A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP14057.

Quantification of the Heat-Related Risk and Burden of Hospitalizations for Cause-Specific Injuries and Contribution of Human-Induced Climate Change: A Time-Stratified Case-Crossover Study in China

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Background: Although ambient temperature has been linked with injury incidence, there have been few nationwide studies to quantify the temperature-related risk and burden of cause-specific injury hospitalizations. Additionally, the impact of human-induced climate change to injury burden remains unknown.

Objectives: Our objectives are to examine the associations between ambient temperature and injury hospitalizations from various causes and to quantify the contribution of human-induced warming to the heat-related burden.

Methods: We collected injury hospitalization data from a nationwide hospital-based registry in China during 2000–2019. Using a time-stratified case-crossover design, we investigated the associations between daily mean temperature (°C) and cause-specific injury hospitalizations. We also quantified the burden of heat-related injuries under the scenarios with and without anthropogenic forcing, using the Detection and Attribution Model Intercomparison Project to assess the contribution of human-induced warming.

Results: Our study included a total of 988,087 patients with hospitalization records for injuries. Overall, compared to the temperature at minimum risk of hospitalization (−12.1°C), the relative risk of hospitalization at extreme hot temperature (30.8°C, 97.5th percentile) was 1.18 [95% confidence interval (CI): 1.14, 1.22], with an approximately linear association between temperature and hospitalization. Vulnerability to heat-related injuries was more pronounced among males, young (<18 years of age) or middle-aged (45–64 years of age) individuals, and those living in the North. The heat-related attributable fraction increased from 23.2% in the 2000s to 23.6% in the 2010s, with a corresponding increase in the contribution of human-induced change over time. In the 2010s, the heat-related attributable fractions for specific causes of injury ranged from 12.4% to 54.4%, with human-induced change accounting for 6.7% to 10.6% of the burden.

Discussion: This nationwide study presents new evidence of significant associations between temperature and cause-specific injury hospitalizations in China and highlights the increasing contribution of human-induced warming to the injury burden. https://doi.org/10.1289/EHP14057

Introduction

External causes of injury, including transportation-related injuries, self-harm, falls, and other injuries, are significant causes of death, particularly among young and middle-aged individuals.[1–3] According to the global burden of disease (GBD) study,[2] injuries caused about 249 million disability-adjusted life-years (DALYs) in 2019, with a high incidence and prevalence in the working-age population,[4] leading to significant health care costs and economic productivity losses.[5,6] Environmental factors are ubiquitous causes of injury. For instance, weather-related events and complex traffic patterns could directly lead to injury; nonoptimal environmental conditions could also diminish cognitive function and increase the risk of injury.[7] Particularly, high temperature was identified as the fourth-leading risk factor for DALYs of injury.[2]

Previous studies have explored the relationship between temperature and injury, suggesting detrimental health effects of nonoptimal ambient temperatures.[8,9] However, most of the evidence is limited to developed countries,[8–10] and few studies have been conducted in developing countries, where individual characteristics, socioeconomic levels, and vulnerability might be different.[11] Additionally, previous studies have primarily focused on specific cities[12–14] or certain types of fatal injuries or cause-specific deaths,[11,15] and the effect of temperature on hospitalizations from nonfatal injuries remains to be elucidated. Notably, previous studies suggested that fatal injuries due to different external causes might reflect differential behavioral patterns and mechanisms.[11,15] It is inferred that nonfatal injuries from various causes might also manifest different behavioral patterns and mechanisms, which may differ greatly from those observed in fatal injuries. However, assessment of the ubiquitous nonfatal injuries remains a challenge due to insufficient evidence for detailed and comprehensive injury categories.

Climate change is closely linked to population health, and the irreversible and inevitable impacts of global warming are a major concern worldwide.[16,17] Based on the Coupled Model Intercomparison Project, emerging scenario-based assessments and projections[11,18] provide useful tools for policy-makers, integrating information on how climate change affects population health and what factors drive such changes. Remarkably, human activities have been currently envisioned as the pivotal drivers of dramatic climate change.[19] A global study reported that 37.0% of warm-season heat-related deaths could be attributed to human activities.[20] Nonetheless, few studies have attempted to investigate how human activities affect heat-related hospitalization, particularly for research specifically within

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Supplemental Material is available online (https://doi.org/10.1289/EHP14057).
The authors declare they have no conflicts of interest related to this work to disclose.

Received 25 September 2023; Revised 7 April 2024; Accepted 26 April 2024; Published 16 May 2024.

the field of injury epidemiology. Therefore, an evidence-based and comprehensive understanding is urgently needed to develop effective interventions for maximizing their potential in population health improvement in the context of climate change.

China's extensive population, vast territory, and diverse climatic conditions offer a wealth of data on population health for tracking cause-specific disease burdens and spatial heterogeneity. Therefore, this study aimed to evaluate the association between temperature and hospitalizations from cause-specific injuries over the past decades in China and further quantify the related burden and the contribution of human activities under climate change scenarios.

