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Diurnal temperature range and hypertension: cross-sectional and longitudinal findings from the China Health and Retirement Longitudinal Study (CHARLS)

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Abstract

Background Research indicates a positive association between short-term diurnal temperature range (DTR) exposure and hypertension. However, the impact of long-term DTR exposure has not been thoroughly studied in population-based cohort research.

Methods This study conducted cross-sectional (including 16,690 participants) and longitudinal analyses (including 9,650 participants) based on the China Health and Retirement Longitudinal Study (CHARLS). Daily temperature data was sourced from the National Scientific Data of the Qinghai-Tibet Plateau. We calculated the moving average of DTR exposure of all the participants in CHARLS with exposure windows of 30-day, 60-day, 180-day, 1-year, and 2-year before the interview month of CHARLS Wave1 (2011). Logistic regression and age-stratified Cox proportional hazards models were employed in our analysis.

Results In the cross-sectional study, 6,572 (39.4%) participants had hypertension. We found higher DTR is associated with a higher prevalence of hypertension across different exposure windows. The effect was strongest when the exposure window of DTR was 180-day, with an adjusted odds ratio (OR) of 1.261 (95% confidence interval (CI): 1.124–1.416 [highest tertile DTR vs. lowest tertile DTR]). In the cohort study, 3,020 (31.3%) participants developed hypertension during 83 months of follow-up. A higher level of DTR (hazard ratio (HR): 1.224, 95% CI: 1.077–1.391) was associated with a higher risk of incident hypertension. We found significant interactions between DTR and age (*P* interaction: <0.001) and residence (*P* interaction: 0.045).

Conclusion We found significant positive associations between DTR and prevalent and incident hypertension. Individuals younger than 65 and those living in rural areas are at an elevated risk of developing hypertension due to DTR.

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Keywords Diurnal temperature range, Hypertension, Prevalence, Incidence

Background

Hypertension is a leading risk factor for morbidity and mortality worldwide, accounting for 218 million disability-adjusted life-years and 10.4 million deaths each year [1]. Meanwhile, it is a significant global health challenge due to its high prevalence and resulting myocardial infarction, heart failure (HF), stroke, and kidney disease [2]. Worldwide, 1.28 billion adults aged 30–79 have hypertension [3]. In China, the prevalence of hypertension has increased substantially in the past half-century and now affects approximately a quarter of all adults living [4]. It's crucial to identify potential risk factors for hypertension to mitigate its disease burden.

Environmental temperature is an important meteorological factor. Diurnal temperature range (DTR), defined as daily maximum minus minimum temperature, is widely used to reflect the within-day temperature variability [5]. Referring to the impact of DTR on human health, numerous studies provide growing evidence of the positive associations of short-term DTR exposure (i.e., days to weeks) with all-cause mortality and cardiovascular and respiratory disease morbidity via time-series regression [6–9]. Previous studies have revealed that high DTR can increase blood pressure, heart rate, and oxygen intake [10]. A study conducted in northwest China demonstrated a positive linear association between DTR and both systolic blood pressure (SBP) and pulse pressure (PP), as well as a negative linear association with diastolic blood pressure (DBP) [6]. Another investigation examining the effects of DTR on cardiovascular markers among the elderly revealed that both SBP and DBP had a positive association with DTR when it was at or above the median level [11]. A large number of studies have found that there is a positive association between DTR and cardiovascular diseases (CVDs) [12–17]. Additionally, research on the impact of DTR in high-altitude areas found a significant positive association between DTR and outpatient and emergency room admissions for cardiovascular diseases, including hypertension, ischemic heart disease, and stroke [16].

The aforementioned studies primarily only focused on the impact of DTR on BP levels without assessing whether these levels exceed the clinical diagnostic criteria for hypertension and its influence on the prevalence and onset of hypertension. Hypertension may mediate the relationship between DTR and CVD. Additionally, the populations in these studies were not representative, as one was conducted in northwest China and the other in a Korean community. And, these studies mainly focused on the impact of short-term DTR. Therefore, there has been no nationwide study systematically exploring the association between DTR and hypertension.

To address these gaps, this study utilized data from the China Health and Retirement Longitudinal Study (CHARLS) 2011–2018 and the National Scientific Data of the Qinghai-Tibet Plateau. We conducted both cross-sectional and longitudinal analyses to investigate the associations between DTR and the prevalence and incidence of hypertension in a prospective cohort in China. This study provides important evidence for the association between DTR exposure and hypertension in developing countries and offers valuable insights for policymakers.

Methods

Study population

We obtained data from the Harmonized CHARLS, which summarizes data from the CHARLS for the period 2011–2018. It combines data from the Health and Retirement Study (HRS), offering advantages such as minimal missing values, high data quality, and ease of international comparison. CHARLS is a national survey representing a sample of Chinese residents aged 45 years and older. The national baseline survey was conducted between 2011 and 2012 (Wave1), with subsequent waves in 2013 (Wave2), 2015 (Wave3), and 2018 (Wave4) [18]. The survey aims to create a high-quality open micro-database containing information ranging from various socioeconomic conditions to individual health status, supporting aging research. To ensure a representative sample, the CHARLS baseline survey covered 150 counties or districts and 450 villages or urban communities across 28 provinces using multi-stage stratified sampling with probability proportional to size. Further details about CHARLS have been reported elsewhere [19]. In the cross-sectional survey, we used data from the 2011 survey. A total of 17,708 people participated in the 2011 survey. We excluded participants aged < 45 years, those with missing age data, lacking DTR exposure data, and uncertain hypertension status. Finally, 16,690 participants were involved. In the longitudinal study, we excluded 6,572 participants who had been diagnosed with hypertension in the 2011 survey, and 468 individuals with missing diagnostic information on hypertension. In total, 9,650 participants were included in the analysis. A flowchart detailing the selection process for participants is provided in Fig. 1.

