not provide clear information to allow for occupational classification into formal or informal sectors. Moreover, 54 of the analysed studies assessed indoor workers, 33 assessed outdoor workers, while 24 of the analysed studies did large-scale epidemiological assessments of many indoor and outdoor workers. To avoid reducing the statistical power of the meta-analyses and the clarity of the review (by presenting 12 meta-analyses), we did not divide our analyses into indoor and outdoor workers.

Our estimate that 35% of individuals working in heat stress conditions experience occupational heat strain is in line with the 30% (95% CI 24–36) prevalence reported for increased susceptibility to heat stress (an inability to mitigate hyperthermia) when working or exercising in hot environments,[139] and with epidemiological data[140,141] for morbidity and mortality during extreme heat events. When compared with normative values for healthy,[142–144] obese,[145] or acutely-ill[146] adults, the average core temperature of 37·6°C estimated for individuals working a shift under heat stress is considered borderline hyperthermia or pyrexia. While core temperature thresholds for hyperthermia, fever, and heat injury vary across individuals,[144] those who are older, obese, unfit, have chronic disease, or experience acute illness or infection are at a high risk for heat-induced pathologies (eg, heat cramps, heat exhaustion, and heat stroke).[1,7,139,147]

We used the standard definitions of kidney disease and acute kidney injury proposed by the KDIGO clinical practice guidelines workgroup[24] and found that 15% of individuals working in heat stress have these conditions, which is markedly higher than the prevalence rates reported for kidney disease (10%)[148] and acute kidney injury in high-income (2%)[149,150] and low-income (3–9%)[151,152] countries. Taken together, these results raise serious concerns for the kidney function of individuals who typically or frequently work in heat stress conditions, because even a single episode of acute kidney injury can lead to chronic kidney disease, with substantial socioeconomic and public health outcomes.[153]

The present systematic review and meta-analysis includes various populations, exposures, and occupations to allow the synthesis of a broad range of evidence.[154] While this approach allowed us to form a meaningful conclusion instead of narrowing down our research question, it resulted in large heterogeneity in our meta-analyses. We addressed this issue by implementing a GRADE analysis, which revealed moderate confidence in the results of our meta-analyses one to four and very low confidence in the results of our meta-analyses five and six, which was largely because 23·5% of studies in five and 28·5% of studies in six were funded by industry.

Overall, this study included over 447 million workers from more than 40 different occupations across 30 countries around the globe, including countries from all continents, relevant climate zones, and WHO regions. The countries included comprise 77% of the world gross domestic product, 65% of the global labour force, and 60% of the world population (figure 2). We did not limit our search based on language, population characteristics, region, date, and occupation, and we adopted standardised and comprehensive search approaches for the identification, screening, and extraction of evidence. This approach, and the fact that we pooled all available data from the included studies, mitigates threats to good quality systematic reviews and meta-analyses[154] and increased the total number of cases in our qualitative and quantitative data synthesis. However, our analysis is not without its limitations. First, some studies included in the meta-analyses for the prevalence of occupational heat strain, kidney disease, and productivity loss used self-reported tools to assess symptoms or productivity loss and, therefore, are susceptible to reporting and recall bias. Therefore, our reported prevalence rates might be overestimated or underestimated. Yet, these studies included representative and large samples, which limits the potential for error in their estimates. Second, the devices and methods used to assess core temperature and urine specific gravity vary across the included studies. However, the adopted methods are well accepted, which minimises this bias. Third, many of the analysed studies did not provide exact WBGT or air temperature values as thresholds for occupational heat strain. To address this issue, we report the ranges of WBGT or air temperature for all the studies in which such data are provided. Fourth, the studies included in our meta-analyses were typically regionally confined and were done in cases where a high prevalence or effect was expected. Therefore, the effects reported in this study might not apply in cold regions, seasons, and jobs that are not associated with occupational heat strain or workplace heat exposure. Nonetheless, this study used the best available data and provides working estimates on the effects of occupational heat strain on workers' health and productivity outcomes across 30 countries and many occupations. These data provide useful indicators of the public health burden of occupational heat strain and provide a basis for health and safety policy and for relevant prevention initiatives.