Methods

Study Design and Population

This study was based on electronic hospitalization records from the SuValue database, a large-scale, nationwide hospital-based disease registry that encompasses 153 hospitals across 20 provincial-level regions of China.[21,22] Hospitalization records for cause-specific injuries from 2000 to 2019, coded according to the 10th Revision of the International Classification of Diseases (ICD-10) codes, were included in the study. The injury hospitalizations were categorized into eight groups based on their sample size (more than 20,000) and characteristics, namely injuries to head and neck (S00–S19), injuries to trunk (S20–S39), injuries to upper limbs (S40–S69), injuries to lower limbs (S70–S99), injuries to multiple or unspecified body region (T00–T14), burn and corrosions (T20–T32), poisoning (T36–T65), and accidental injuries and other causes (V01–V99, W00–X59, T15–T19, T33–T35, T66–T78, T79, T80–T88, T90–T98, X60–Y98). We excluded records from 16 hospitals that did not have injury records for at least 1 year and ultimately analyzed records from 137 hospitals that were widely distributed across 59 main cities in 20 provincial regions.[23] Individual-level data, including age, sex, and hospitalization date, were extracted from the hospitalization records. Records with missing data on individual covariates were further excluded. The proportions of missing data were $<0.5\%$ for sex and no missing data for other covariates and hospitalization date.

Meteorological Data

The daily meteorological data on temperature (°C), relative humidity (%), and precipitation (mm) for each hospital were collected from the nearest monitoring station through the National Meteorological Data Network of the Chinese Meteorological Bureau (http://data.cma.cn/). To assess the impact of human-induced climate change, we utilized model simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) for two climate change scenarios, i.e., the historical scenario (with natural and anthropogenic forcings) and the hist-nat scenario (with only natural forcing).[20] DAMIP is part of the Coupled Model Intercomparison Project Phase 6 (CMIP6), which aims to understand the contributions of various external factors (e.g., anthropogenic forcing) to climate change in the past and future.[24] The two scenarios differ markedly in terms of whether human activities and related greenhouse gases have influenced historical climate since the preindustrial era.

To model the historical temperature series under two scenarios, we used 12 global climate models (GCMs) (Table S1). In line with a previous study,[20] we obtained the daily 2-meter temperature (T2M) datasets from each GCM under the historical scenario (2000–2014), the SSP245 scenario (2015–2019), and the hist-nat scenario (2000–2019), respectively. As historical simulations were only available up to the year 2014, we merged the historical data with simulations from the SSP245 scenario for each GCM to generate temperature series under the scenario with anthropogenic and natural forcings. The simulations derived from the hist-nat scenario were then used to represent the scenario that only accounted for natural forcing. We further downscaled the GCM datasets to a spatial resolution of $1.0^{\circ} \times 1.0^{\circ}$ using bi-linear interpolation[25] and extracted city-specific modeled temperature series in China by linking the coordinate of the city center location to the corresponding cell of the grid. Then, we applied a bias correction procedure using previously described methods.[18,23] Briefly, we collected observed temperature series through the nearest monitoring station for each city center, and generated the correcting factors based on the city-specific historical observations and modeled temperature series under the scenario with anthropogenic and natural forcings. Finally, we applied the same correcting factors to the modeled temperature series under the scenario without anthropogenic forcing.

Statistical Analyses

Associations between temperature and injury hospitalizations. We included the full-year data to assess the associations between ambient temperature and hospitalizations from cause-specific injuries. To maximize the advantage of individual-level data, we applied a time-stratified case-crossover study design in the analyses. This self-matched study design was proposed to evaluate the transient effects of risk factors, allowing for efficient control of measured and unmeasured confounders, such as body mass index (BMI), preexisting conditions, socioeconomic status, and behavioral characteristics.[26] In brief, each record was defined as a case on the hospitalization date, and the corresponding controls were selected as the same weekdays in the same month and year as the case.

The conditional logistic regression model is typically used to perform the analyses of the case-crossover study. In the model, we treated the case and the control as 1 and 0 for the dependent variable, respectively. Additionally, we used the distributed lag nonlinear model (DLNM) to explore the nonlinear and lagged effects of temperature.[27] We selected a natural cubic spline for temperature with 3 degrees of freedom (internal knots placed equally at spaced percentiles of the temperature distributions) to model the exposure–response dimension. As injury hospitalizations from nonoptimal temperature could occur within a short time,[11] we used a natural cubic spline with two internal knots placed at equally spaced values on the log scale over 5 days to account for the lag-response dimension. In addition, we included public holidays to control for holiday effects and included the natural spline for relative humidity with 3 degrees of freedom in the regression model.

With a continuing rise in global temperatures in the context of climate change, this study focused on heat-related risk and burden. Therefore, we excluded injury hospitalizations that were not present with heat-related effect in the further analyses based on prior knowledge, such as frostbite. Consistent with previous studies,[18,28] we assessed the heat-related effect within all temperatures above the reference temperatures, which were defined as the temperature of minimum morbidity risk corresponding to the specific geographic area (Nationwide, North, and South). Here, heat refers to all temperatures above the reference temperature, not temperatures that would be perceived as hot. We assessed the corresponding exposure–response relationships between temperature and each subcategory of injury hospitalizations, based on which we would further exclude those injury hospitalizations that were only significantly associated with temperatures below the reference temperature (i.e., cold-related effects) but not with hot temperatures, as the present study only focused on the heat effects. Finally, we showed the overall cumulative exposure–response curves and reported the relative risk and the corresponding 95% confidence interval (CI) at the extreme hot temperature relative to the reference temperature for injury hospitalizations from eight categories of heat-related cause-specific injuries at the national level. Extreme hot temperature was defined as the 97.5th percentile of temperature distributions.