The study was conducted by the Declaration of Helsinki, the original CHARLS was approved by the Ethical Review Committee of Peking University, and all participants signed informed consent at the time of participation.

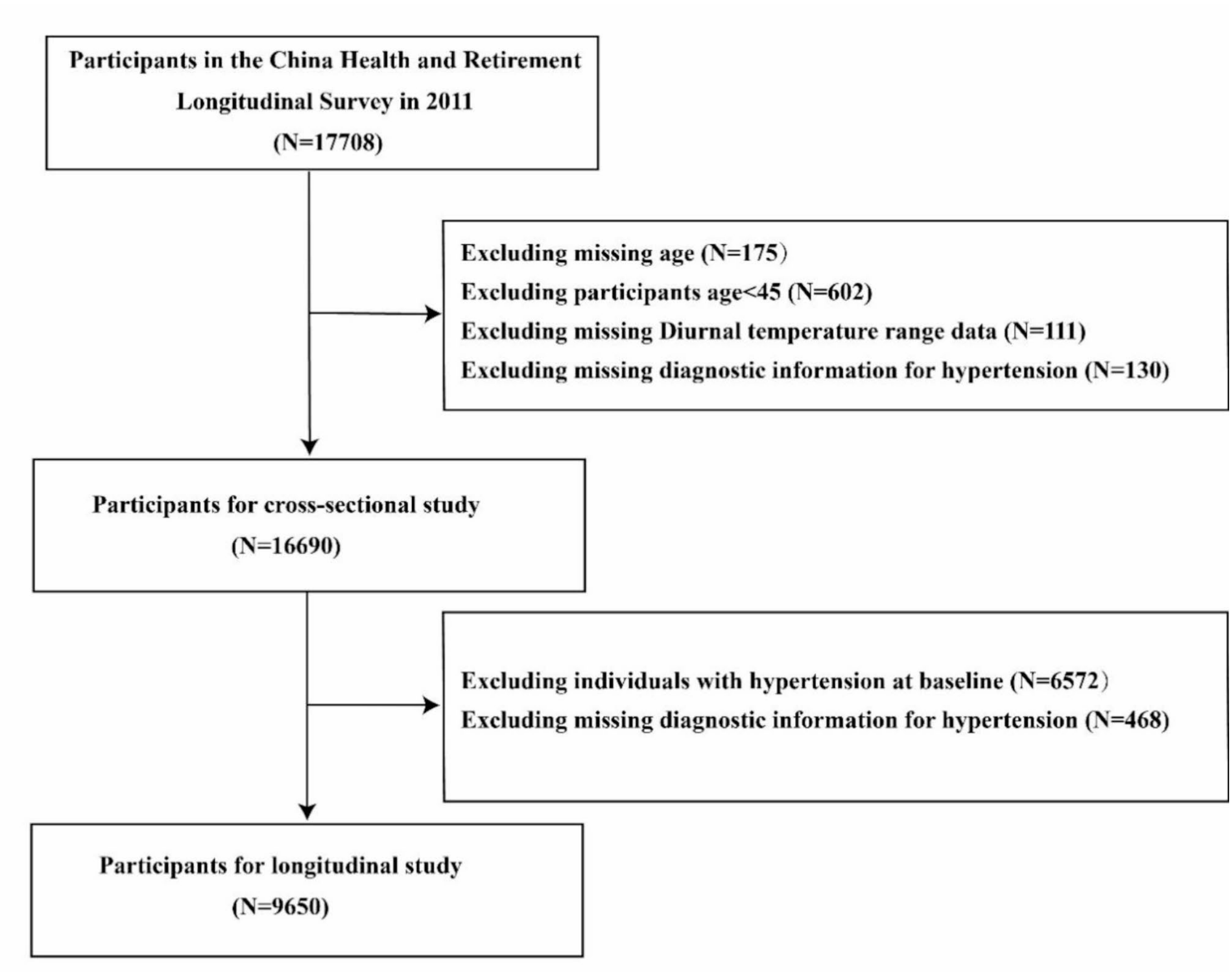

Fig. 1 Participant flowchart

Assessment of hypertension

During the follow-up visit, professionally trained nurses measured each participant's SBP and DBP three times, with 45-second intervals between measurements [20]. We used the average of the second and third readings (or the average of the first and second readings if the third reading was unavailable) as the final blood pressure value. According to measurements and self-reported questionnaires, the criteria for identifying hypertension included: (1) individuals whose blood pressure exceeded clinically critical levels (SBP ≥ 140mmHg or DBP ≥ 90mmHg) during physical examinations; (2) individuals who self-reported a diagnosis of hypertension between the two surveys; (3) individuals who self-reported the use of anti-hypertensive medications between the two surveys [20, 21]. Specifically, blood pressure measurements were not conducted during the 2018 follow-up survey; instead, self-reported questionnaires were collected. Consequently, new onset hypertension was identified using the latter two criteria during the 2018 follow-up survey. The time of incident hypertension was defined as the time of first diagnosis of hypertension. Considering the discrepancies in follow-up frequency and intervals between medical visits among participants, we defined the first diagnosis of hypertension during follow-up visits as the endpoint for those who developed hypertension. Therefore, participants were censored at the date associated with the incidence of hypertension, date of death, or last known follow-up, whichever occurred first.

