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Extreme Heat Exposure and Acute Cardiovascular Events in Pakistan: Clinical Risk, Multisystem Complications and Health-System Resilience

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ABSTRACT:

Background: Extreme heat represents a growing challenge for cardiovascular health and health systems in climate-vulnerable regions. This study investigated the associations between ambient heat exposure, acute cardiovascular presentations, clinical outcomes, and hospital operational performance at tertiary cardiovascular centers in Pakistan.

Methods: This multicenter retrospective hospital-based observational study included 13,392 cardiovascular presentations over 552 hospital-days in Karachi, Lahore, and Peshawar. The primary exposure was daily maximum temperature, with extreme heat defined by center-specific 95th-percentile thresholds. Negative binomial regression was used to assess daily presentation counts, and multivariable logistic regression evaluated patient-level outcomes.

Results: Thirty-eight hospital-days met the extreme-heat criterion, accounting for 1,018 presentations. Each 5°C increase in same-day maximum temperature was associated with increased daily cardiovascular presentation rates (IRR 1.14, 95% CI 1.09–1.20; *P*<.001). Higher temperatures were also associated with acute kidney injury (AOR 1.28), multiorgan dysfunction (AOR 1.38), CCU/ICU admission (AOR 1.16), mechanical ventilation (AOR 1.26), and in-hospital mortality (AOR 1.27). Extreme-heat periods were characterized by higher occupancy and longer door-to-balloon times, while median length of stay remained unchanged. Sensitivity analyses confirmed the consistency of the hospital-day association.

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Conclusion: Higher ambient temperatures were associated with increased cardiovascular burden, greater clinical severity, and heightened hospital service pressure in Pakistan. These findings support the need for heat-adaptive cardiovascular preparedness and ongoing multi-year investigation.

INTRODUCTION

Extreme heat constitutes an increasingly significant medical and public health threat as rising ambient temperatures, recurrent heatwaves, rapid urbanization, and greater population exposure intensify the physiological consequences of thermal stress. The health effects of heat extend beyond classical heat exhaustion and heatstroke; elevated ambient temperatures can destabilize pre-existing chronic diseases, precipitate acute clinical deterioration, increase hospital utilization, and contribute to premature mortality among susceptible populations.[1] A substantial proportion of contemporary heat-related mortality has been attributed to anthropogenic climate change.[2] Global analyses reveal marked geographical variation in temperature-associated mortality, indicating that health effects depend not only on absolute temperature but also on local climatology, population acclimatization, socioeconomic conditions, and adaptive capacity.[3] These factors are particularly relevant in countries such as Pakistan, where large urban populations experience significant seasonal temperature variation, a considerable cardiovascular disease burden, and heterogeneous healthcare capacity.

The cardiovascular system is especially susceptible to thermal stress. Systematic evidence demonstrates that elevated ambient temperatures and heatwave exposure are associated with increased cardiovascular morbidity and mortality.[4] Physiologically, heat exposure triggers peripheral vasodilation and increased cutaneous blood flow to dissipate heat, while sweating causes progressive fluid and electrolyte loss. The consequent reduction in circulating plasma volume may lower cardiac preload and stimulate compensatory tachycardia and increased cardiac output, thereby elevating myocardial workload.[5] In individuals with impaired cardiovascular reserve, these physiological responses can destabilize otherwise compensated disease. Multinational studies involving hundreds of cities have shown associations between extreme temperature and mortality from cardiovascular disease, including ischemic heart disease and heart failure.[6] Recent global estimates further indicate that cardiovascular mortality attributable to non-optimal temperature remains substantial, with Southern Asia identified as a region where temperature-related cardiovascular burden warrants particular attention.[7]

Multiple mechanisms support the biological plausibility of a short-term association between extreme heat and acute cardiovascular events. Heat-induced dehydration may promote hemoconcentration, increased blood viscosity, sympathetic activation, endothelial stress, and alterations in thrombogenic potential, while peripheral vasodilation and volume depletion can reduce effective coronary perfusion. In individuals with underlying coronary atherosclerosis, the combination of increased myocardial oxygen demand and reduced circulatory reserve may precipitate myocardial ischemia or acute coronary events. Epidemiological studies indicate that the relationship between temperature and myocardial infarction is not necessarily linear, and that the cardiovascular consequences of thermal exposure may vary across temperature ranges and populations.[8] Medication use may further modify susceptibility, particularly among patients receiving therapies that affect blood pressure, heart rate, renal sodium handling, circulating volume, or thermoregulatory responses.[9] Evidence from tropical settings suggests that ambient temperature can influence acute myocardial infarction presentations, with associations that may differ by patient age.[10] Extreme heat and humidity may also increase the risk of ventricular arrhythmia among patients with established cardiovascular disease, including those with coronary artery disease, heart failure, hypertension, diabetes mellitus, or previous myocardial infarction.[11]

The cardiovascular consequences of heat are unlikely to be distributed uniformly across the population. Older adults and individuals with hypertension, diabetes mellitus, chronic kidney disease, heart failure, established ischemic heart disease, and multimorbidity often have reduced physiological reserve and a diminished capacity to maintain cardiovascular and thermoregulatory homeostasis during extreme heat. Pooled evidence has demonstrated associations between adverse temperature conditions and cardiovascular hospitalization.[12] More recent patient-level research indicates that emergency hospitalization during hot weather increases among individuals with multimorbidity, particularly those with chronic kidney and cardiopulmonary disease.[13] These findings suggest that temperature should not be viewed solely as an external environmental exposure; underlying disease, age, medication use, and baseline physiological vulnerability may modify its clinical effects.

The consequences of thermal stress may extend beyond the primary cardiovascular diagnosis. Dehydration, reduced renal perfusion, electrolyte disturbances, hypotension, hypoxemia, and systemic physiological stress can contribute to acute kidney injury, circulatory instability, respiratory compromise, neurological dysfunction, hepatic injury, and other extracardiac complications. Clinically, these complications are significant because they may increase the need for coronary or intensive care, mechanical ventilation, prolonged hospitalization, and other resource-intensive interventions. Therefore, evaluation of heat-related cardiovascular disease should not be limited to the occurrence of myocardial infarction or heart failure alone. It should also assess whether cardiovascular patients presenting during high-temperature conditions experience greater clinical severity and multiorgan dysfunction.