We performed several stratified analyses by sex (male and female), age (<18, 18–44, 45–64, and ≥65 years of age), and region (North and South) for injury hospitalizations from total causes. Additionally, we assessed the exposure–response relationships between temperature and hospitalizations from cause-specific injuries by region. The cause–region-specific reference temperatures were assessed accordingly. The geographical dividing line between North and South China was selected as the Qin Mountain–Huai River Line. The Z-test and F-test were used to assess between-group differences, and the Bonferroni test was further used to perform multiple-comparison correction for the age subgroups. Besides, several sensitivity analyses were performed to test the robustness of our results. First, we changed the maximum lag periods from 5 to 3 and 7 d. Second, we changed the degrees of freedom for temperature from 3 to 4 and 5. Third, we changed the placement of knots for temperature, with the knots placed at the 10th, 50th, and 90th percentiles or the 10th, 75th, and 90th percentiles of temperature distributions. Fourth, we controlled for daily precipitation in the main model.

Heat-related burden under the climate change scenarios. Based on the temperature–injury association, we evaluated the heat-related attributable fraction (AF) within the temperatures above the reference temperature for both scenarios.[18,23] To provide a comprehensive assessment of the heat-related burden across the study periods and regions, we combined relative risks (RRs) from case-crossover analysis and an aggregated time-series framework to evaluate the attributable burden. This method has been typically applied in the previous investigations assessing attributable burden under the climate change scenarios.[23,29,30] Firstly, we computed the number of excess injury hospitalizations from each cause on the basis of the estimated cumulative relative risk from the corresponding exposure–response association for a given temperature for each day, city, GCM, and scenario. The total number of excess injury hospitalizations was calculated by aggregating the estimates of cause-specific injuries. Then, the corresponding AFs were calculated as the ratio of the corresponding excess injury hospitalizations to the hospitalizations from the cause-specific injuries or total causes. Uncertainties were derived from both the exposure–response relationships and the variability in the temperature series across model simulations in each scenario. In line with previous studies,[18,23] we quantified the uncertainty of estimates by the Monte Carlo analysis with 1,000 simulations, and 95% empirical CIs (95% eCIs) were used to report the results. Additionally, we subtracted the heat-related AF under the scenario without anthropogenic forcing from that under the historical scenario with anthropogenic forcing to represent the magnitude of human-induced change. Finally, we computed the proportion of the human-induced change in the heat-related burden under the historical scenario with anthropogenic forcing. Notably, the contribution of human-induced warming is calculated by model simulations to show the impacts of human activities in the context of climate change. As human-induced warming has intensified in recent decades, we reported our results for 2000–2009 and 2010–2019. We provided the estimated heat-related burdens of injury hospitalizations from total causes and eight categories of cause-specific injuries. We also computed the corresponding burdens of injury hospitalizations from total causes for seven geographical regions (north, northeast, northwest, central, east, south, and southwest) in China to further explore the potential geographical discrepancies. Similarly, city-specific burdens were calculated based on the corresponding cause-region-specific exposure–response associations, then the estimates were aggregated at the regional level.

All statistical analyses were performed in the R statistical software (version 4.1.1) using the "dlnm" and "survival" packages. A two-tailed p-value of <0.05 indicated statistical significance.

Results

Descriptive Data

This study comprised a total of 988,087 patients who were hospitalized for cause-specific injuries in China. There were 28.1% (227,988) hospitalizations for injuries to head and neck, 13.9% (137,726) for injuries to trunk, 25.2% (248,926) for injuries to upper limbs, 19.8% (195,373) for injuries to lower limbs, 7.2% (70,944) for injuries to multiple or unspecified body region, 2.7% (26,761) for burns and corrosions, 3.1% (30,491) for poisoning, and 5.0% (49,878) for accidental injuries and other causes (Table 1). The average of daily mean temperature on the date of hospitalization was 18.4°C [standard deviation $(SD) = 9.7$], the daily mean relative humidity was 72.6% ($SD = 16.4$), and the daily precipitation was 4.0 mm ($SD = 12.3$). The patients included in the analyses had an average age of 41.6 years ($SD = 19.8$). Of these patients, approximately half of the patients (48.6%) were 18–44 years of age and 32.2% were female (Table 2).

Table 1. Summary on hospitalizations from cause-specific injuries and meteorological conditions on the hospital admission dates in 137 hospitals of China between 2000 and 2019.

Variable	ICD codes	Cases [n (%)]	Temperature [mean ± SD (°C)]	Relative humidity [mean ± SD (%)]	Precipitation [mean ± SD (mm)]
Total	S00–Y98	988,087	18.4 ± 9.7	72.6 ± 16.4	4.0 ± 12.3
Injuries to body	S00–T14	880,957 (89.1)	18.3 ± 9.4	72.5 ± 16.3	4.0 ± 12.4
Injuries to head and neck	S00–S19	227,988 (28.1)	17.1 ± 10.0	71.1 ± 17.1	3.4 ± 11.0
Injuries to trunk	S20–S39	137,726 (13.9)	17.4 ± 9.7	71.8 ± 16.9	3.5 ± 11.4
Injuries to upper limbs	S40–S69	248,926 (25.2)	20.4 ± 8.6	74.3 ± 14.9	4.8 ± 13.7
Injuries to lower limbs	S70–S99	195,373 (19.8)	18.0 ± 10.0	72.6 ± 16.3	4.1 ± 12.7
Injuries to multiple or unspecified body regions	T00–T14	70,944 (7.2)	19.4 ± 8.9	73.2 ± 15.8	4.1 ± 12.5
Burns and corrosions	T20–T32	26,761 (2.7)	20.4 ± 9.0	73.6 ± 15.3	4.7 ± 13.5
Poisoning	T36–T65	30,491 (3.1)	16.4 ± 10.6	71.0 ± 17.3	3.1 ± 10.6
Accidental injuries and other causes	V01–V99, W00–X59, X60–Y98, T15–T19, T33–T35, T66–T98	49,878 (5.0)	17.6 ± 10.7	70.7 ± 18.0	3.7 ± 12.0