Exposure assessment

The daily temperature information of all selected cities in the same period (2009–2012) was obtained from the National Scientific Data of the Qinghai-Tibet Plateau (https://data.tpdc.ac.cn), including daily average temperature, daily highest temperature, and daily lowest temperature. Researchers constructed different temperature reconstruction models for different meteorological conditions, and through the calibration equation of other areas to improve the accuracy of the data, generated from 1979 to 2018 China daily temperature data, including daily maximum temperature, daily minimum temperature, and daily average temperature. The processing of the temperature data and the details can be found in another article [22]. DTR is the difference between daily maximum and minimum temperatures. We calculated the moving average of DTR exposure of all the participants in CHARLS with exposure windows of 30-day, 60-day, 180-day, 1-year, and 2-year before the interview month of CHARLS Wave1 (2011) [23, 24]. In our study, 30 days and 60 days were considered short-term exposure, while above 60 days were considered long-term exposure [25]. In cross-sectional and longitudinal analyses, we categorized the population into three groups based on the tertile of the DTR distribution. Participants were classified into lowest, middle, and highest groups according to their respective position within the lowest, middle, and highest tertile: those with a DTR less than or equal to the first tertile were assigned to the lowest group, those with a DTR greater than the first but less than or equal to the second tertile were assigned to the middle group, and those with a DTR greater than the second tertile were assigned to the highest group. And, the lowest tertile was used as the reference group in the categorical variables. The details of DTR values for each tertile and overall DTR in different exposure windows are shown in Supplemental Table 1.

Covariates

The covariates in this study were selected by reviewing previous studies related to hypertension [4, 20, 26–30], including socio-demographic factors, health behavior variables, disease history, and other pertinent covariates. Socio-demographic factors included age (continuous), gender ("male", "female"), marital status ("married" [living with a spouse, living apart from spouse] and "single" [separated, divorced, and widowed, never married]), education attainment ("elementary school or below", "middle school or above"), household income per capita ("< average household income", "≥ average household income") and residence ("rural", "urban"). Smoking status ("no", "yes"), and drinking status ("no", "yes") were included in the model as health behavior variables. Disease history including history of dyslipidemia ("no", "yes"), history of heart disease ("no", "yes") (including heart attack, coronary heart disease, angina, congestive heart failure, or other heart problems) [31], history of stroke ("no", "yes"), and history of diabetes ("no", "yes"). Body mass index (BMI) was calculated as weight in kilograms divided by squared height in meters. BMI categories are as follows: underweight (<18.5 kg/m^2), normal weight (18.5–23.9 kg/m^2), overweight-to-obesity (>23.9 kg/m^2). The BMI cut-offs were selected based on the Chinese recommended standard [32]. We also further adjusted the presence of air conditioning ("no", "yes"). Finally, the cities were divided into southern and northern regions by the Kunlun-Qinling-Huaihe line [28]. The relative humidity of all selected cities was obtained from the China Meteorological Science Data Sharing Service Network (http://data.cma.cn). The assessment of relative humidity (continuous) and average temperature (continuous) utilized the same method that was used for estimating the DTR in each exposure window. We also selected green space areas in each city as an additional covariate. The data on the green space area was obtained from the China Urban Statistical Yearbook.

Statistical analysis

The baseline characteristics of participants in the cross-sectional analysis and cohort analysis are presented as percentages for categorical variables and median and interquartile range (IQR) for non-normally distributed continuous variables. In the cross-sectional survey, the associations between DTR exposure across different windows and prevalent hypertension were examined using multivariable logistic regression. Three models were conducted: Model 1 was adjusted for gender, age, education level, marital status, residence, smoking status, drinking status, BMI categories, and household income per capita. Model 2 was further adjusted for the history of dyslipidemia, heart disease, stroke, and diabetes. Model 3 was additionally adjusted for air conditioning, average temperature, relative humidity, and geographic regions. We selected Model 3 as our main model. The ORs and 95% CIs of DTR for hypertension were calculated with exposure as a categorical variable (tertiles). We used the Bonferroni correction method to adjust the P value and confidence intervals in the main model.

Then, we further conducted a cohort analysis based on the cross-sectional study to explore the effect of DTR on the incidence of hypertension. To mitigate seasonal bias to some extent, examine the chronic impact of DTR, and reflect the long-term average DTR in an individual's living environment, we selected 1-year exposure window and applied age-stratified Cox proportional hazards models to assess the relationship between DTR and hypertension incidence. We assessed the proportionality of hazards assumption using the Schoenfeld residuals technique and no violations were observed (Supplemental Table 2). The HRs and 95% CIs of DTR for hypertension were calculated with exposure as a categorical variable (tertiles). Model adjustments were consistent with those in the cross-sectional study and Model 3 was selected as the main model. To test for trends, we entered the median value of each DTR category as a continuous variable in the models. Furthermore, we also performed several subgroup analyses. These analyses were stratified by age (<65/≥ 65 years), sex (female/male), residence (rural/urban), household income per capita (<average income/≥ average income), smoking status (no/yes), drinking status (no/yes), air conditioning (no/yes). We also applied interaction analyses to test whether these covariates could modify the association between DTR and hypertension. A likelihood ratio test was performed to assess the statistical significance of the interaction.

Additionally, we conducted several sensitivity analyses to confirm the robustness of our findings. First, considering death as a competing risk for the incidence of hypertension, we employed the Fine-Gray sub-distribution hazard model to examine potential biases arising from competing risks. Second, we conducted the main analyses exclusively among participants with complete covariate data to minimize potential biases due to missing information. Third, we conducted the main analyses exclusively among participants without existing comorbidities affecting the association between DTR and hypertension risk, including diabetes, dyslipidemia, heart disease, and stroke. Fourth, we additionally adjusted for green space in the main model, as emerging evidence indicates a relationship between green space and hypertension [33]. Fifth, considering the clustering effect of the exposure as DTR, we added a frailty model by incorporating the city and follow-up month as random effects. To address any missing covariate values, we employed multiple imputations utilizing the "mice" R package [34], ensuring the statistical power and minimizing inferential bias. All statistical analyses in this study were performed in R software version 4.1.1. We employed two-sided tests for all statistical analyses, considering a *P* value of less than 0.05 as statistically significant.