Our findings show that occupational heat strain, a fully preventable condition, has important health and productivity outcomes and should be recognised as a public health problem. Concerted international action is needed to mitigate the effects of occupational heat strain, particularly in light of climate change and the anticipated rise in environmental heat stress. The presented evidence shows the urgent need to establish a surveillance system to monitor prevalence of occupational heat strain throughout the world. At the same time, increased efforts should be made to educate workers and employers about the health and performance effects of occupational heat strain, and appropriate screening protocols should be incorporated within health and safety legislation. Importantly, physicians and other health-care providers can play a crucial part in the primary prevention and management of occupational heat strain.

Contributors

ADF, LN, GH, GPK, and TK led the conception of the study. ADF, PCD, LGI, and LN led the design of the study. ADF, PCD, and LGI led the data collection, quality assessment, and data extraction and analysis. All authors contributed to data interpretation. ADF led the manuscript writing. PCD, LGI, GH, and GPK contributed to writing the manuscript. All authors contributed to the revision and final formulation of the manuscript.

Declaration of interests

We declare no competing interests.

Acknowledgments

This work was funded by the EU Horizon 2020 research and innovation programme (no.668786).

References

1 Mora C, Dousset B, Caldwell IR, et al. Global risk of deadly heat. *Nat Clim Chang* 2017; **7:** 501–06.
2 Borden KA, Cutter SL. Spatial patterns of natural hazards mortality in the United States. *Int J Health Geogr* 2008; **7:** 64.
3 Luber G, McGeehin M. Climate change and extreme heat events. *Am J Prev Med* 2008; **35:** 429–35.
4 Ioannou LG, Tsoutsoubi L, Samoutis G, et al. Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers. *Temperature (Austin)* 2017; **4:** 330–40.
5 Quiller G, Krenz J, Ebi K, et al. Heat exposure and productivity in orchards: implications for climate change research. *Arch Environ Occup Health* 2017; **72:** 313–16.
6 Sahu S, Sett M, Kjellstrom T. Heat exposure, cardiovascular stress and work productivity in rice harvesters in India: implications for a climate change future. *Ind Health* 2013; **51:** 424–31.
7 Kenny GP, Groeller H, McGinn R, Flouris AD. Age, human performance, and physical employment standards. *Appl Physiol Nutr Metab* 2016; **41** (6 suppl 2)**:** S92–107.
8 Kjellstrom T, Lemke B, Otto M, Hyatt OKD. Occupational heat stress: contribution to WHO project on "Global assessment of the health impacts of climate change", which started in 2009. Mapua: Health and Environment International Trust, 2014.
9 Kjellstrom T, Lemke B, Otto M, Hyatt O, Briggs D, Freyberg C. Threats to occupational health, labor productivity and the economy from increasing heat during climate change: an emerging global health risk and a challenge to sustainable development and social equity. Mapua: Health and Environment International Trust, 2014.
10 Lowe D, Ebi KL, Forsberg B. Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. *Int J Environ Res Public Health* 2011; **8:** 4623–48.
11 WHO. World Health Assembly resolution WHA60·26, "Workers' Health: Global Plan of Action". Geneva: World Health Organization, 2007.
12 Nybo L, Kjellstrom T, Bogataj LK, Flouris AD. Global heating: attention is not enough; we need acute and appropriate actions. *Temperature (Austin)* 2017; **4:** 199–201.
13 Moher D, Liberati A, Tetzlaff J, Altman DG, and the PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med* 2009; **6:** e1000097.
14 Viswanathan M, Berkman ND, Dryden DM, Hartling L. Assessing risk of bias and confounding in observational studies of interventions or exposures: further development of the RTI Item Bank. Rockville, MD: Agency for Healthcare Research and Quality (US), 2013.
15 Margulis AV, Pladevall M, Riera-Guardia N, et al. Quality assessment of observational studies in a drug-safety systematic review, comparison of two tools: the Newcastle-Ottawa Scale and the RTI item bank. *Clin Epidemiol* 2014; **6:** 359–68.

16 Al-Saleh MA, Armijo-Olivo S, Thie N, et al. Morphologic and functional changes in the temporomandibular joint and stomatognathic system after transmandibular surgery in oral and oropharyngeal cancers: systematic review. *J Otolaryngol Head Neck Surg* 2012; **41:** 345–60.

17 ACGIH. Heat Stress and Strain: TLV Physical Agents Documentation. Cincinatti, OH: American Conference of Governmental Industrial Hygienists, 2007.

18 ISO. Ergonomics of the thermal environment—analytical determination and interpretation of heat stress using calculation of the predicted heat strain (ISO 7933:2004). London: The British Standards Institution, 2004.