Extreme heat can also affect healthcare delivery at the system level. Sudden increases in emergency presentations and hospital admissions place pressure on emergency departments, coronary care units, intensive care services, diagnostic facilities, and interventional cardiovascular programs. During the 2021 British Columbia heatwave, emergency department utilization and hospital admissions changed substantially during and after the extreme-heat period, showing that health-service effects can extend beyond immediate heat exposure.[14] Evidence from South Asia is particularly relevant because population density, occupational exposure, housing quality, access to cooling, baseline disease burden, and healthcare resources differ from those in many high-income settings. A multicity study from India identified significant heatwave-related mortality with notable heterogeneity between cities, reinforcing the need for locally defined exposure thresholds and site-specific assessment rather than direct extrapolation from temperate populations.[15]

Pakistan is an important setting for such investigation, yet cardiovascular evidence remains limited. A study at the National Institute of Cardiovascular Diseases in Karachi examined associations between meteorological variation and daily primary percutaneous coronary intervention activity for acute myocardial infarction.[16] While the study demonstrated the feasibility of linking cardiovascular and meteorological data in Pakistan, its single-center design and reliance on procedural activity limited assessment of the broader spectrum of acute cardiovascular presentations, patient-level clinical severity, and healthcare-system burden. Existing Pakistani literature has more frequently focused on classical heat-related illness. During the severe Karachi heat episode of 2015, hospital-based research documented substantial mortality among heatstroke patients and reported neurological, renal, hepatic, and coagulation abnormalities, illustrating the potential for severe heat exposure to cause multiorgan dysfunction.[17] Additional evidence from Karachi has identified pre-existing illness among patients with severe heat-related disease and highlighted the need for inpatient and critical-care resources during extreme heat events.[18] Exposure also has implications for healthcare preparedness in Pakistan. Reports from Karachi have described substantial pressure on tertiary emergency services during periods of very high summer temperatures and have emphasized the need for improved institutional preparedness for heat-related surges.[19] Encouragingly, a long-term evaluation of the Heat Emergency Awareness and Treatment intervention demonstrated that structured emergency-department education improved recognition and management of heat-related illness in Karachi.[20] These findings suggest that health-system responses to extreme heat are modifiable. However, health-system strain and resilience should be distinguished analytically: increased patient volume reflects greater service demand, whereas operational resilience refers to hospitals' ability to maintain timely and effective cardiovascular care despite that demand.

Despite the growing international evidence, a significant clinical and methodological gap persists in Pakistan. Existing local studies have primarily examined heatstroke, heat-related mortality, or single-center cardiovascular procedural activity, rather than linking meteorological exposure with the full spectrum of acute cardiovascular presentations across multiple climatically distinct settings. Evidence is particularly limited regarding whether short-term variation in ambient temperature is associated with the daily burden of acute cardiovascular events, whether patients presenting during extreme-heat conditions experience greater multiorgan complications or adverse in-hospital outcomes, and whether increased cardiovascular demand during hot periods is accompanied by measurable health-system strain or deterioration in operational performance. Additionally, the extent to which clinically vulnerable groups—including older adults and patients with diabetes, chronic kidney disease, ischemic heart disease, or heart failure—experience differential heat-associated risk remains insufficiently characterized in Pakistani cardiovascular populations.

Accordingly, this multicenter study integrated meteorological, patient-level clinical, and hospital operational data from tertiary cardiovascular centers in climatically distinct regions of Pakistan. The primary objective was to examine the association between daily maximum ambient temperature and the daily number of acute cardiovascular presentations. Secondary objectives included determining whether extreme-heat exposure was associated with multiorgan complications, critical-care utilization, prolonged

hospitalization, and in-hospital mortality among patients with acute cardiovascular events; assessing whether heat-associated effects differed across clinically vulnerable patient subgroups; and evaluating heat-related changes in cardiovascular service demand and operational performance as indicators of health-system strain and resilience. By distinguishing population-level cardiovascular event burden from patient-level clinical severity and hospital-level operational consequences, the study aimed to generate clinically and operationally relevant evidence for cardiovascular risk recognition, emergency preparedness, and adaptation of health services to increasing extreme-heat exposure in Pakistan.

METHODS

Study Design and Setting

A multicenter retrospective hospital-based observational study was conducted to examine associations between ambient heat exposure, acute cardiovascular presentation burden, patient-level clinical outcomes, and hospital operational performance in Pakistan. The study incorporated two complementary analytical components: a hospital-day time-series analysis evaluating daily cardiovascular presentation counts and a patient-level analysis evaluating clinical severity and in-hospital outcomes among patients with acute cardiovascular conditions.

The study included three tertiary cardiovascular centers: the National Institute of Cardiovascular Diseases, Karachi; Punjab Institute of Cardiology, Lahore; and Peshawar Institute of Cardiology, Peshawar. The study period extended from 1 March through 31 August 2026, providing 184 observation days per center and 552 hospital-days overall.

Study Population and Eligibility

The study population comprised adults aged 20 years or older presenting with an acute cardiovascular condition during the study period. Principal cardiovascular diagnoses were mutually exclusive and included arrhythmia, non-ST-segment elevation myocardial infarction (NSTEMI), ST-segment elevation myocardial infarction (STEMI), acute heart failure, cardiac arrest of presumed cardiovascular origin, and hypertensive emergency.

The principal diagnosis was based on the final clinical assessment recorded during the index hospital encounter. Baseline characteristics included age, sex, hypertension, diabetes mellitus, chronic kidney disease, established ischemic heart disease, pre-existing heart failure, smoking status, and referral status.

Elective admissions, stable chronic cardiovascular disease without acute deterioration, trauma-related admissions, elective surgical admissions, and admissions primarily attributable to non-cardiovascular conditions were excluded. Duplicate records and records lacking sufficient information for temporal or meteorological linkage were also excluded.

A complete-enumeration approach was used, whereby all eligible cardiovascular presentations occurring at the participating centers during the predefined study period were included.

Data Sources and Linkage

Patient-level data were obtained from clinical and hospital records at the participating cardiovascular centers. Relevant information included demographic characteristics, principal cardiovascular diagnosis, baseline comorbidities, referral status, clinical complications, critical-care utilization, invasive mechanical ventilation, length of hospital stay, and in-hospital mortality.

Hospital operational data were aggregated at the hospital-day level and included daily cardiovascular presentation counts, critical-care occupancy, and door-to-balloon time among eligible primary PCI recipients.

Meteorological information corresponding to Karachi, Lahore, and Peshawar was linked with clinical and hospital operational data according to calendar date and study center. Daily maximum, mean, and minimum temperatures and relative humidity were used for exposure assessment.

Following application of the predefined eligibility criteria and data-quality procedures, the final analytical dataset comprised 13,392 cardiovascular presentations across 552 hospital-days.

Heat Exposure Definition

Daily maximum ambient temperature (*T*max) was the primary continuous environmental exposure and was expressed in degrees Celsius. Site-specific temperature distributions were used because climatic conditions differed substantially across Karachi, Lahore, and Peshawar.

An extreme-heat day was defined as a hospital-day on which daily maximum temperature reached or exceeded the site-specific 95th percentile of the corresponding historical March-August temperature distribution. Extreme-heat thresholds were therefore derived separately for the three study locations rather than using a single national temperature threshold. The resulting thresholds are reported in Table 1.