Results

Baseline characteristics of cross-sectional study

Table 1 presents the baseline characteristics of 16,690 participants in the cross-sectional study, stratified by tertile of DTR for the 1-year DTR exposure window. The median age of participants was 58.0 years, with 51.1% being female. Besides, 52.6% of participants had a normal BMI, and 53.6% resided in the southern region. The prevalence of hypertension was 39.4%. Compared to participants in the lowest DTR category, those in the highest category were more likely to be young, overweight or obese, more educated, living in northern, living in rural areas, smokers, having low household incomes, and having less access to air conditioning. They were also more likely to have heart disease, stroke, and dyslipidemia. Additionally, participants exposed to high levels of DTR experienced relatively low relative humidity and average temperatures. Baseline characteristics of the 16,690 participants are also shown in Supplemental Table 3, categorized by their hypertension status. Furthermore, the baseline characteristics of participants in the cross-sectional study, categorized by tertile of DTR for the 180-day DTR exposure window, are presented in Supplemental Table 4.

Diurnal temperature range (DTR) and prevalent hypertension

Table 2 presents the association between DTR in different exposure windows and hypertension prevalence. In model 1, we observed the largest effect of high levels of DTR with the prevalence of hypertension in different exposure windows. After fully adjusting for potential confounders, model 3 revealed that, although the association between high levels of DTR and hypertension prevalence became statistically insignificant in the 60-day exposure window, it remained significant in the 30-day, 90-day, 180-day, 1-year, and 2-year exposure windows. The strongest effect was observed in the 180-day DTR exposure window, where the adjusted ORs for hypertension were 1.243 (95% CI: 1.128–1.369) for the middle tertile and 1.261 (95% CI: 1.124–1.416) for the highest tertile, compared to the lowest tertile of DTR. The results of unadjusted and Bonferroni-adjusted *P* values and confidence intervals in the main model are shown in Supplemental Table 5.

Baseline characteristics of longitudinal cohort

We further explored the relationship between DTR and hypertension incidence in a longitudinal cohort. Table 3 presents the characteristics of participants in the longitudinal cohort. A total of 9,650 participants were included in the analysis. The median age was 56 years, and 50.1% of participants were male. Additionally, 58.9% had a normal BMI, and 56.5% resided in the southern region. During a median follow-up period of 83 months, 3,020 individuals (31.3%) were diagnosed with hypertension. The highest incidence of hypertension (33.7%) was observed in the participants with the highest tertile of DTR. Compared to participants in the lowest tertile of DTR, those in the highest tertile were more likely to reside in rural, northern areas, with lower average temperatures, lower relative humidity, lower household income per capita, and less access to air conditioning. They were also more likely to have heart disease, stroke, and dyslipidemia.

Diurnal temperature range (DTR) and hypertension incidence

Table 4 presents the association between 1-year average DTR and hypertension incidence in the longitudinal analysis. In Model 1, participants exposed to the highest tertile of DTR (HR: 1.180; 95% CI: 1.079–1.290) had a significantly higher risk of hypertension compared to those in the lowest tertile. In Model 3, after fully adjusting

Table 1 The baseline characteristics of participants in the cross-sectional study, by tertile of DTR, for the 1-year DTR exposure window

Characteristic	Diurnal temperature range, ℃			
	Overall	**Lowest tertile ≤ 8.4**	**Middle tertile 8.4–10.3**	**Highest tertile > 10.3**
Participants, n	16,690	5804	5470	5416
Age (year, median [IQR])	58.0 [51.0, 65.0]	58.0 [52.0, 66.0]	58.0 [51.0, 65.0]	57.0 [51.0, 64.0]
Gender, n (%)				
Male	8156 (48.9)	2845 (49.0)	2668 (48.8)	2643 (48.8)
Female	8534 (51.1)	2959 (51.0)	2802 (51.2)	2773 (51.2)
BMI (kg/m^2), n (%)				
< 18.5	900 (6.9)	388 (8.5)	240 (5.7)	272 (6.4)
18.5–23.9	6840 (52.6)	2590 (56.8)	2119 (50.8)	2131 (50.0)
> 23.9	5255 (40.4)	1578 (34.6)	1815 (43.5)	1862 (43.7)
Education attainment, n (%)				
Elementary or below	11,082 (66.4)	4131 (71.2)	3491 (63.8)	3460 (63.9)
Middle or above	5604 (33.6)	1670 (28.8)	1978 (36.2)	1956 (36.1)
Residence, n (%)				
Rural	9927 (59.5)	3445 (59.4)	3014 (55.1)	3468 (64.0)
Urban	6763 (40.5)	2359 (40.6)	2456 (44.9)	1948 (36.0)
Geographic regions, n (%)				
South China	8946 (53.6)	5435 (93.6)	2614 (47.8)	897 (16.6)
North China	7744 (46.4)	369 (6.4)	2856 (52.2)	4519 (83.4)
Marital status, n (%)				
Single	2159 (12.9)	782 (13.5)	688 (12.6)	689 (12.7)
Married/living together	14,529 (87.1)	5020 (86.5)	4782 (87.4)	4727 (87.3)
Smoking status, n (%)				
No	9935 (59.6)	3526 (60.9)	3239 (59.3)	3170 (58.6)
Yes	6725 (40.4)	2267 (39.1)	2219 (40.7)	2239 (41.4)
Drinking status, n (%)				
No	9705 (58.3)	3215 (55.5)	3191 (58.5)	3299 (61.0)
Yes	6947 (41.7)	2574 (44.5)	2264 (41.5)	2109 (39.0)
Diabetes history, n (%)				
No	15,495 (93.8)	5459 (95.1)	5016 (92.8)	5020 (93.3)
Yes	1032 (6.2)	281 (4.9)	389 (7.2)	362 (6.7)
Heart disease history, n (%)				
No	14,536 (87.7)	5282 (91.8)	4760 (87.5)	4494 (83.4)
Yes	2045 (12.3)	474 (8.2)	677 (12.5)	894 (16.6)
Stroke history, n (%)				
No	16,172 (97.2)	5630 (97.4)	5306 (97.3)	5236 (97.0)
Yes	464 (2.8)	153 (2.6)	147 (2.7)	164 (3.0)
Dyslipidemia history, n (%)				
No	14,710 (90.0)	5280 (92.9)	4738 (88.8)	4692 (88.1)
Yes	1639 (10.0)	405 (7.1)	598 (11.2)	636 (11.9)
Air conditioning, n (%)				
No	13,162 (79.6)	4354 (75.8)	4102 (75.6)	4706 (87.8)
Yes	3366 (20.4)	1390 (24.2)	1322 (24.4)	654 (12.2)
Average household income (yuan/year, median [IQR])	3717.0 [910.0, 9750.0]	3811.0 [800.0, 9812.0]	3848.0 [1067.0, 10267.0]	3578.0 [879.8, 9020.5]
Average temperature (℃, median [IQR])	14.4 [10.7, 16.6]	17.0 [15.4, 18.8]	14.9 [12.9, 16.0]	10.7 [7.8, 12.7]
Relative humidity (%, median [IQR])	67.8 [58.7, 73.2]	73.3 [71.8, 75.2]	65.8 [58.4, 70.2]	58.9 [52.7, 63.9]