19 WHO. Health factors involved in working under conditions of heat stress. Technical report 412. WHO Scientific Group on health factors involved in working under conditions of heat stress. Geneva: World Health Organization, 1969.

20 World Meteorological Organization, WHO. Heatwaves and health: guidance on warning-system development. Geneva: World Meteorological Organization, 2015.

21 Sawka MN, Burke LM, Eichner ER, et al. American College of Sports Medicine position stand. Exercise and fluid replacement. *Med Sci Sports Exerc* 2007; **39:** 377–90.

22 WHO. International Expert Consultation on chronic kidney Disease of unknown etiology. Colombo: World Health Organization, 2016.

23 Menon M, Resnick MI. Urinary lithiasis: etiology, diagnosis, and medical management. In: Walsh PC, Retik AB, Vaughan EDJ, Wein AJ, eds. Campbell's Urology. 8th ed. Philadelphia, PA: WB Saunders, 2002: 3229–34.

24 Acute Kidney Injury Work Group. Kidney Disease: Improving Global Outcomes (KDIGO). KDIGO clinical practice guideline for acute kidney injury. *Kidney Int* 2012; **2** (suppl)**:** 1–138.

25 Halonen JI, Zanobetti A, Sparrow D, Vokonas PS, Schwartz J. Outdoor temperature is associated with serum HDL and LDL. *Environ Res* 2011; **111:** 281–87.

26 Vangelova K, Deyanov C, Ivanova M. Dyslipidemia in industrial workers in hot environments. *Cent Eur J Public Health* 2006; **14:** 15–17.

27 Review Manager (RevMan) [Computer program]. Version 5.3. Copenhagen: The Nordic Cochrane Centre. The Cochrane Collaboration, 2014.

28 Guyatt GH, Oxman AD, Kunz R, et al. What is "quality of evidence" and why is it important to clinicians? *BMJ* 2008; **336:** 995–98.

29 Higgins JPT, Green S (eds). Cochrane handbook for systematic reviews of interventions version 5.1.0 [updated March 2011]. The Cochrane Collaboration, 2011. http://handbook.cochrane.org (accessed Sept 28, 2018).

30 International Monetary Fund. World economic and financial surveys. World economic outlook database, 2017. https://www.imf.org/external/pubs/ft/weo/2017/02/weodata/index.aspx (accessed Nov 8, 2018).

31 Central Intelligence Agency. World factbook, 2018. https://www.cia.gov/library/publications/the-world-factbook/fields/2018.html (accessed Nov 8, 2018).

32 UN DESA. World population prospects. The 2017 revision. New York, NY: UN Department of Economic and Social Affairs, 2017.

33 Venugopal V, Rekha S, Manikandan K, et al. Heat stress and inadequate sanitary facilities at workplaces—an occupational health concern for women? *Glob Health Action* 2016; **9:** 31945.

34 Vangelova KK, Deyanov CE. Blood pressure and serum lipids in industrial workers under intense noise and a hot environment. *Rev Environ Health* 2007; **22:** 303–11.

35 Hunt AP, Parker AW, Stewart IB. Symptoms of heat illness in surface mine workers. *Int Arch Occup Environ Health* 2013; **86:** 519–27.

36 Arcury TA, Summers P, Talton JW, et al. Heat illness among North Carolina Latino Farmworkers. *J Occup Environ Med* 2015; **57:** 1299–304.

37 Wesseling C, Aragón A, González M, et al. Heat stress, hydration and uric acid: a cross-sectional study in workers of three occupations in a hotspot of Mesoamerican nephropathy in Nicaragua. *BMJ Open* 2016; **6:** e011034.

38 Langkulsen U, Vichit-Vadakan N, Taptagaporn S. Health impact of climate change on occupational health and productivity in Thailand. *Glob Health Action* 2010; **3:** 3.

39 Meade RD, D'Souza AW, Krishen L, Kenny GP. The physiological strain incurred during electrical utilities work over consecutive work shifts in hot environments: a case report. *J Occup Environ Hyg* 2017; **14:** 986–94.

40 Hunt AP, Parker AW, Stewart IB. Heat strain and hydration status of surface mine blast crew workers. *J Occup Environ Med* 2014; **56:** 409–14.

41 Mairiaux P, Malchaire J. Workers self-pacing in hot conditions: a case study. *Appl Ergon* 1985; **16:** 85–90.

42 Meade RD, Lauzon M, Poirier MP, Flouris AD, Kenny GP. An evaluation of the physiological strain experienced by electrical utility workers in North America. *J Occup Environ Hyg* 2015; **12:** 708–20.