Note: Injuries to trunk include injuries to thorax, abdomen, lower back, lumbar spine, pelvis, and external genitals. Injuries to upper limbs includes injuries to shoulder, upper arm, elbow, forearm, wrist, hand, and fingers. Injuries to lower limbs includes injuries to hip, thigh, knee, lower leg, ankle, and foot. ICD, International Classification of Diseases; SD, standard deviation.

Table 2. Estimated relative risks and 95% confidence intervals of injury hospitalizations from total causes associated with heat, stratified by age, sex, and region in 137 hospitals of China between 2000 and 2019.

Variable	Cases (*n*)	Temperature [mean ± SD (°C)]	Reference temperature (°C)	Extreme hot temperature (°C)	Relative risk	Between-group *p*-value
Total	929,787	18.5 ± 9.6	−12.1	30.8	1.18 (1.14, 1.22)	—
Sex						
Male	631,771	18.9 ± 9.4	−11.8	30.9	1.32 (1.26, 1.39)	0.002
Female	298,016	17.8 ± 9.9	−12.6	30.8	1.20 (1.12, 1.30)	—
Age						
<18	94,058	17.9 ± 9.9	−12.8	30.7	1.82 (1.57, 2.12)	<0.001
18–44	452,140	19.3 ± 9.4	−12.1	30.9	1.26 (1.18, 1.34)	—
45–64	275,738	17.7 ± 9.7	−12.1	30.8	1.32 (1.22, 1.43)	—
≥65	107,851	17.9 ± 9.3	3.1	30.9	1.16 (1.07, 1.26)	—
Region						
North	249,825	11.0 ± 11.0	−16.4	28.8	1.32 (1.24, 1.42)	<0.001
South	679,962	21.4 ± 7.2	1.4	31.1	1.16 (1.11, 1.20)	—

Note: Reference temperature was defined as the temperature of minimum morbidity risk. Extreme hot temperature was defined as the 97.5th percentile of temperature distributions. Relative risk was the hospitalization risk at the extreme hot temperature relative to the reference temperature. The between-group *p*-values were calculated by *z*-test and *F*-test. —, no data; SD, standard deviation.

Modeled Temperature Series under the Scenarios with and without Anthropogenic Forcing

Figure S1 illustrates the modeled annual temperature under the scenarios with and without anthropogenic forcing in China from 2000 to 2019. The data indicates a notable growth trend in anthropogenically driven climate change in the past decades, with most regions experiencing a widening temperature gap between the two scenarios. The annual temperature has remained nearly constant (around 13.5°C) under the scenario without anthropogenic forcing since the 2000s, while the scenario with anthropogenic forcing witnessed an increment of 0.4°C in the annual temperature from the 2000s to the 2010s. Notably, the North experienced a larger magnitude of human-induced warming (>1°C), whereas in the South, the between-scenario differences were <0.8°C in the 2010s.

Associations between Temperature and Hospitalizations from Cause-Specific Injuries

Figure S2 shows the exposure–response curves for the associations between temperature and hospitalizations from subcategories of injury. Generally, high temperatures were linked with an increased risk for most causes of injury. However, we observed that low temperatures were significantly associated with an increased risk of injuries to hip and thigh, whereas the effect of high temperatures was estimated at a nonsignificant relative risk close to 1, suggesting that injuries to hip and thigh might be cold-related. Additionally, carbon monoxide (CO) poisoning was found to be significantly associated with low temperatures without any heat effect. Therefore, hospitalizations from injuries to hip and thigh and CO poisoning were excluded from further analyses of heat-related injury hospitalizations.

For heat-related injury hospitalizations from total causes, the cumulative relative risk at the extreme hot temperature (30.8°C) over lag 0–5 d was 1.18 (95% CI: 1.14, 1.22) relative to the reference temperature (−12.1°C) (Table 2). As shown in Figure 1, the cumulative exposure–response curve for the association between temperature and injury hospitalizations from total causes followed an approximately linear pattern, indicating that higher temperatures were associated with an increased risk of hospitalization. However, the shape of the curves varied by specific causes of injury. For instance, the corresponding curve for injuries to head and neck became constant in high temperature ranges. Figure S3 shows the lag structures for the effects of extreme hot temperatures on hospitalizations from cause-specific injuries. Generally, the risk of extreme hot temperature was strongest on the present day and then attenuated to lag day 1.