Abbreviation: DTR, diurnal temperature range; IQR, interquartile range; BMI, body mass index

for potential confounders, the HRs for hypertension were 1.055 (95% CI: 0.954–1.166) for the middle tertile and 1.224 (95% CI: 1.077–1.391) for the highest tertile, compared to the lowest tertile of DTR. Additionally, a statistically significant trend was observed in each model. In addition, subgroup analysis stratified by age, gender, residence, smoking status, drinking status, household income per capita, and air conditioning showed results

Table 2 The effect of diurnal temperature range in different exposure windows on the prevalence of hypertension

Tertiles of DTR	Model 1	Model 2	Model 3
	OR (95% CI); *P*	OR (95% CI); *P*	OR (95% CI); *P*
30 days			
Lowest	1(Reference)	1(Reference)	1(Reference)
Middle	1.161 (1.071, 1.259); <0.001	1.116 (1.028, 1.212); 0.009	1.074 (0.982, 1.175); 0.120
Highest	1.360 (1.255, 1.473); <0.001	1.260 (1.160, 1.368); <0.001	1.131 (1.004, 1.275); 0.043
60 days			
Lowest	1(Reference)	1(Reference)	1(Reference)
Middle	1.024 (0.947,1.107); 0.554	0.964 (0.890, 1.045); 0.372	0.941 (0.865, 1.023); 0.156
Highest	1.175 (1.083, 1.276); <0.001	1.118 (1.028, 1.216); 0.009	1.034 (0.944, 1.132); 0.472
180 days			
Lowest	1(Reference)	1(Reference)	1(Reference)
Middle	1.328 (1.225, 1.439); <0.001	1.259 (1.160, 1.366); <0.001	1.243 (1.128, 1.369); <0.001
Highest	1.429 (1.317, 1.550); <0.001	1.305 (1.200, 1.419); <0.001	1.261 (1.124, 1.416); <0.001
1 year			
Lowest	1(Reference)	1(Reference)	1(Reference)
Middle	1.252 (1.156, 1.356); <0.001	1.204 (1.109, 1.307); <0.001	1.143 (1.039, 1.257); 0.006
Highest	1.449 (1.338, 1.570); <0.001	1.351 (1.244, 1.468); <0.001	1.250 (1.110, 1.408); <0.001
2 years			
Lowest	1(Reference)	1(Reference)	1(Reference)
Middle	1.317 (1.214, 1.428); <0.001	1.219 (1.122, 1.324); <0.001	1.132 (1.025, 1.251); 0.014
Highest	1.418 (1.308, 1.537); <0.001	1.305 (1.201, 1.417); <0.001	1.149 (1.023, 1.290); 0.019

Model 1: Adjusted age, gender, residence, education attainment, marital status, average household income, smoking status, drinking status, and BMI categories

Model 2: Model 1+ history of dyslipidemia, history of heart disease (including heart attack, coronary heart disease, angina, congestive heart failure, or other heart problems), history of stroke, history of diabetes

Model 3: Model 2+ average temperature, relative humidity, geographic regions, air conditioning

Abbreviation: DTR, diurnal temperature range; OR, odds ratio; CI, confidence interval; BMI, body mass index

consistent with our main analysis (Supplemental Figs. 1–7, Supplemental Tables 6–12). Notably, we found significant interactions between DTR and age categories (*P* for interaction: <0.001; likelihood ratio test) and residence (*P* for interaction: 0.045; likelihood ratio test). Individuals younger than 65 and those living in rural areas are more affected by DTR.

Several additional sensitivity analyses were conducted to assess the robustness of our findings, as presented in Table 5. These included using competing risk regression; restricting the analysis to participants with complete covariate data; excluding participants with baseline diabetes, dyslipidemia, heart disease, and stroke; further adjusting for green space; and extending the main model with the city and enrollment month as random effects. The results from all sensitivity analyses were consistent with the main findings.