These thresholds were analytical exposure definitions and were not interpreted as official city-specific heat-warning thresholds.

A heatwave was defined as at least two consecutive days meeting the corresponding site-specific extreme-heat criterion.

Short-term temperature exposure was evaluated using lag 0, lag 1, mean lag 0-1, and mean lag 0-3 days. Lag 0 represented temperature on the day of presentation, whereas lag 1 represented temperature on the preceding day. Lag-window temperatures were calculated as arithmetic means.

Temperature observations from 26-28 February 2026 were used only to permit complete lag calculations for presentations occurring at the beginning of the study period and were not included as study outcome days.

Daily mean temperature and daily minimum temperature were evaluated as alternative continuous exposure measures in sensitivity analyses.

Study Outcomes

The primary hospital-day outcome was the daily number of acute cardiovascular presentations recorded at each participating center.

Patient-level outcomes included acute kidney injury (AKI), multiorgan dysfunction involving at least two extracardiac organ systems, CCU/ICU admission, invasive mechanical ventilation, length of hospital stay, and in-hospital mortality.

AKI was identified from the documented clinical diagnosis recorded during the index hospital encounter. The recorded AKI classification was not independently re-adjudicated using complete serial serum creatinine measurements or urine-output data. Accordingly, AKI was analyzed as a clinically documented diagnostic outcome rather than as an independently reconstructed laboratory-based KDIGO endpoint.

Multiorgan dysfunction was defined as involvement of at least two extracardiac organ systems among the renal, circulatory, respiratory, hepatic, and neurological systems. Each affected system was counted once when determining the composite outcome.

The timing of complications was classified relative to the index cardiovascular presentation. AKI documented at presentation or within the first 24 hours was classified as early AKI, whereas AKI first documented more than 24 hours after presentation was classified as subsequent AKI.

For multiorgan dysfunction, timing was determined by when the second qualifying extracardiac organ system became involved. Consequently, a patient could have one organ-system complication within the first 24 hours and subsequently reach the multiorgan threshold after 24 hours.

CCU/ICU admission and invasive mechanical ventilation were determined from hospital treatment records. Length of stay was calculated from admission until discharge or in-hospital death. In-hospital mortality was defined as death occurring during the index hospital encounter.

Hospital Operational Measures

Hospital service demand and operational performance were assessed descriptively within each participating center. Indicators included mean cardiovascular presentations per day, critical-care occupancy, and door-to-balloon time among primary PCI recipients.

Critical-care occupancy (%) was calculated as the number of occupied staffed critical-care beds divided by the number of available staffed critical-care beds, multiplied by 100.

$$\text{Critical-care occupancy (\%)} = \frac{\text{Occupied staffed critical-care beds}}{\text{Available staffed critical-care beds}} \times 100$$

Door-to-balloon time was defined as the interval between hospital arrival and balloon inflation among eligible primary PCI recipients and was summarized using the median and interquartile range.

Operational indicators were compared within centers between extreme-heat and non-extreme-heat periods. These comparisons were descriptive and were not interpreted as adjusted estimates of an independent causal effect of heat on hospital operational performance.

Covariates

Patient-level models incorporated age, sex, baseline comorbidities, smoking status, referral status, hospital, relative humidity, and calendar time.

Baseline comorbidities included hypertension, diabetes mellitus, chronic kidney disease, established ischemic heart disease, and pre-existing heart failure.

Acute clinical complications occurring after heat exposure were not included as baseline confounders because they could represent intermediate events on the pathway between environmental exposure and adverse clinical outcomes.

Hospital-day models incorporated hospital, relative humidity, day of the week, public holidays, and calendar time.

Statistical Analysis

Continuous variables were summarized using means with standard deviations when approximately normally distributed and medians with interquartile ranges when distributions were skewed. Categorical variables were summarized using frequencies and percentages.

Patient characteristics were summarized overall and separately for presentations occurring during extreme-heat and non-extreme-heat conditions. These comparisons were descriptive and were not interpreted as adjusted estimates of temperature effects.

Hospital-Day Analysis

Daily cardiovascular presentation counts were analyzed using negative binomial regression after examination of the count distribution indicated overdispersion.

Separate regression models evaluated lag 0 maximum temperature per 5°C, lag 1 maximum temperature per 5°C, mean lag 0-1 temperature per 5°C, mean lag 0-3 temperature per 5°C, extreme heat versus other hospital-days, and ≥2-day heatwave exposure versus other days.

Associations were reported as incidence rate ratios (IRRs) with 95% confidence intervals.

Each model adjusted for hospital fixed effects, relative humidity, day of the week, public holidays, and calendar time modeled using a natural spline with three degrees of freedom.

Because successive daily observations within each center could exhibit temporal dependence, confidence intervals were calculated using a within-center Newey-West sandwich estimator with seven lags. Covariance was not clustered across the three hospitals.

Patient-Level Analysis

Multivariable logistic regression was used to evaluate associations between temperature exposure and binary patient-level outcomes, including AKI, multiorgan dysfunction, CCU/ICU admission, invasive mechanical ventilation, and in-hospital mortality.

Two principal exposure specifications were evaluated: continuous temperature per 5°C increase and extreme-heat exposure versus non-extreme-heat conditions.

Associations were reported as adjusted odds ratios (AORs) with 95% confidence intervals. Models adjusted for age, sex, baseline comorbidities, smoking status, referral status, hospital, relative humidity, and calendar time.

Acute clinical complications were not included as baseline confounders. Standard errors were clustered by hospital-day to account for the shared daily environmental exposure among patients presenting on the same hospital-day.

Length of hospital stay was analyzed descriptively and summarized using the median and interquartile range.

Sensitivity Analyses

Robustness of the hospital-day temperature association was evaluated using several alternative exposure specifications.

Extreme heat was alternatively defined using the site-specific 90th, 97.5th, and 99th percentiles of the reference temperature distributions. A more restrictive heatwave definition requiring at least three consecutive extreme-heat days was also evaluated.

Daily mean temperature and daily minimum temperature were examined as alternative continuous exposure metrics, with associations expressed per 5°C increase.

Leave-one-center-out analyses were conducted by sequentially excluding Karachi, Lahore, and Peshawar to assess whether the pooled temperature association depended disproportionately on any single center.

Sensitivity analyses were considered exploratory, and no adjustment for multiple comparisons was applied.

Statistical Inference

All statistical tests were two-sided, and a *P* value < .05 was considered statistically significant. Interpretation emphasized effect estimates and 95% confidence intervals rather than statistical significance alone, particularly for secondary and sensitivity analyses.

Ethical Considerations

Ethical approval was obtained from the relevant institutional authorities of the participating hospitals. Because the study involved retrospective analysis of clinical and hospital operational data with no direct patient intervention, patient confidentiality was maintained throughout data extraction, linkage, storage, and statistical analysis.