As presented in Table 2, subgroups who were male, <18 years of age, and living in the North might be more vulnerable to ambient hot temperatures. Compared to the reference temperatures, the corresponding relative risks at the extreme hot temperatures were 1.82 (95% CI: 1.57, 2.12) for the young (<18 years of age), 1.26 (95% CI: 1.18, 1.34) and 1.32 (95% CI: 1.22, 1.43) for the middle-aged (18–44 and 45–64 years of age), and 1.16 (95% CI: 1.07, 1.26) for the old (≥65 years of age). The results of the multiple comparison tests suggested significant differences between the young and other subgroups. Additionally, a higher risk was observed in males than in females, corresponding to relative risks of 1.32 (95% CI: 1.26, 1.39) and 1.20 (95% CI: 1.12, 1.30), respectively. The relative risks of heat-related injury hospitalizations for the region-specific extreme hot temperatures (28.8°C and 31.1°C) were 1.32 (95% CI: 1.24, 1.42) and 1.16 (95% CI: 1.11, 1.20) compared to the reference temperatures (−16.4°C and 1.4°C) in the North and the South, respectively (Table 2). Overall, we found significant between-group differences for these subgroups. The stratified results of the cumulative exposure–response curves by sex, age, and region are shown in Figure S4. The shape of the curves was approximately linear in various subgroups. The region-specific exposure–response curves for the associations between temperature and hospitalizations from cause-specific injuries are presented in Figure S5. Generally, we observed higher relative risks in the North than in the South for most hospitalizations from cause-specific injuries, except for accidental injuries and other causes. Finally, the results of the sensitivity analyses suggested that the findings remained robust after changing the maximum lag, the degrees of freedom, or the placement of knots and adjusting for daily precipitation in the model (Table S2).

Attributable Fraction and Human-Induced Contribution

We computed heat-related AFs above the corresponding reference temperatures for hospitalizations from cause-specific injuries since the 2000s. Generally, human activities have contributed to a rapidly increasing trend in the AF, particularly in the 2010s (Figure 2). As presented in Table S3, the AF was estimated to increase from 23.2% in the 2000s to 23.6% in the 2010s under the scenario with anthropogenic forcing. During this period, the estimate of human-induced change increased from 0.5% to 1.9%. The increment in heat-related AF was totally induced by human-induced climate change. Under the scenario with anthropogenic forcing, the AF was the highest (54.4%) for poisoning, followed by injuries to multiple or unspecified body region (50.1%), accidental injuries and