Discussion

In this study, we employed both cross-sectional and cohort analyses to elucidate the association between DTR and hypertension. In the cross-sectional study, we observed that higher DTR was associated with higher hypertension prevalence in different exposure windows. The strongest association between DTR and hypertension was observed in the 180-day exposure window. In the cohort study, we found that long-term exposure to higher DTR was associated with an increased risk of incident hypertension (HR: 1.224 (95% CI: 1.077–1.391) [highest tertile vs. lowest tertile]). In subgroup analyses, we found significant interactions between DTR and the age categories and residence. Additionally, the observed association remained consistent across several sensitivity analyses.

Our study revealed that higher levels of DTR were associated with a higher risk of hypertension. Prior investigations of the harmful health effects of DTR exposure have been almost exclusively concentrated on short-term exposures, i.e., days to weeks. One study found that per 1℃ increase in DTR was associated with a 0.58% (95% CI: 0.38–0.79%) increase in outpatient and emergency room admissions for hypertension [16]. Another study showed that per 1 °C increase in DTR was associated with a 1.53% increase in hypertensive hospital admissions for women aged over 75 years [35]. These studies established an association between short-term DTR and hypertension-related outpatient and emergency room admissions using a time series database. Furthermore, our study indicates that long-term DTR exposure also significantly affects hypertension. The estimated effects of long-term DTR exposure in our study were greater than those observed in studies focusing on short-term DTR exposure, consistent with the possibility that longer-term exposures may have stronger and more persistent cumulative impacts. There are also studies exploring the association between DTR exposure and CVD [36–38]. Hypertension is a known risk factor for CVD, and our study found an association between DTR and hypertension. Hypertension may mediate the relationship between DTR and CVD. Similarly, Lim et al. [11] suggest that blood pressure may serve as a mediator in the relationship between DTR and CVD. Therefore, our study may provide additional evidence supporting this relationship. In cross-sectional analyses, we found different trends in the 60-day exposure window compared to the other exposure windows and the results were not statistically significant. We suspect that this difference may stem from several reasons. First, the 60-day exposure window

Table 3 The baseline characteristics of participants involved in the Longitudinal Cohort study

Characteristic	Diurnal temperature range, ℃			
	Overall	**Lowest tertile ≤ 8.4**	**Middle tertile 8.4–10.3**	**Highest tertile > 10.3**
Participants, n	9650	3334	3349	2967
Age (year, median [IQR])	56.0 [50.0, 63.0]	57.0 [51.0, 63.8]	56.0 [49.0, 62.0]	56.0 [49.0, 62.0]
Gender, n (%)				
Male	4832 (50.1)	1653 (49.6)	1696 (50.6)	1483 (50.0)
Female	4818 (49.9)	1681 (50.4)	1653 (49.4)	1484 (50.0)
BMI (kg/m^2), n (%)				
< 18.5	607 (8.3)	267 (10.3)	168 (6.7)	172 (7.6)
18.5–23.9	4326 (58.9)	1570 (60.8)	1451 (58.0)	1305 (57.7)
> 23.9	2416 (32.9)	747 (28.9)	884 (35.3)	785 (34.7)
Education attainment, n (%)				
Elementary or below	6267 (64.9)	2308 (69.2)	2131 (63.6)	1828 (61.6)
Middle or above	3383 (35.1)	1026 (30.8)	1218 (36.4)	1139 (38.4)
Residence, n (%)				
Rural	6078 (63.0)	2058 (61.7)	2049 (61.2)	1971 (66.4)
Urban	3572 (37.0)	1276 (38.3)	1300 (38.8)	996 (33.6)
Geographic regions, n (%)				
South China	5455 (56.5)	3133 (94.0)	1778 (53.1)	544 (18.3)
North China	4195 (43.5)	201 (6.0)	1571 (46.9)	2423 (81.7)
Marital status, n (%)				
Single	978 (10.1)	351 (10.5)	320 (9.6)	307 (10.3)
Married/living together	8672 (89.9)	2983 (89.5)	3029 (90.4)	2660 (89.7)
Smoking status, n (%)				
No	5668 (58.8)	2014 (60.5)	1917 (57.4)	1737 (58.6)
Yes	3969 (41.2)	1316 (39.5)	1425 (42.6)	1228 (41.4)
Drinking status, n (%)				
No	5568 (57.8)	1841 (55.3)	1927 (57.7)	1800 (60.7)
Yes	4063 (42.2)	1488 (44.7)	1411 (42.3)	1164 (39.3)
Hypertension, n (%)				
No	6630 (68.7)	2358 (70.7)	2306 (68.9)	1966 (66.3)
Yes	3020 (31.3)	976 (29.3)	1043 (31.1)	1001 (33.7)
Diabetes history, n (%)				
No	9221 (96.5)	3193 (97.0)	3176 (95.9)	2852 (96.5)
Yes	339 (3.5)	100 (3.0)	137 (4.1)	102 (3.5)
Heart disease history, n (%)				
No	8824 (92.0)	3125 (94.5)	3070 (92.2)	2629 (89.0)
Yes	765 (8.0)	183 (5.5)	258 (7.8)	324 (11.0)
Stroke history, n (%)				
No	9500 (98.8)	3284 (98.8)	3298 (98.9)	2918 (98.6)
Yes	120 (1.2)	40 (1.2)	38 (1.1)	42 (1.4)
Dyslipidemia history, n (%)				
No	8932 (94.4)	3138 (95.8)	3068 (94.0)	2726 (93.2)
Yes	531 (5.6)	137 (4.2)	196 (6.0)	198 (6.8)
Air conditioning, n (%)				
No	7672 (80.2)	2523 (76.2)	2568 (77.4)	2581 (87.9)
Yes	1889 (19.8)	786 (23.8)	749 (22.6)	354 (12.1)
Average household income (yuan/year, median [IQR])	3776.5 [965.5, 9412.0]	3811.0 [839.2, 9703.8]	4000.0 [1120.0, 9600.0]	3624.0 [1000.0, 8942.0]
Average temperature (℃, median [IQR])	14.7 [11.0, 16.8]	17.0 [15.4, 18.8]	15.1 [12.9, 16.2]	10.8 [8.2, 12.7]
Relative humidity (%, median [IQR])	69.5 [59.7, 73.5]	73.5 [71.9, 75.2]	66.6 [59.7, 70.6]	59.4 [53.0, 64.4]
Follow-up time (month, median [IQR])	83.0 [48.0, 84.0]	83.0 [47.0, 84.0]	83.0 [48.0, 84.0]	83.0 [47.0, 84.0]