RESULTS

Sample and heat exposure

The dataset comprised 13,392 cardiovascular presentations across 552 hospital-days, with each of the three participating centers contributing 184 observation days. Of these, 38 hospital-days met the predefined extreme-heat criterion and accounted for 1,018 cardiovascular presentations. Overall, Karachi recorded 5,673 presentations, Lahore 4,348, and Peshawar 3,371.

Table 1. Study coverage and meteorological exposure.

Center label	Days	Presentations	T max, mean (SD), °C	P95, °C	Extreme days	Days in ≥2-day episodes
Karachi	184	5673	35.4 (3.0)	39.28	13	9
Lahore	184	4348	37.0 (3.5)	41.90	11	5
Peshawar	184	3371	36.2 (3.2)	40.76	14	7

Thresholds were derived from the corresponding historical daily reference temperature series for March through August. These analytical thresholds should not be interpreted as official city-specific heat-warning thresholds. Temperature observations from 26–28 February 2026 were included solely to permit complete lag calculations at the beginning of the study period.

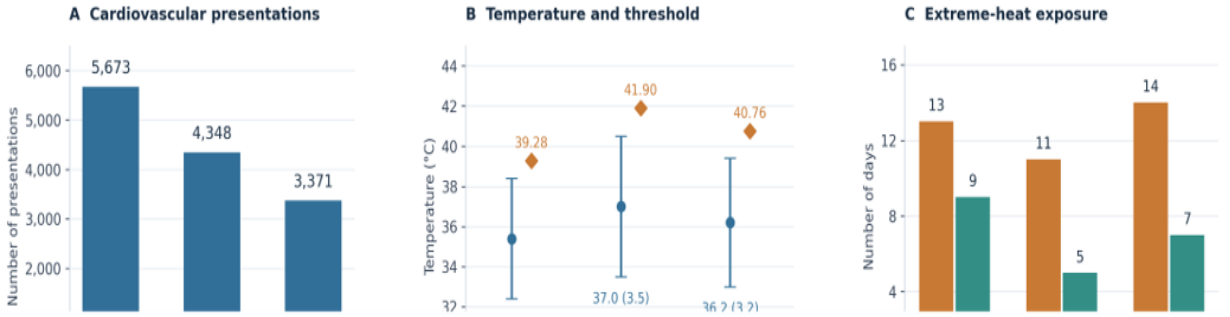

Figure 1 study coverage and meteorological exposure.

Patient characteristics

Table 2. Characteristics by extreme-heat status.

Characteristic	Overall	Non-extreme heat	Extreme heat
Presentations	13,392	12,374	1,018
Age, mean (SD)	59.0 (12.7)	59.0 (12.7)	59.0 (13.1)
Male	8,935 (66.7%)	8,268 (66.8%)	667 (65.5%)
Hypertension	7,825 (58.4%)	7,223 (58.4%)	602 (59.1%)
Diabetes	4,255 (31.8%)	3,923 (31.7%)	332 (32.6%)
Chronic kidney disease	1,555 (11.6%)	1,441 (11.6%)	114 (11.2%)
Established ischemic heart disease	4,551 (34.0%)	4,239 (34.3%)	312 (30.6%)
Pre-existing heart failure	2,288 (17.1%)	2,126 (17.2%)	162 (15.9%)
Transferred presentation	2,366 (17.7%)	2,204 (17.8%)	162 (15.9%)
Arrhythmia	1,793 (13.4%)	1,641 (13.3%)	152 (14.9%)
NSTEMI	2,841 (21.2%)	2,643 (21.4%)	198 (19.4%)
STEMI	3,693 (27.6%)	3,435 (27.8%)	258 (25.3%)
Acute heart failure	3,137 (23.4%)	2,876 (23.2%)	261 (25.6%)
Cardiac arrest	549 (4.1%)	509 (4.1%)	40 (3.9%)
Hypertensive emergency	1,379 (10.3%)	1,270 (10.3%)	109 (10.7%)

Values are presented as n (%) unless otherwise specified. Diagnostic categories correspond to mutually exclusive principal diagnoses. Comparisons are descriptive and have not been adjusted for temperature effects.

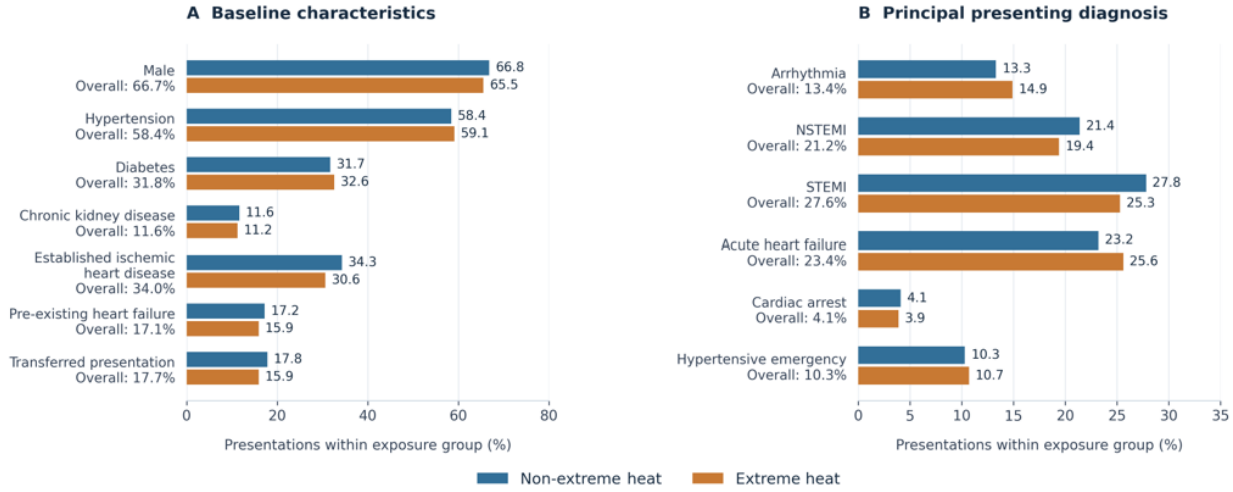

Figure 2 characteristics by extreme-heat status.

Temperature and daily cardiovascular presentations

In the primary negative binomial model, a 5°C increase in same-day maximum temperature was associated with an adjusted incidence rate ratio (IRR) of 1.14 (95% CI, 1.09–1.20; P < .001) for daily cardiovascular presentations. The estimated negative binomial overdispersion parameter was 0.032.

Table 3. Adjusted hospital-day associations in the dataset.