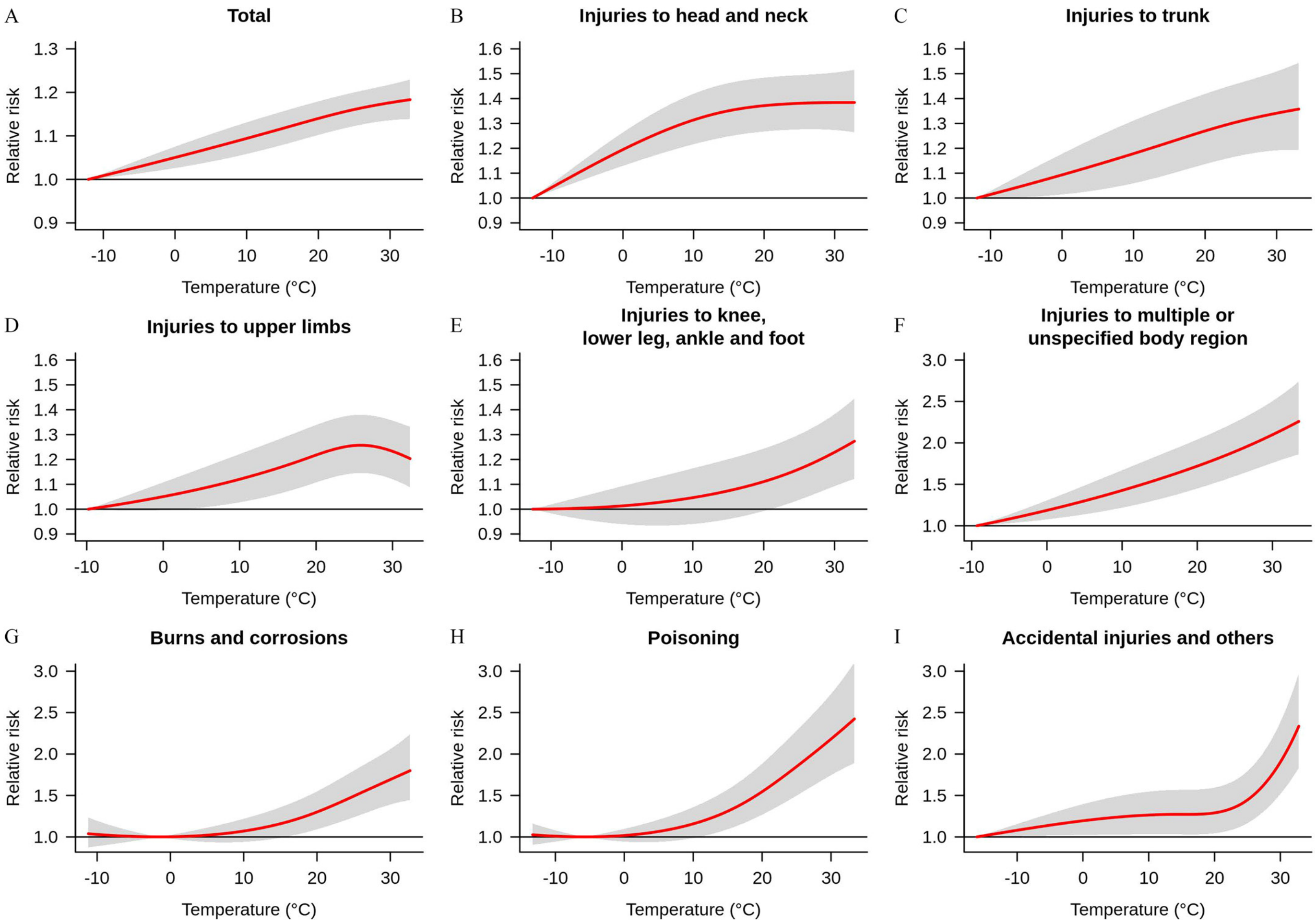

Figure 1. Exposure–response curves for the associations between temperature and heat-related injury hospitalizations ($n = 929,787$) for (A) total; (B) injuries to head and neck; (C) injuries to trunk; (D) injuries to upper limbs; (E) injuries to knee, lower leg, ankle, and foot; (F) injuries to multiple or unspecified body regions; (G) burns and corrosions; (H) poisoning; and (I) accidental injuries and others in 137 hospitals of China between 2000 and 2019. Solid red lines denote mean estimates and gray areas denote 95% confidence intervals. Corresponding numeric data is shown in Supplemental Excel Table S1.

other causes (40.7%), burns and corrosions (37.5%), injuries to head and neck (29.2%), injuries to trunk (18.8%), and injuries to upper or lower limbs (12.4%) in the 2010s. However, hospitalizations for burns and corrosions might be more susceptible to human-induced warming, which contributed to 10.6% of its heat-related AF in the 2010s. Meanwhile, the proportion of human-induced change in the heat-related AF was the lowest for injuries to head and neck (6.7%), followed by injuries to upper limbs (7.5%), injuries to trunk (8.1%), injuries to lower limbs (8.8%), injuries to multiple or unspecified body region (8.9%), accidental injuries and other causes (9.6%), and poisoning (9.8%).

Spatial variations in heat-related AFs and human-induced impacts were observed across regions. Overall, the North might be more affected by the human-induced climate change, with a heavier burden of heat-related hospitalization compared to the South. As presented in Table S4, the AFs for injury hospitalizations in the North ranged from 27.4% to 32.0%, with the proportions of human-induced change ranging from 7.9% to 9.7% in the 2010s. Correspondingly, AFs were 15.5%–24.9% in the South, with the proportions of human-induced change ranging from 7.6% to 8.5%.

Discussion

In the present study of approximately one million injured patients in China, we found significant associations between ambient heat and hospitalizations from cause-specific injuries. Moreover, the corresponding burden continued to increase, together with the enlarging contribution of human-induced climate change. To our knowledge, this is the first nationwide investigation that has utilized hospitalization records in China to examine the temperature–injury association and to quantify the cause-specific injury burden attributed to human activities. Our findings provide supportive and novel evidence regarding the effects of ambient heat on the injury in the context of climate change.

Our findings contribute to the existing literature by providing nationwide evidence and more comprehensive cause-specific estimates in a developing country. Consistent with previous studies that were conducted in high-income countries, such as the US,[13] the UK,[31] the Netherlands,[32] and South Korea,[33] our findings also suggested a significant association between heat and injury hospitalization. However, temperature–injury association might vary by cause, subgroup, and climate in China, where demographic, socioeconomic, and geographical characteristics differ significantly from high-income countries. Additionally, the limited number of hospitals or small areas in previous studies may undermine the credibility and generalizability as indicated in a previous systematic literature review.[8] We also observed considerable differences in risk estimates among these studies, which might be explained by the differences in study design, health outcomes, location, and study population. Notably, the existing evidence primarily focuses on injury mortality[11,15] and occupational