Abbreviation: IQR, interquartile range; BMI, body mass index

Table 4 The effect of the 1-year average diurnal temperature range on the incidence of hypertension

Exposure	Tertiles of DTR			*P* for trend
	Lowest HR (95% CI); *P*	**Middle HR (95% CI); *P***	**Highest HR (95% CI); *P***	
Model 1	1 (Reference)	1.031 (0.944,1.126); 0.498	1.180 (1.079,1.290); <0.001	< 0.001
Model 2	1 (Reference)	1.027 (0.940,1.122); 0.556	1.172 (1.071,1.281); 0.001	0.001
Model 3	1 (Reference)	1.055 (0.954,1.166); 0.298	1.224 (1.077,1.391); 0.002	0.004

Model 1: Stratified for age and adjusted gender, residence, education attainment, marital status, average household income, smoking status, drinking status, and BMI categories

Model 2: Model 1+ history of dyslipidemia, history of heart disease (including heart attack, coronary heart disease, angina, congestive heart failure, or other heart problems), history of stroke, history of diabetes

Model 3: Model 2+ average temperature, relative humidity, geographic regions, air conditioning

Abbreviation: DTR, diurnal temperature range, HR, hazard ratio; CI, confidence interval; BMI, body mass index

represents an intermediate period between short-term (e.g., 30 days) and long-term exposure (e.g., 180 days, 1 year, 2 years), potentially leading to a more complex effect mechanism that is influenced by other variables. Second, seasonal variations during this period could lead to larger DTR exposure ranges, which might not accurately reflect actual temperature differences. Third, the non-significant ORs for the middle DTR group may be due to small disparities between tertiles (Supplemental Table 1). Additionally, the lack of significance in the high DTR group after adjusting for humidity and geography suggests that these covariates may significantly modify the impact of DTR within this exposure window.

In the subgroup analyses, we found that the association between DTR and risk of hypertension was stronger in people living in rural areas and those aged < 65 years. In terms of region group analysis, this finding may be attributed to the fact that rural areas are less equipped with more advanced air conditioning than urban areas. Additionally, rural inhabitants are more frequently engaged in outdoor agricultural labor, in contrast to urban inhabitants who predominantly participate in indoor occupations. The nature of indoor work may substantially diminish the actual exposure levels experienced by urban inhabitants. Additionally, rural areas have less accessible health services and a lower level of health awareness compared to urban regions. Previous studies have suggested that socioeconomic status may confound or modify the relationship between DTR and human health [39]. Rural areas often have lower socioeconomic levels compared to urban areas. Consequently, residents of rural areas might be more susceptible to DTR. In terms of age group analysis, previous studies have reported inconsistent results. Some studies have suggested that the elderly are most vulnerable to the adverse effects of DTR [39, 40]. However, there is a study indicated that young adults are more sensitive to DTR than older adults [41]. Our findings align with the latter, indicating that individuals under 65 are more susceptible to DTR. We thought several reasons were contributing to this phenomenon. First, older individuals are more aware of the importance of staying warm, which may reduce their actual level of exposure to DTR. Second, elderly individuals are likely to be retired and spend extended periods indoors, further

Table 5 Sensitivity analysis on the association of participants' diurnal temperature range with incident hypertension

Tertiles of DTR	Main analysis	Sensitive analysis 1	Sensitive analysis 2	Sensitive analysis 3	Sensitive analysis 4	Sensitive analysis 5
	HR (95% CI); *P*	**HR (95% CI); *P***	**HR (95% CI); *P***	**HR (95% CI); *P***	**HR (95% CI); *P***	**HR (95% CI); *P***
Lowest	1(Reference)	1(Reference)	1(Reference)	1(Reference)	1(Reference)	1(Reference)
Middle	1.055 (0.954,1.166); 0.298	1.060 (0.960,1.169); 0.250	1.104 (0.955,1.277); 0.181	1.077 (0.964,1.203); 0.190	1.045 (0.944,1.157); 0.396	1.064 (0.919,1.232); 0.404
Highest	1.224 (1.077,1.391); 0.002	1.214 (1.071,1.377); 0.002	1.322 (1.100,1.589); 0.003	1.208 (1.050,1.390); 0.008	1.209 (1.061,1.376); 0.004	1.241 (1.027,1.500); 0.025
P for trend	0.004	0.005	0.006	0.011	0.009	0.039

Models were adjusted for gender, age, residence, education attainment, marital status, average household income, smoking status, drinking status, BMI categories, history of dyslipidemia, history of heart disease (including heart attack, coronary heart disease, angina, congestive heart failure, or other heart problems), history of stroke, history of diabetes, average temperature, relative humidity, geographic regions, air conditioning

Sensitivity analysis 1: Using a competing risk model (Fine and Gray) with death as a competing risk

Sensitivity analysis 2: Reconstruct the model among participants with complete covariate data

Sensitivity analysis 3: Excluding participants who had diabetes, dyslipidemia, heart disease, and stroke

Sensitivity analysis 4: Further adjusted for green space

Sensitivity analysis 5: Extended main model with the city and enrollment month as random effects

Abbreviation: DTR, diurnal temperature range, HR, hazard ratio; CI, confidence interval; BMI, body mass index reducing their actual level of exposure to DTR. In contrast, younger people may be more frequently exposed to high DTR due to occupational characteristics [29]. Third, in our study, only a smaller proportion (20%) of the cohort study participants were aged 65 years or older. The imbalance in sample sizes may also be one of the reasons for this difference. In the subgroup analysis of air conditioning use, among individuals without air conditioning, the HR was 1.280 (95% CI: 1.115–1.470) for the highest tertile of DTR compared to the lowest tertile of DTR. However, among individuals with air conditioning, the HRs corresponding to each tertile were not statistically significant. This discrepancy may be attributed to air conditioning's ability to moderate the actual DTR, thereby reducing the actual exposure levels and consequently diminishing the effect of DTR on hypertension.