Exposure contrast	Adjusted IRR (95% CI)	P
Lag 0, per 5°C	1.14 (1.09–1.20)	<.001
Lag 1, per 5°C	1.06 (1.01–1.11)	0.028
Mean lag 0–1, per 5°C	1.13 (1.06–1.19)	<.001
Mean lag 0–3, per 5°C	1.08 (1.00–1.16)	0.049
Extreme heat vs other days	1.11 (1.01–1.22)	0.028
≥2-day heatwave vs other days	1.16 (1.02–1.31)	0.020

Each row corresponds to a distinct model adjusted for hospital fixed effects, relative humidity, day of the week, holiday indicator, and a natural calendar-time spline with three degrees of freedom. Confidence intervals are calculated using a within-

center Newey–West sandwich estimator with seven lags. Covariance is not clustered across the three hospitals. Lag-window temperatures are calculated as arithmetic means. Heatwave days are defined as days that belong to qualifying episodes.

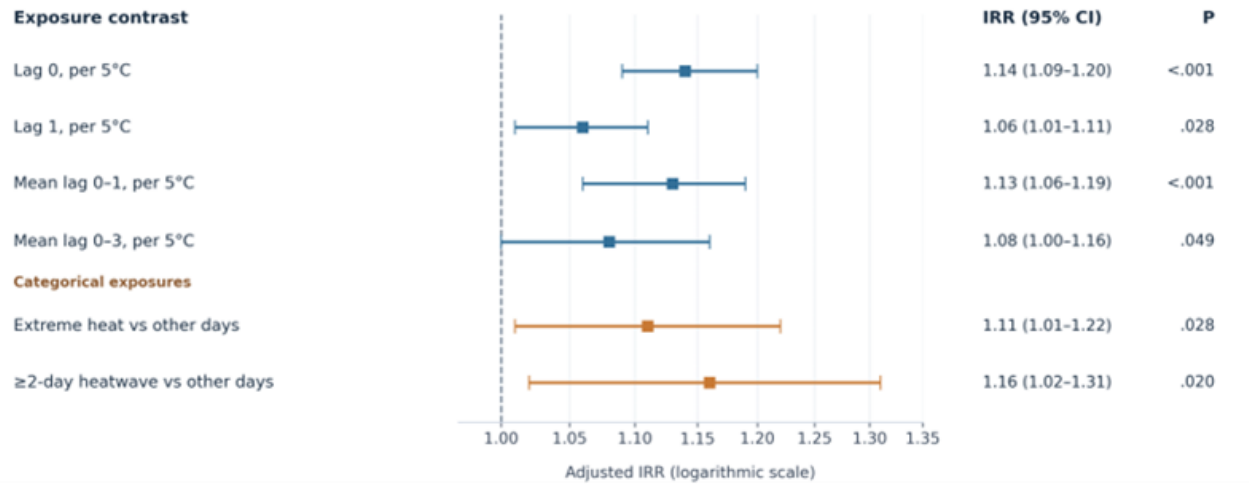

Figure 3 Adjusted hospital-day associations in the dataset.

Clinical complications and outcomes

Table 4. Outcomes and adjusted patient-level associations.

Outcome	Non-extreme heat	Extreme heat	AOR per 5°C (95% CI)	P	AOR extreme heat (95% CI)
Acute kidney injury	1,675 (13.5%)	175 (17.2%)	1.28 (1.14–1.44)	<.001	1.25 (1.02–1.52)
≥2 extracardiac organ systems	526 (4.3%)	64 (6.3%)	1.38 (1.16–1.65)	<.001	1.44 (1.08–1.92)
CCU/ICU admission	3,032 (24.5%)	287 (28.2%)	1.16 (1.08–1.25)	<.001	1.12 (0.97–1.29)
Invasive mechanical ventilation	679 (5.5%)	62 (6.1%)	1.26 (1.05–1.51)	0.014	1.06 (0.74–1.52)
In-hospital death	490 (4.0%)	45 (4.4%)	1.27 (1.07–1.51)	0.006	1.14 (0.83–1.55)

The models were adjusted for age, sex, baseline comorbidities, smoking status, referral status, hospital, humidity, and calendar time. Acute complications were excluded as confounders. Standard errors were clustered by hospital-day (552 clusters) to account for shared daily exposures. The denominator comprised all eligible presentations, while in-hospital death was defined as deaths occurring during the index hospital encounter.

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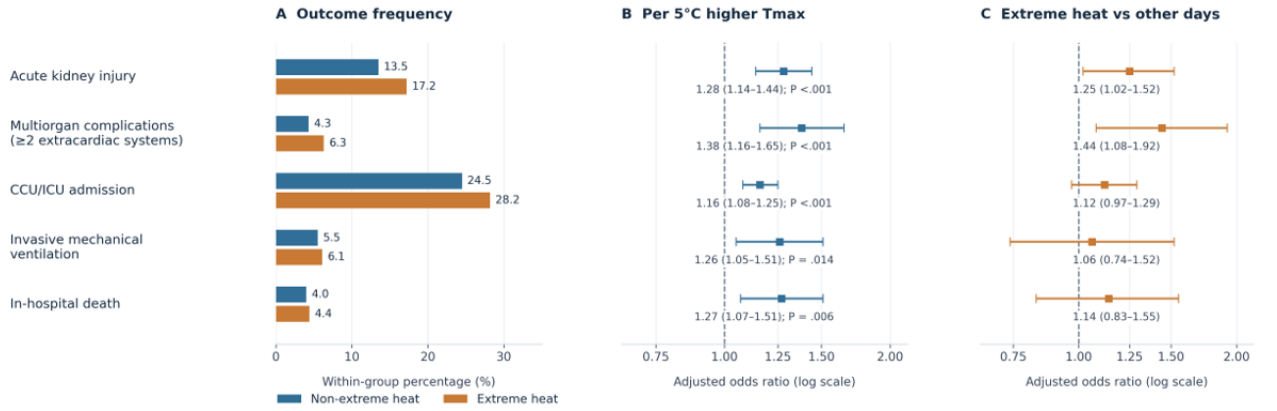

Table 5. Timing of complications.

Complication timing	Overall	Non-extreme heat	Extreme heat
AKI: ≤24 h	1,202 (9.0%)	1,092 (8.8%)	110 (10.8%)
AKI: >24 h	648 (4.8%)	583 (4.7%)	65 (6.4%)
Multiorgan threshold reached ≤24 h	232 (1.7%)	209 (1.7%)	23 (2.3%)
Multiorgan threshold reached >24 h	358 (2.7%)	317 (2.6%)	41 (4.0%)

Multiorgan dysfunction was defined as involvement of at least two extracardiac organ systems, including the renal, circulatory, respiratory, hepatic, and neurological systems, with each system counted only once. Subsequent multiorgan dysfunction was defined by the involvement of a second qualifying extracardiac organ system more than 24 hours after presentation and could include patients in whom one organ system was affected within the first 24 hours. Acute kidney injury (AKI) was identified from the documented clinical diagnosis recorded during the index hospital encounter and was not independently revalidated using complete serial serum creatinine measurements or urine-output criteria.