43 Peiffer JJ, Abbiss CR. Thermal stress in North Western Australian iron ore mining staff. *Ann Occup Hyg* 2013; **57:** 519–27.

44 Brearley M, Harrington P, Lee D, Taylor R. Working in hot conditions—a study of electrical utility workers in the northern territory of Australia. *J Occup Environ Hyg* 2015; **12:** 156–62.

45 Atan L, Andreoni C, Ortiz V, et al. High kidney stone risk in men working in steel industry at hot temperatures. *Urology* 2005; **65:** 858–61.

46 Borghi L, Meschi T, Amato F, Novarini A, Romanelli A, Cigala F. Hot occupation and nephrolithiasis. *J Urol* 1993; **150:** 1757–60.

47 Crowe J, Nilsson M, Kjellstrom T, Wesseling C. Heat-related symptoms in sugarcane harvesters. *Am J Ind Med* 2015; **58:** 541–48.

48 Donoghue AM, Sinclair MJ, Bates GP. Heat exhaustion in a deep underground metalliferous mine. *Occup Environ Med* 2000; **57:** 165–74.

49 Dutta P, Rajiva A, Andhare D, et al. Perceived heat stress and health effects on construction workers. *Indian J Occup Environ Med* 2015; **19:** 151–58.

50 Indulski JA, Spioch FM. Heat stress and voluntary dehydration in steelworkers. *Pol J Occup Med* 1988; **1:** 286–97.

51 Krishnamurthy M, Ramalingam P, Perumal K, et al. Occupational heat stress impacts on health and productivity in a steel industry in southern India. *Saf Health Work* 2017; **8:** 99–104.

52 Montazer S, Farshad AA, Monazzam MR, Eyvazlou M, Yaraghi AA, Mirkazemi R. Assessment of construction workers' hydration status using urine specific gravity. *Int J Occup Med Environ Health* 2013; **26:** 762–69.

53 Moyce S, Mitchell D, Armitage T, Tancredi D, Joseph J, Schenker M. Heat strain, volume depletion and kidney function in California agricultural workers. *Occup Environ Med* 2017; **74:** 402–09.

54 Singh A, Kamal R, Mudiam MKR, et al. Heat and PAHs emissions in indoor kitchen air and its impact on kidney dysfunctions among kitchen workers in Lucknow, North India. *PLoS One* 2016; **11:** e0148641.

55 Gun RT, Budd GM. Effects of thermal, personal and behavioural factors on the physiological strain, thermal comfort and productivity of Australian shearers in hot weather. *Ergonomics* 1995; **38:** 1368–84.

56 Sett M, Sahu S. Effects of occupational heat exposure on female brick workers in West Bengal, India. *Glob Health Action* 2014; **7:** 21923.

57 Yi W, Chan APC. Effects of heat stress on construction labor productivity in Hong Kong: a case study of rebar workers. *Int J Environ Res Public Health* 2017; **14:** E1055.

58 Baron S, Courbebaisse M, Lepicard EM, Friedlander G. Assessment of hydration status in a large population. *Br J Nutr* 2015; **113:** 147–58.

59 Bardosono S, Ilyas E. Health, nutrition and hydration status of Indonesian workers: A preliminary study in two different environmental settings. *Med J Indonesia* 2014; **23:** 112–16.

60 Bates GP, Schneider J. Hydration status and physiological workload of UAE construction workers: a prospective longitudinal observational study. *J Occup Med Toxicol* 2008; **3:** 21.

61 Bethel JW, Harger R. Heat-related illness among Oregon farmworkers. *Int J Environ Res Public Health* 2014; **11:** 9273–85.

62 Brabant C. Heat exposure standards and women's work: equitable or debatable? *Women Health* 1992; **18:** 119–30.

63 Brabant C, Bédard S, Mergler D. Cardiac strain among women workers in an industrial laundry. *Ergonomics* 1989; **32:** 615–28.

64 Dehghan H, Mortazavi S, Jafari M, Maracy M, Jahangiri M. The evaluation of heat stress through monitoring environmental factors and physiological responses in melting and casting industries workers. *Int J Env Health Eng* 2012; **1:** 21.