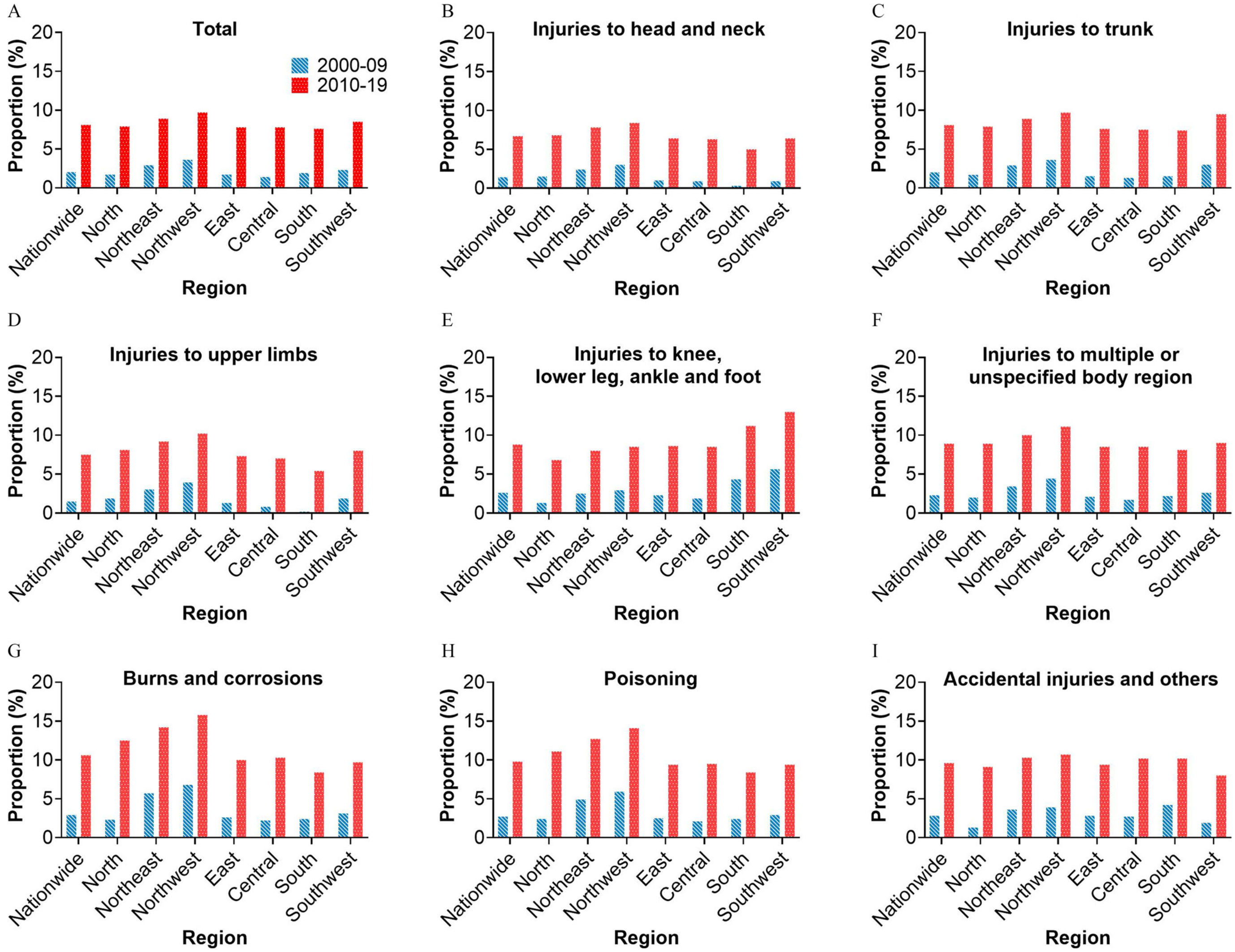

Figure 2. The fractions of the human-induced changes in the heat-related burdens under the scenario with historical anthropogenic climate forcing over the past decades for (A) total; (B) injuries to head and neck; (C) injuries to trunk; (D) injuries to upper limbs; (E) injuries to knee, lower leg, ankle, and foot; (F) injuries to multiple or unspecified body regions; (G) burns and corrosions; (H) poisoning; and (I) accidental injuries and others in 137 hospitals of China between 2000 and 2019. Human-induced change denotes the difference between the scenarios with anthropogenic forcing and without anthropogenic forcing; proportion denotes the fraction of the human-induced change in the heat-related burden in the historical scenario with anthropogenic forcing. The dotted red patterns denote estimates for 2010–2019, and the slashed blue patterns denote estimates for 2000–2009. Corresponding numeric data is shown in Supplemental Excel Table S2.

injury,[14,34–36] which might underestimate the magnitude of nonfatal injuries with a broad range of types. Therefore, more multicenter studies with large sample sizes and cause-specific records are warranted to provide a reliable assessment.

The underlying biological mechanisms that explain the observed association between heat and injury hospitalization are not yet fully understood, but several hypotheses have been proposed previously. Most of the hospitalization records included in the present study were unintentional injury (e.g., injuries to body and accidental injuries). This indicated that thermal discomfort induced by heat stress could be a plausible mechanism explaining the heightened risk at higher temperature ranges, typically observed above 30°C.[34] Thermal discomfort might lead to a series of adverse behavioral performances, such as fatigue, decreased concentration, impaired judgment, and diminished cognitive function, which might result in an inability to take protective measures against accidents.[34,35] Additionally, at moderate heat conditions, people tend to have more outdoor activities, thus increasing the likelihood of injuries.[8] Notably, high temperatures could drastically increase the hospitalization risk of poisoning (including drug poisoning, alcohol poisoning, pesticide poisoning, etc.), which is plausible in terms of the following aspects. For one thing, individuals exposed to alcohol, drugs or other intoxicants may be less likely to recognize the risk of heat and more likely to put themselves in risky conditions, such as falling asleep outside or staying indoors without air conditioning. For another, intoxicants could also exacerbate the adverse physiological responses to heat, including dehydration and electrolyte imbalance,[37] thermoregulation imbalance,[37,38] and thrombosis.[39] The potential mechanism for intentional injuries (e.g., suicide and assault) might be entirely different. High temperatures might induce impulsive aggression and impair decision-making, leading to an increased risk of intentional injury.[12] Finally, the present study could not explain the exact biological mechanisms underlying the differences in susceptibility to human-induced warming across various causes of injury, and further mechanistic studies are needed to elucidate the underlying pathways.