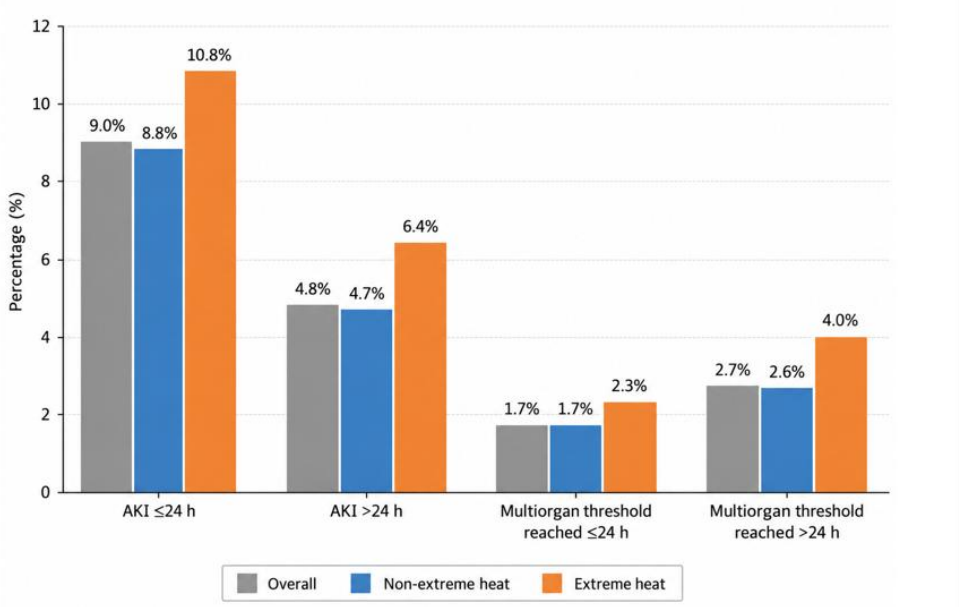

Figure 4 Timing of complications.

Service demand and operational performance

Table 6. Within-center descriptive service comparisons.

Center	Presentations/day: non-extreme	Extreme	Occupancy %: non-extreme	Extreme	Door–balloon min: non-extreme	Extreme
Karachi	30.7	32.7	75.9	80.6	77.2 (64.9–88.9)	86.6 (75.4–101.8)
Lahore	23.4	27.5	77.2	81.7	80.3 (68.2–92.7)	90.7 (80.2–103.7)
Peshawar	18.1	20.7	76.6	83.3	79.3 (67.7–90.8)	90.8 (80.7–105.3)

Occupancy is defined as the ratio of occupied staffed beds to available staffed beds, based on daily census measures rather than same-day admission counts. Door-to-balloon times are reported as median and interquartile range (IQR) among primary PCI recipients. Analyses of within-center changes are used to avoid equating hospitals with different baseline volumes. These unadjusted operational comparisons do not demonstrate an independent effect on resilience.

Among admitted patients, the length of stay was 4.0 days (interquartile range 3.0–5.0) overall, 4.0 days (3.0–5.0) on non-extreme days, and 4.0 days (3.0–5.0) on extreme days. These descriptive statistics do not differentiate between discharge alive and death as competing outcomes.

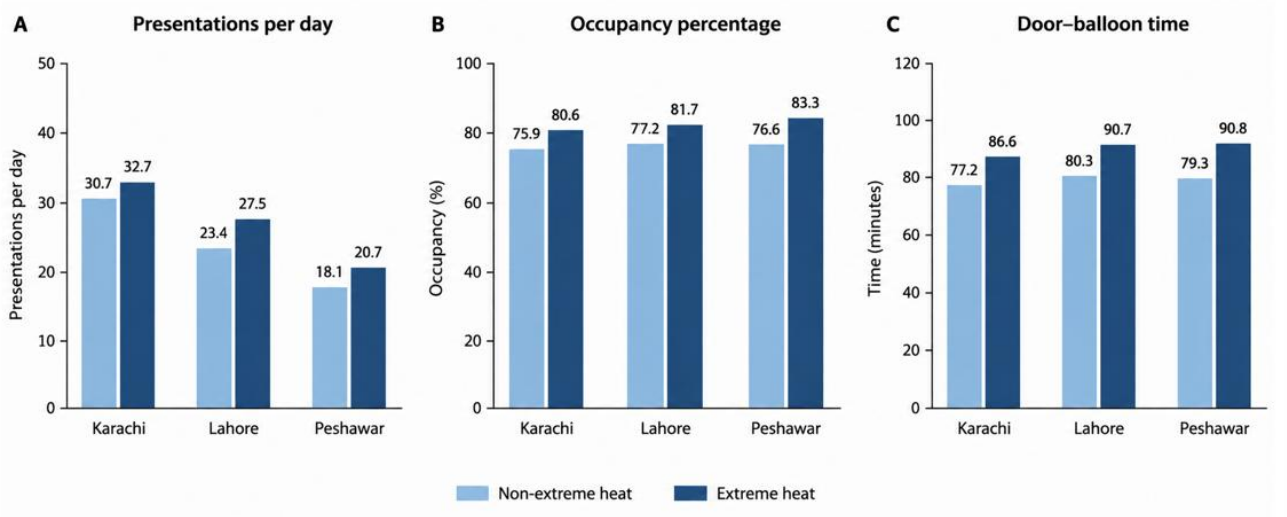

Figure 5 Within-center descriptive service comparisons.

Sensitivity analyses

Table 7. Alternative exposures and center exclusions.

Specification	Adjusted IRR (95% CI)	P
extreme90	1.10 (1.03–1.18)	0.004
extreme975	1.15 (1.00–1.32)	0.043
extreme99	1.21 (1.03–1.43)	0.022
heatwave3	1.19 (1.02–1.37)	0.022
T mean	1.14 (1.09–1.19)	<.001
T min	1.12 (1.07–1.17)	<.001

Per 5°C, excluding Karachi	1.18 (1.10–1.25)	<.001
Per 5°C, excluding Lahore	1.14 (1.08–1.21)	<.001
Per 5°C, excluding Peshawar	1.12 (1.06–1.18)	<.001

The terms extreme90, extreme975, and extreme99 refer to reference percentiles. The heatwave3 criterion requires at least three consecutive extreme days. Both mean and minimum temperature models, as well as center-exclusion models, utilize 5°C contrasts. Sparse extreme categories may yield imprecise estimates. These models are exploratory, and no correction for multiplicity was applied.