65 Dehghan H, Mortazavi SB, Jafari MJ, Maracy MR. Evaluation of wet bulb globe temperature index for estimation of heat strain in hot/humid conditions in the Persian Gulf. *J Res Med Sci* 2012; **17:** 1108–13.

66 Delgado Cortez O. Heat stress assessment among workers in a Nicaraguan sugarcane farm. *Glob Health Action* 2009; **2:** 2.

67 el-Said KF, el-Sharkawy MF, Abdel-Hamid HA. Biochemical changes and environmental factors in manual and semiautomatic bakeries. *J Egypt Public Health Assoc* 2003; **78:** 95–111.

68 Fleischer NL, Tiesman HM, Sumitani J, et al. Public health impact of heat-related illness among migrant farmworkers. *Am J Prev Med* 2013; **44:** 199–206.

69 García-Trabanino R, Jarquín E, Wesseling C, et al. Heat stress, dehydration, and kidney function in sugarcane cutters in El Salvador–A cross-shift study of workers at risk of Mesoamerican nephropathy. *Environ Res* 2015; **142:** 746–55.

70 Giahi O, Darvishi E, Aliabadi M, Khoubi J. The efficacy of radiant heat controls on workers' heat stress around the blast furnace of a steel industry. *Work* 2015; **53:** 293–98.

71 Gomes J, Lloyd O, Norman N. The health of the workers in a rapidly developing country: effects of occupational exposure to noise and heat. *Occup Med (Lond)* 2002; **52:** 121–28.

72 Hamerezaee M, Dehghan SF, Golbabaei F, Fathi A, Barzegar L, Heidarnejad N. Assessment of semen quality among workers exposed to heat stress: a cross-sectional study in a steel industry. *Saf Health Work* 2018; **9:** 232–35.

73 Huang YK, Lin CW, Chang CC, et al. Heat acclimation decreased oxidative DNA damage resulting from exposure to high heat in an occupational setting. *Eur J Appl Physiol* 2012; **112:** 4119–26.

74 Inaba R, Mirbod SM. Comparison of subjective symptoms and hot prevention measures in summer between traffic control workers and construction workers in Japan. *Ind Health* 2007; **45:** 91–99.

75 Kalkowsky B, Kampmann B. Physiological strain of miners at hot working places in German coal mines. *Ind Health* 2006; **44:** 465–73.

76 Knez W, Girard O, Racinais S, Walsh A, Gaoua N, Grantham J. Does living and working in a hot environment induce clinically relevant changes in immune function and voluntary force production capacity? *Ind Health* 2014; **52:** 235–39.

77 Koh D. An outbreak of occupational dermatosis in an electronics store. *Contact Dermat* 1995; **32:** 327–30.

78 Krishnan S, Kumar AP, Maruthy KN, Jeremiah PR, Venugopal V. Physiological implications of occupational heat stress for maintenance workers in a residential complex in Chennai—an exploratory intervention trial. *Indian J Physiol Pharmacol* 2017; **61:** 23–29.

79 Logan PW, Bernard TE. Heat stress and strain in an aluminum smelter. *Am Ind Hyg Assoc J* 1999; **60:** 659–65.

80 Lundgren-Kownacki K, Kjellberg SM, Gooch P, Dabaieh M, Anandh L, Venugopal V. Climate change-induced heat risks for migrant populations working at brick kilns in India: a transdisciplinary approach. *Int J Biometeorol* 2018; **62:** 347–58.

81 Lutz EA, Reed RJ, Turner D, Littau SR. Occupational heat strain in a hot underground metal mine. *J Occup Environ Med* 2014; **56:** 388–96.

82 Macfarlane WV, Howard B, Morrison JF, Wyndham CH. Content and turnover of water in Bantu miners acclimatizing to humid heat. *J Appl Physiol* 1966; **21:** 978–84.

83 Maeda T, Kaneko SY, Ohta M, Tanaka K, Sasaki A, Fukushima T. Risk factors for heatstroke among Japanese forestry workers. *J Occup Health* 2006; **48:** 223–29.

84 Mazlomi A, Golbabaei F, Farhang Dehghan S, et al. The influence of occupational heat exposure on cognitive performance and blood level of stress hormones: a field study report. *Int J Occup Saf Ergon* 2017; **23:** 431–39.

85 Mazloumi A, Golbabaei F, Mahmood Khani S, et al. Evaluating effects of heat stress on cognitive function among workers in a hot Industry. *Health Promot Perspect* 2014; **4:** 240–46.