So far, the mechanism of the relationship between DTR and hypertension has not been fully understood, but several plausible explanations exist. Sudden temperature changes, such as DTR, disrupt normal physiological thermoregulation [8, 42], affecting plasma viscosity, heart rate, blood pressure, blood cholesterol levels, oxygen uptakes, and the immune system [28, 43]. These sudden changes may increase the cardiovascular burden and enhance the body's sensitivity to DTR. Prior studies have suggested that large DTRs can alter heart rate, activating the sympathetic nervous system and subsequently increasing blood pressure [39]. Activation of the sympathetic nervous system could also result in elevated BP through vasoconstriction of the blood vessels or impaired endothelium-dependent vasodilatation [44, 45]. Previous studies have demonstrated a positive association between SBP and DTR [6, 11]. However, the relationship between DBP and DTR has yielded inconsistent results. In the future, more research is needed to further explore the relationship between DBP and DTR. Temperature variability (TV) is another measure of temperature change. TV was calculated as the standard deviation (SD) of the minimum and maximum air temperatures during the exposure days [12]. A recent study in China found that TV will significantly increase the levels of high-sensitivity C reactive protein (hs-CRP) [46, 47]. In addition, previous studies suggest that a higher hs-CRP level is a risk factor for hypertension [48, 49]. Further research should be done to determine whether a mechanism has the same relationship between hs-CRP and DTR as between hs-CRP and TV.

Our study has important implications for public health, particularly in the prevention of hypertension. Firstly, we found a positive correlation between DTR and the risk of developing hypertension. This finding suggests that individuals should avoid exposure to extreme temperatures and maintain warmth to reduce the impact of extreme DTR. Secondly, we found that young people and individuals living in rural areas are at an increased risk of developing hypertension due to DTR. This indicates that preventive measures should be encouraged for these groups. Finally, the results of our study offer valuable insights for policymakers about the health risks associated with DTR, which can guide public health strategies. Relevant authorities should issue timely and accurate weather warnings to encourage people to take protective measures in advance.

This study has several strengths. First, the relationship between DTR and hypertension was investigated in cross-sectional and cohort studies. The simultaneous confirmation of the two studies strengthens the evidence base. Second, this study, conducted in mainland China, was representative of the middle-aged and elderly Chinese population and adds to evidence of the association between DTR exposure and the risk of hypertension. CHARLS is a nationwide cohort study that provides strong representativeness of the population. Furthermore, we calculated individuals' multiple exposure windows, including pre-baseline exposure with distinct periods, to estimate the optimum exposure time windows to define exposure risk and the semi-acute or chronic effects on hypertension. We first explored the relationship between DTR and the prevalence of hypertension across various exposure windows. Additionally, we examined the long-term effects of DTR on hypertension, revealing its sustained impact.

However, this study still has some limitations. First, participants' exact home addresses were not disclosed to general users to protect their privacy, exposure to DTR was assessed at the city level. Therefore, this study was the lack of information on individual-level exposure assessment, thus potentially contributing to exposure misclassification. Second, the survival event was assessed during each follow-up. The exact date of hypertension incidence was not obtainable, which led to some assessment bias. Third, our study focused on middle-aged and elderly people, limiting the generalizability of the study to populations of all ages. Fourth, since this is an observational study, it cannot establish causality. Fifth, in the cohort study, we selected 1-year exposure window but did not consider the DTR exposure between baseline and the time of hypertension development. Individuals might have traveled or relocated before or after the baseline measurement. This suggests that the measured DTR exposure might not accurately reflect the actual exposure levels. Future research endeavors should incorporate multiple follow-up visits to accurately capture the true extent of temperature difference exposure.

Conclusions

In conclusion, we found positive significant associations of exposure to DTR with both prevalent and incident hypertension. Individuals younger than 65 and those living in rural areas are at an elevated risk of developing hypertension due to DTR. Further studies are required to investigate the underlying mechanisms of this association.

Abbreviations

DTR	Diurnal temperature range
CHARLS	The China Health and Retirement Longitudinal Study
OR	Odds ratio
CI	Confidence interval
HR	Hazard ratio
HF	Heart failure
CVDs	Cardiovascular diseases
SBP	Systolic blood pressure
PP	Pulse pressure
DBP	Diastolic blood pressure
HRS	The Health and Retirement Study
BMI	Body mass index
IQR	Interquartile range
TV	Temperature variability
SD	Standard deviation
hs-CRP	High-sensitivity C reactive protein

Supplementary Information

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Supplementary Material 1

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Author contributions

Authors' Contributions Tiange Yan: Data curation, Formal analysis, Methodology, Writing an original draft. Qilin Song: Data curation, Formal analysis, Methodology, Writing an original draft. Ming Yao: Software, Visualization. Xingyuan Zhang: Validation, Supervision, Writing - review & editing. Yaxiong He: Project administration, Writing - review & editing. All authors reviewed the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

All procedures performed in studies involving human participants were by the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The original CHARLS was approved by the Ethical Review Committee of Peking University, and all participants signed informed consent at the time of participation.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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