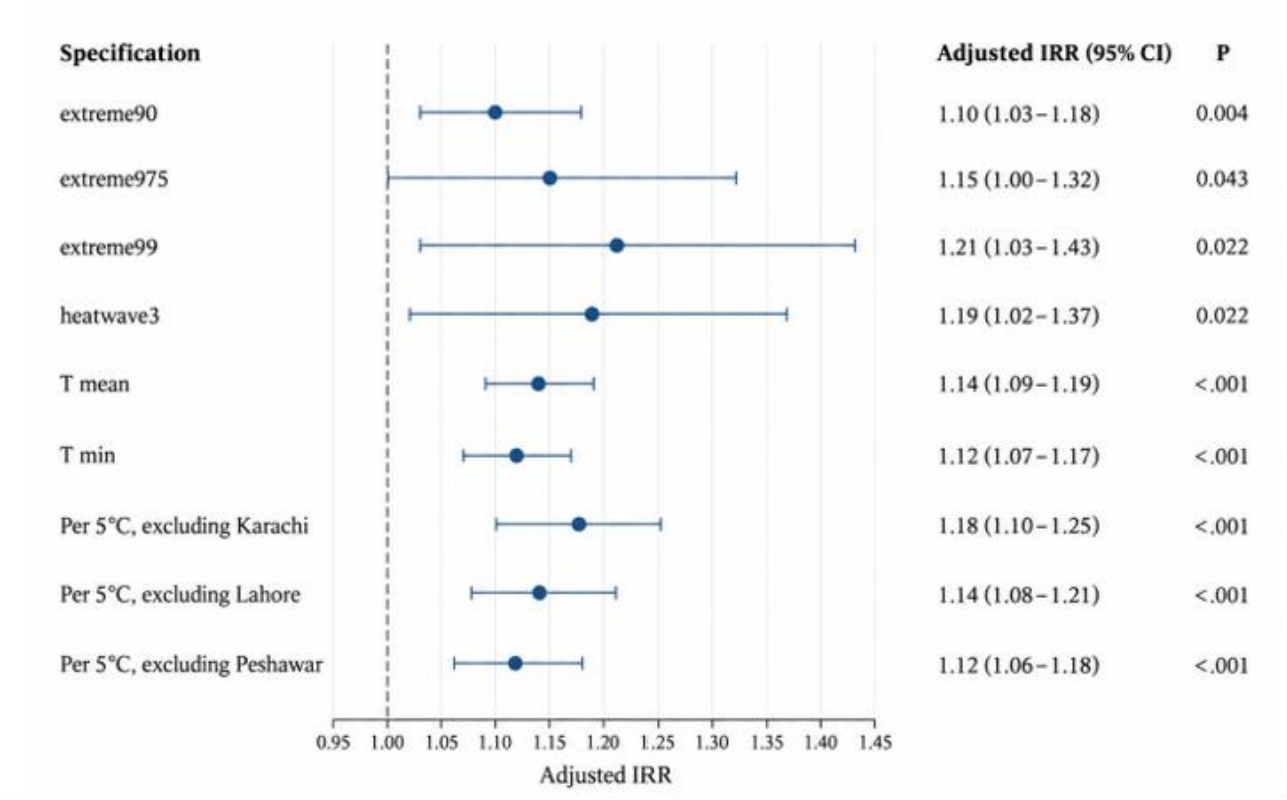

Figure 6 Alternative exposures and center exclusions.

DISCUSSION

This study evaluated three interconnected aspects of heat-associated cardiovascular burden: daily cardiovascular presentations, clinical severity among patients, and hospital operational performance. Analysis of 13,392 presentations over 552 hospital-days demonstrated that each 5°C increase in same-day maximum temperature corresponded to a 14% higher adjusted daily presentation count. Elevated continuous temperature was also associated with acute kidney injury, multiorgan dysfunction, critical-care admission, invasive mechanical ventilation, and in-hospital mortality. In contrast, categorical extreme-heat estimates were less precise for several outcomes, and the median length of stay did not change. [21]

The daily-count analysis focused on service burden rather than population-level cardiovascular incidence. The observed positive association with temperature aligns with previous research on high temperatures and cardiovascular hospital admissions in New York and temporal changes in cardiovascular hospitalization in Queensland.[22,23] However, differences in climate, exposure metrics, diagnostic coverage, referral pathways, and access to care limit direct comparison of effect sizes. The present composite encompassed multiple cardiovascular emergencies, and individual diagnostic categories were not analyzed separately. Therefore, the overall incidence rate ratio (IRR) cannot be specifically attributed to myocardial infarction, heart failure, or arrhythmia.

Additionally, without a defined catchment population denominator, the analysis cannot estimate the probability that a community resident develops cardiovascular disease.

The clinical plausibility of heat-associated cardiovascular stress is grounded in the circulatory demands of thermoregulation. Increased skin blood flow and sweating impose competing demands on cardiovascular function and fluid balance, especially when physiological reserve is limited. Cramer and colleagues have demonstrated that age, disease, and individual characteristics influence these responses.[24] While these mechanisms support the biological plausibility of the observed associations, the underlying physiological pathways were not directly measured in this study. Furthermore, the inclusion of hypertension, diabetes, chronic kidney disease, and pre-existing cardiovascular disease as covariates does not demonstrate that these conditions modified temperature associations. Such conclusions would require prespecified interaction analyses, which were not conducted.

The largest continuous-temperature point estimate was observed at lag 0 (IRR 1.14, 95% CI 1.09–1.20), compared with 1.06 (1.01–1.11) at lag 1. The mean-temperature estimates for lag 0–1 and lag 0–3 were 1.13 and 1.08, respectively. However, these models utilized correlated exposures and had overlapping confidence intervals, which precludes establishing a statistically significant difference between lag periods. Additionally, moving-average exposure coefficients do not represent cumulative effects as in distributed-lag models. Distributed-lag nonlinear models, which explicitly characterize exposure–response and lag–response relationships, would be more appropriate in a sufficiently long and stable observational series.[25] Therefore, the current short-lag findings should not be interpreted as excluding delayed effects or as evidence of a linear biological response.

The distinction between continuous and categorical exposure models is central to interpretation. Continuous temperature was associated with mortality (AOR 1.27, 95% CI 1.07–1.51), while the extreme-heat comparison was inconclusive (AOR 1.14, 95% CI 0.83–1.55). Similar uncertainty was observed for categorical estimates of critical-care admission and ventilation. Although dichotomization can result in information loss, these model specifications address different exposure questions, and their significance levels do not formally test disagreement.[26] Only 38 hospital-days and 1,018 presentations were classified as extreme heat. Therefore, the categorical estimates do not establish the absence of adverse associations, nor do they justify asserting that extreme heat increased every outcome. Odds ratios should be interpreted as changes in odds, rather than as equivalent percentage changes in risk.