86 Mirabelli MC, Quandt SA, Crain R, et al. Symptoms of heat illness among Latino farm workers in North Carolina. *Am J Prev Med* 2010; **39:** 468–71.

87 Morioka I, Miyai N, Miyashita K. Hot environment and health problems of outdoor workers at a construction site. *Ind Health* 2006; **44:** 474–80.

88 Mutic AD, Mix JM, Elon L, et al. Classification of Heat-Related Illness Symptoms Among Florida Farmworkers. *J Nurs Scholarsh* 2018; **50:** 74–82.

89 Nag PK, Dutta P, Nag A. Critical body temperature profile as indicator of heat stress vulnerability. *Ind Health* 2013; **51:** 113–22.

90 Parameswarappa SB, Narayana J. Assessment of effectiveness of cool coat in reducing heat strain among workers in steel industry. *Indian J Occup Environ Med* 2017; **21:** 29–35.

91 Patel HC, Rao NM, Saha A. Heat exposure effects among firefighters. *Indian J Occup Environ Med* 2006; **10:** 121–23.

92 Paull JM, Rosenthal FS. Heat strain and heat stress for workers wearing protective suits at a hazardous waste site. *Am Ind Hyg Assoc J* 1987; **48:** 458–63.

93 Rodrigues VA, Braga CS, Campos JC, et al. Assessment of physical workload in boiler operations. *Work* 2012; **41**(suppl 1)**:** 406–13.

94 Shearer S. Dehydration and serum electrolyte changes in South African gold miners with heat disorders. *Am J Ind Med* 1990; **17:** 225–39.

95 Spector JT, Krenz J, Blank KN. Risk factors for heat-related illness in Washington crop workers. *J Agromed* 2015; **20:** 349–59.

96 Spioch FM, Nowara M. Voluntary dehydration in men working in heat. *Int Arch Occup Environ Health* 1980; **46:** 233–39.

97 Taylor NA, Caldwell JN, Dyer R. The physiological demands of horseback mustering when wearing an equestrian helmet. *Eur J Appl Physiol* 2008; **104:** 289–96.

98 Vangelova K, Deyanov C, Velkova D, Ivanova M, Stanchev V. The effect of heat exposure on cortisol and catecholamine excretion rates in workers in glass manufacturing unit. *Cent Eur J Public Health* 2002; **10:** 149–52.

99 Vangelova KK, Deyanov C, Velkova D, Ivanova M, Stanchev V. Heat stress in two manufacturing units. *Acta Medica Bulgarica* 2008; **35:** 40–46.

100 Vangelova KK, Deyanov CE. The effect of high ambient temperature on the adjustment of operators to fast rotating 12-hour shiftwork. *Rev Environ Health* 2000; **15:** 373–79.

101 Wegman DH, Apelqvist J, Bottai M, et al. Intervention to diminish dehydration and kidney damage among sugarcane workers. *Scand J Work Environ Health* 2018; **44:** 16–24.

102 Wojtczak-Jaroszowa J, Jarosz D. Health complaints, sicknesses and accidents of workers employed in high environmental temperatures. *Can J Public Health* 1986; **77** (suppl 1)**:** 132–35.

103 Wyndham CH, Strydom NB, Morrison JF, Du Toit FD, Kraan JG. A new method of acclimatization to heat. *Arbeitsphysiologie* 1954; **15:** 373–82.

104 Xiang J, Hansen A, Pisaniello D, Bi P. Workers' perceptions of climate change related extreme heat exposure in South Australia: a cross-sectional survey. *BMC Public Health* 2016; **16:** 549.

105 Lamb S, Kwok KC. A longitudinal investigation of work environment stressors on the performance and wellbeing of office workers. *Appl Ergon* 2016; **52:** 104–11.

106 Tawatsupa B, Lim LL, Kjellstrom T, Seubsman SA, Sleigh A, and the Thai Cohort Study Team. Association between occupational heat stress and kidney disease among 37,816 workers in the Thai Cohort Study (TCS). *J Epidemiol* 2012; **22:** 251–60.

107 Armed Forces Health Surveillance Center. Update: heat injuries, active component, U.S. Armed Forces, 2011. *MSMR* 2012; **19:** 14–16.

108 Armed Forces Health Surveillance Center. Update: heat injuries, active component, U.S. Armed Forces, 2012. *MSMR* 2013; **20:** 17–20.