This study reveals that certain subgroups, particularly young to middle-aged males, may be potentially more vulnerable to heat-related injury than others. These findings are consistent with previous research conducted in various countries, including the US,[15] Italy,[40] Spain,[41] and China.[11] This vulnerability may be explained by the substantial age and sex differences in the workforce, where younger and middle-aged males tend to engage in more physically demanding occupations (e.g., agriculture and construction) and are thus more frequently exposed to heat.[42] The increased susceptibility of young individuals to injuries might be attributable to a combination of concurrent risk factors, such as inadequate experience, skills, and awareness of hazards.[43,44] In this regard, effective occupational interventions that broadly target these subgroups should be a public health priority. Additionally, the North of China might be a hot-spot area for population health since the North might experience heavier burdens of injury hospitalization and be more affected by human-induced climate change. Therefore, tailored measures should be established based on the local conditions.

Furthermore, our findings revealed the exacerbating impacts of human activities on global warming and public health. Although limited studies have provided relevant evidence, several investigations might support our findings. For instance, Parks et al.[15] found anomalously warmer temperature in the US was associated with excess injury mortality, and human-induced abnormal warmer climate might be an important contributor. Hu et al.[11] reported considerable future excess deaths in a changing climate in China, consistent with the surging contribution of anthropogenically driven forcing observed in the present study. Furthermore, we observed larger burdens in several causes, such as poisoning, accidental injuries, as well as burns and corrosions, while a larger ratio of increase in human-induced impact was also found in these causes. Therefore, more attention should be paid to such cause-specific injuries with increasing vulnerability in the context of climate. Additionally, despite the hospitalization risk stabilizing within high-temperature ranges for specific causes (e.g., injuries to head and neck), we consistently observed an escalating heat-related burden attributable to anthropogenic climate change because climate change causes an overall increase in temperature. Therefore, it remains important to implement adaptation strategies to mitigate injury risks.

The present study highlights the priority of current efforts to promote timely climate action. Our findings suggested that the injury burden resulting from anthropogenically driven climate change is exacerbating, indicating sustainable co-benefits of adopting human-produced greenhouse gas mitigation policies and implementing well-adapted and evidence-informed interventions.[45] As we presented significant and differentiated associations between heat and hospitalizations from cause-specific injuries, tailored interventions should be implemented to minimize health risks from these causes. Particularly, more emphasis should be placed on the prevention of heat-related workplace injuries.[16,46] A comprehensive prevention framework for occupational health and safety should be established.[34,47,48] Finally, community-level strategies to protect the general population should be prioritized, such as establishing early heat warning systems, strengthening education and awareness campaigns, and providing adequate green spaces.[49]

Certain limitations should be acknowledged in this study. First, meteorological data obtained from fixed-site monitoring stations may not fully represent individual exposure levels, thereby introducing exposure measurement errors. Second, as fatal injuries accounted for a small part of the whole, the relatively small sample size for several injury types (e.g., suicide) limits the statistical power to evaluate the cause-specific burden. Third, the current division of the study area into North and South may not fully capture all variations in exposure–response associations, highlighting the need for future research to provide a more accurate assessment at a finer geographical scale. Fourth, this study aimed to assess heat-related burden without accounting for the potential reductions in risk and burden associated with temperatures below the reference temperature, as done in previous projection studies.[20,50] There is a possibility of overestimating the impact of climate change on injury burdens. Therefore, our results should be interpreted cautiously, as they may not accurately reflect the overall impacts of climate change when considering both increases and decreases in risk across different temperature ranges. Finally, we assessed the heat-related burden based on the time-invariant exposure–response relationships through the study period, assuming that the average exposure–response relationship remains relatively constant over time, that could account for potential dynamic changes in responses to climate change. Therefore, future studies are warranted to comprehensively assess injury burden and inform policy development to better adapt to exacerbating climate change.

In conclusion, our study provides evidence of varying effects of heat exposure and disease burden across different cause-specific injuries, subgroups, and regions in China, which is helpful for policymakers to implement evidence-based interventions targeted at the specific causes, geographical regions, and vulnerable subgroups, taking into account local conditions (e.g., meteorological, geographical, and demographical conditions). Additionally, human-induced warming has contributed to an increasing injury burden in China in recent decades. Overall, these findings reinforce the need to incorporate high temperatures in the comprehensive risk factor assessment and management of injury, frame injury as a predictable and preventable public health concern in the context of climate change, and develop clinical and public health practices to alleviate the current and future disease burden associated with heat exposure.

Acknowledgments

Lu Zhou: investigation, methodology, formal analysis, writing of original draft, writing—review and editing. Cong Liu: investigation, methodology, formal analysis, writing of original draft, writing—review and editing. Cheng He: data curation and methodology. Jian Lei: data curation. Yixiang Zhu: data curation. Ya Gao: data curation. Jianwei Xuan: Project administration and resources. Haidong Kan: project administration, funding acquisition, conceptualization, supervision, writing—review and editing. Renjie Chen: project administration, conceptualization, validation, supervision, writing—review and editing.

This work was supported by the Shanghai Municipal Science and Technology Major Project (grant number 2023SHZDZX02), Shanghai B&R Joint Laboratory Project (grant number 22230750300), Shanghai International Science and Technology Partnership Project (grant number 21230780200), and Shanghai 3-year Public Health Action Plan (grant numbers GWVI-11.1-39 and GWVI-11.2-YQ32).

The study protocol was approved by the institutional review board at the School of Public Health, Fudan University (IRB number 2021-04-0889) with a waiver of informed consent. The electronic hospitalization records have been de-identified to safeguard patient privacy. Data authorization was obtained by the SuValue database before the initiation of this analysis, and thus no informed consent was needed.

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