Renal complications represented a significant component of the clinical burden. Acute kidney injury (AKI) occurred in 17.2% of presentations during extreme heat and 13.5% during other conditions, with positive associations observed in both adjusted exposure models. This finding aligns with Hansen and colleagues' report of increased renal disease and acute renal failure admissions during heatwaves in South Australia.[27] Similarly, Bobb and colleagues identified increased admissions for renal failure and fluid-and-electrolyte disorders among older US adults during extreme heat, while observing lower heart-failure admission rates.[28] Such heterogeneity underscores the need to avoid assuming uniform responses across diseases. In this study, AKI was identified based on the documented clinical diagnosis during the index hospital encounter and was not independently re-adjudicated using complete serial serum creatinine measurements or urine-output data. Therefore, interpret the AKI findings as associations with clinically documented AKI, rather than a retrospectively reconstructed laboratory-based KDIGO endpoint.

Distinguishing between early and subsequent complications provided clinically relevant temporal detail. Early AKI was more common than later AKI in both exposure groups, while the multiorgan dysfunction threshold was more frequently reached after 24 hours. This classification included patients with an early affected system whose second organ-system complication developed later; it did not require all organ dysfunction to begin after 24 hours. Severe heatstroke can involve systemic inflammation and multiorgan injury, offering a related mechanistic context.[29] However, existing literature does not establish the same mechanism in cardiovascular patients without documented heatstroke. Additionally, admission-day ambient temperature does not capture subsequent ward exposure, and timing alone cannot differentiate the effects of prehospital heat, the cardiovascular illness, treatment, or other hospital complications.

Operational comparisons indicated increased service demand and potential performance pressure. Mean occupancy increased from 75.9% to 80.6% in Karachi, 77.2% to 81.7% in Lahore, and 76.6% to 83.3% in Peshawar. Median door-to-balloon intervals lengthened by approximately 9 to 12 minutes. These changes should be considered collectively, as increased volume alone does not necessarily indicate reduced resilience. Research on emergency-department crowding has documented associations with delayed assessment and treatment, although the measures and study quality vary.[30] Evidence linking treatment delay to mortality after primary angioplasty further supports the importance of monitoring reperfusion performance.[31] However, the current

operational results were unadjusted, and door-to-balloon time was available only for primary PCI recipients. These findings do not establish that heat caused service deterioration or that treatment delay mediated mortality.

Hospitalization duration did not indicate a parallel descriptive deterioration: both exposure groups had a median stay of 4 days and an interquartile range of 3 to 5 days. Identical summaries do not demonstrate equivalence, but they also do not support a claim of prolonged admission. To draw such a conclusion, an adjusted length-of-stay analysis that accounts for death and discharge would be necessary. Similarly, higher critical-care admission rates may reflect clinical need, triage decisions, or available capacity, and are not, in isolation, a direct measure of hospital resilience.

A key practical implication is the need to evaluate heat preparedness using both demand and care-performance indicators. An observational assessment of Ahmedabad's Heat Action Plan reported reduced heat-associated mortality following implementation, supporting further evaluation of coordinated warning and response programs in South Asian contexts.[32] Broader prevention research highlights the importance of combining effective cooling strategies with communication, surveillance, and monitoring.[33] Future studies should investigate whether integrating heat-warning information with staffing and bed-capacity planning can alleviate operational pressure, while also incorporating standardized complication surveillance and prospective monitoring of reperfusion delays. These recommendations are informed by external evidence; the thresholds referenced are not validated local warning cut-offs, and this analysis did not evaluate an intervention.

Sensitivity analyses demonstrated that the positive daily-count association persisted across alternative temperature metrics, percentile thresholds, and sequential center exclusions. Leave-one-center-out IRRs ranged from 1.12 to 1.18 per 5°C, indicating internal consistency within the dataset, but not external validation or protection against unmeasured confounding. With only 184 observation days per center, the analysis could not evaluate interannual variability, long-term adaptation, or complete annual seasonality. The large number of patient records does not equate to an equally large number of independent weather exposures. Environmental time-series guidance emphasizes temporal adjustment, exposure specification, and autocorrelation assessment.[34] Hospital fixed effects and dependence-aware standard errors were incorporated; however, residual autocorrelation and potential nonlinearity in the temperature–response relationship cannot be excluded.

Interpret the observed associations with caution, as residual confounding, measurement error, and unmeasured factors may have influenced the estimated effects. Statistical significance alone does not establish a causal clinical relationship. The diagnostic flags and covariates used do not account for measurement error or missing data likely present in retrospective records. Variables such as PM2.5, medication use, individual cooling access, occupational exposure, and residential meteorology were not analyzed. Restricting the patient-level analysis to individuals presenting with cardiovascular illness could introduce selection bias if presentation was influenced by both heat exposure and other determinants of clinical severity. This reflects the general issue of conditioning on a common effect, as described by Cole and colleagues.[35] A longer, preferably multi-year study with broader geographic coverage, more detailed individual-level exposure assessment, and prespecified subgroup analyses would enhance the evaluation of cardiovascular risk and hospital resilience during extreme heat in Pakistan.

CONCLUSION

This multicenter retrospective hospital-based study demonstrates that higher ambient temperatures are associated with an increased burden of cardiovascular presentations, greater clinical severity, and elevated hospital service demand, as well as less favorable operational indicators across three tertiary cardiovascular centers in Pakistan. Among 13,392 cardiovascular presentations recorded over 552 hospital-days, each 5°C increase in same-day maximum temperature corresponded to a 14% higher adjusted rate of daily cardiovascular presentations. The strongest association was observed for same-day exposure, with positive associations also identified across the evaluated short-lag periods.

At the patient level, higher continuous temperature was associated with increased odds of clinically documented acute kidney injury, multiorgan dysfunction, CCU/ICU admission, invasive mechanical ventilation, and in-hospital mortality after adjustment for demographic, clinical, hospital, humidity, and temporal factors. In contrast, estimates based on the categorical extreme-heat definition were less precise for several outcomes, indicating that continuous and threshold-based temperature measures should not be interpreted interchangeably. Temporal analysis of complications suggested that both early and subsequent organ dysfunction contributed to the clinical burden observed during periods of elevated temperature.

Hospital operational findings supported the clinical results. Periods of extreme heat were marked by higher daily cardiovascular presentation volumes, increased critical-care occupancy, and prolonged door-to-balloon times across the participating centers.

However, these comparisons are descriptive and do not establish that heat independently caused deterioration in hospital performance. The median length of stay did not differ between extreme-heat and non-extreme-heat conditions.

These findings should be interpreted in light of several limitations, including the six-month observational period, restriction to three tertiary centers, hospital-based rather than population-based ascertainment, potential residual confounding, and reliance on clinically documented acute kidney injury rather than independently reconstructed laboratory-based criteria. Nevertheless, this study highlights the importance of integrating environmental exposure, clinical outcomes, and operational indicators when assessing heat-related cardiovascular burden. Longer multi-year studies with broader geographic coverage, more detailed exposure assessment, and prespecified subgroup analyses are needed to strengthen the evidence base for heat-adaptive cardiovascular care and hospital preparedness in Pakistan.

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