109 Armed Forces Health Surveillance Center. Update: heat injuries, active component, U.S. Armed Forces, 2013. *MSMR* 2014; **21:** 10–13.

110 Armed Forces Health Surveillance Center. Update: Heat injuries, active component, U.S. Armed Forces, 2014. *MSMR* 2015; **22:** 17–20.

111 Armed Forces Health Surveillance Center. Update: Heat illness, active component, U.S. Armed Forces, 2016. *MSMR* 2017; **24:** 9–13.

112 Adam-Poupart A, Smargiassi A, Busque MA, et al. Summer outdoor temperature and occupational heat-related illnesses in Quebec (Canada). *Environ Res* 2014; **134:** 339–44.

113 Arbury S, Jacklitsch B, Farquah O, et al. Heat illness and death among workers—United States, 2012–2013. *MMWR Morb Mortal Wkly Rep* 2014; **63:** 661–65.

114 Armed Forces Health Surveillance Center. Update: Heat injuries, active component, U.S. Army, Navy, Air Force, and Marine Corps, 2015. *MSMR* 2016; **23:** 16–19.

115 Bonauto D, Anderson R, Rauser E, Burke B. Occupational heat illness in Washington State, 1995–2005. *Am J Ind Med* 2007; **50:** 940–50.
116 Dellinger AM, Kachur SP, Sternberg E, Russell J. Risk of heat-related injury to disaster relief workers in a slow-onset flood disaster. *J Occup Environ Med* 1996; **38:** 689–92.
117 Dickinson JG. Heat illness in the services. *J R Army Med Corps* 1994; **140:** 7–12.
118 Donoghue AM. Heat illness in the U.S. mining industry. *Am J Ind Med* 2004; **45:** 351–56.
119 Fortune MK, Mustard CA, Etches JJ, Chambers AG. Work-attributed illness arising from excess heat exposure in Ontario, 2004–2010. *Can J Public Health* 2013; **104:** e420–26.
120 Gubernot DM, Anderson GB, Hunting KL. Characterizing occupational heat-related mortality in the United States, 2000–2010: an analysis using the Census of Fatal Occupational Injuries database. *Am J Ind Med* 2015; **58:** 203–11.
121 Harduar Morano L, Bunn TL, Lackovic M, et al. Occupational heat-related illness emergency department visits and inpatient hospitalizations in the southeast region, 2007–2011. *Am J Ind Med* 2015; **58:** 1114–25.
122 Ricco M. Air temperature exposure and agricultural occupational injuries in the Autonomous Province of Trento (2000–2013, North-Eastern Italy). *Int J Occup Med Environ Health* 2018; **31:** 317–31.
123 Spector JT, Krenz J, Rauser E, Bonauto DK. Heat-related illness in Washington State agriculture and forestry sectors. *Am J Ind Med* 2014; **57:** 881–95.
124 Tawatsupa B, Lim LL, Kjellstrom T, Seubsman SA, Sleigh A, and the Thai Cohort Study Team. The association between overall health, psychological distress, and occupational heat stress among a large national cohort of 40,913 Thai workers. *Glob Health Action* 2010; **3:** 10.3402/gha.v3i0.5034.
125 Tawatsupa B, Yiengprugsawan V, Kjellstrom T, Berecki-Gisolf J, Seubsman SA, Sleigh A. Association between heat stress and occupational injury among Thai workers: findings of the Thai Cohort Study. *Ind Health* 2013; **51:** 34–46.
126 Xiang J, Bi P, Pisaniello D, Hansen A, Sullivan T. Association between high temperature and work-related injuries in Adelaide, South Australia, 2001–2010. *Occup Environ Med* 2014; **71:** 246–52.
127 Dang BN, Dowell CH. Factors associated with heat strain among workers at an aluminum smelter in Texas. *J Occup Environ Med* 2014; **56:** 313–18.
128 Brake DJ, Bates GP. Deep body core temperatures in industrial workers under thermal stress. *J Occup Environ Med* 2002; **44:** 125–35.
129 Rahman J, Fakhruddin SHM, Rahman AKMF, Halim MA. Environmental heat stress among young working women: a pilot study. *Ann Glob Health* 2016; **82:** 760–67.
130 Rastogi SK, Gupta BN, Husain T, Mathur N. Physiological responses to thermal stress in a glass bangle factory. *J Soc Occup Med* 1988; **38:** 137–42.
131 Brake DJ, Bates GP. Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. *Occup Environ Med* 2003; **60:** 90–96.
132 Spector JT, Krenz J, Calkins M, et al. Associations between heat exposure, vigilance, and balance performance in summer tree fruit harvesters. *Appl Ergon* 2018; **67:** 1–8.
133 Venugopal V, Chinnadurai JS, Lucas RA, Kjellstrom T. Occupational heat stress profiles in selected workplaces in India. *Int J Environ Res Public Health* 2015; **13:** E89.
134 Chen ML, Chen CJ, Yeh WY, Huang JW, Mao IF. Heat stress evaluation and worker fatigue in a steel plant. *AIHA J (Fairfax, Va)* 2003; **64:** 352–59.
135 Figà-Talamanca I, Dell'Orco V, Pupi A, et al. Fertility and semen quality of workers exposed to high temperatures in the ceramics industry. *Reprod Toxicol* 1992; **6:** 517–23.
136 Luo H, Turner LR, Hurst C, Mai H, Zhang Y, Tong S. Exposure to ambient heat and urolithiasis among outdoor workers in Guangzhou, China. *Sci Total Environ* 2014; **472:** 1130–36.
137 Bates GP, Miller VS, Joubert DM. Hydration status of expatriate manual workers during summer in the middle East. *Ann Occup Hyg* 2010; **54:** 137–43.
138 Lumingu HMM, Dessureault P. Physiological responses to heat strain: a study on personal monitoring for young workers. *J Therm Biol* 2009; **34:** 299–305.
139 Flouris AD, McGinn R, Poirier MP, et al. Screening criteria for increased susceptibility to heat stress during work or leisure in hot environments in healthy individuals aged 31–70 years. *Temperature (Austin)* 2017; **5:** 86–99. 142
140 Fouillet A, Rey G, Laurent F, et al. Excess mortality related to the August 2003 heat wave in France. *Int Arch Occup Environ Health* 2006; **80:** 16–24.
141 Rey G, Jougla E, Fouillet A, et al. The impact of major heat waves on all-cause and cause-specific mortality in France from 1971 to 2003. *Int Arch Occup Environ Health* 2007; **80:** 615–26.
142 Del Bene VE. Temperature. In: Walker HK, Hall WD, Hurst JW, eds. Clinical methods: the history, physical, and laboratory examinations. Boston, MA: Butterworths, 1990.
143 Kurz A. Physiology of thermoregulation. *Best Pract Res Clin Anaesthesiol* 2008; **22:** 627–44.
144 Mackowiak PA, Wasserman SS, Levine MM. A critical appraisal of 98·6 degrees F, the upper limit of the normal body temperature, and other legacies of Carl Reinhold August Wunderlich. *JAMA* 1992; **268:** 1578–80.
145 Heikens MJ, Gorbach AM, Eden HS, et al. Core body temperature in obesity. *Am J Clin Nutr* 2011; **93:** 963–67.
146 Laupland KB. Fever in the critically ill medical patient. *Crit Care Med* 2009; **37** (suppl): S273–78.
147 WHO. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. Geneva: World Health Organization, 2014.
148 Eckardt KU, Coresh J, Devuyst O, et al. Evolving importance of kidney disease: from subspecialty to global health burden. *Lancet* 2013; **382:** 158–69.
149 Waikar SS, Curhan GC, Wald R, McCarthy EP, Chertow GM. Declining mortality in patients with acute renal failure, 1988 to 2002. *J Am Soc Nephrol* 2006; **17:** 1143–50.
150 Xue JL, Daniels F, Star RA, et al. Incidence and mortality of acute renal failure in Medicare beneficiaries, 1992 to 2001. *J Am Soc Nephrol* 2006; **17:** 1135–42.
151 Naicker S, Aboud O, Gharbi MB. Epidemiology of acute kidney injury in Africa. *Semin Nephrol* 2008; **28:** 348–53.
152 Krishnamurthy S, Mondal N, Narayanan P, Biswal N, Srinivasan S, Soundravally R. Incidence and etiology of acute kidney injury in southern India. *Indian J Pediatr* 2013; **80:** 183–89.
153 Lameire NH, Bagga A, Cruz D, et al. Acute kidney injury: an increasing global concern. *Lancet* 2013; **382:** 170–79.
154 Ioannidis J. Next-generation systematic reviews: prospective meta-analysis, individual-level data, networks and umbrella reviews. *Br J Sports Med* 2017; **51:** 1456–58.