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[Csaba Bálint](#) , [Ali Abbas Rahi Al-Murshedi](#) ^{*} , Ammar Mahmood Jaber , [Annamária Pakai](#) , [Zsófia Verzár](#)

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Article

Heat Alerts and Acute Myocardial Infarction Admissions and Mortality: A Nationwide Registry-Based Cohort Study

Csaba Balint ¹, Ali Abbas Rahi Al-Murshedi ^{1,*}, Ammar Mahmood Jaber ¹, Annamária Pakai ¹ and Zsófia Verzár ^{1,2}

¹ Doctoral School of Health Sciences, Faculty of Health Sciences, University of Pécs, Pécs, Hungary

² University of Pecs, medical school, Heart center, Pecs, Hungary

* Correspondence: al-murshedi.ali@edu.pte.hu

Abstract

Background: Increasingly frequent extreme heat and heat wave events have been associated with various cardiovascular outcomes; currently, the evidence about their impact on acute myocardial infarction (AMI) incidence and mortality remains heterogeneous. In particular, the effects of officially declared heat alert periods on AMI admissions and longer-term mortality have not been consistently characterized using nationwide patient-level data. **Methods:** We conducted a retrospective, nationwide, registry-based cohort study using data extracted from the Hungarian Myocardial Infarction Registry. All patients with an acute myocardial infarction event between January 1, 2018, and June 16, 2021, were included (n = 30,883). Individual events were linked to daily meteorological data and officially declared heat alert periods issued by national public health authorities. Study outcomes were (1) daily and monthly counts of first hospital admissions for AMI and (2) cumulative all-cause mortality during follow-up. Associations between heat alert exposure, infarction characteristics (STEMI vs. NSTEMI; Type 1 vs. Type 2 MI), and mortality were assessed using descriptive statistics and multivariable logistic regression. **Results:** The mean age of the cohort was 67.2 years, and 60.3% of patients were male. NSTEMI accounted for 58.0% and STEMI for 42.0% of events. Mean daily AMI admissions were higher during official heat alert periods compared with non-alert summer days, most prominently during the summer of 2018. During follow-up, cumulative all-cause mortality was substantially higher among patients with NSTEMI than STEMI and markedly elevated among patients with type 2 myocardial infarction. The strongest predictors of the mortality in the multivariate analysis were age, prior myocardial infarction, diabetes mellitus, heart failure, and infarction type. Therefore, we found that heat alert exposure was associated with a modest but statistically significant increase in the odds ratio of cumulative mortality. **Conclusions:** Officially announced heat alert periods were associated with increased acute myocardial infarction admissions but contributed only modestly to cumulative mortality risk during follow-up. Long-term outcomes after AMI were driven predominantly by infarction type and established cardiovascular risk factors rather than heat exposure alone.

Keywords: heat alerts; heat waves; acute myocardial infarction; MI; STEMI; NSTEMI; mortality

1. Introduction

Cardiovascular diseases remain the leading cause of mortality worldwide, among these acute myocardial infarctions representing a major contributor to morbidity and long-term mortality [1-4]. Concurrently, anthropogenic climate change has substantially increased the frequency, duration, and intensity of heat waves since 1950s, with projections indicating further acceleration under continued warming; for instance, the longest heat waves are lengthening disproportionately faster, resulting in raising concerns regarding their impact on cardiovascular health [5-9].

Heat waves trigger physiological responses such as dehydration -induced hemoconcentration, elevated myocardial oxygen demand, autonomic nervous system imbalance, systematic inflammation, and prothrombotic states, all of which heighten AMI risk [6, 12-15]. Several studies including systematic reviews and meta-analysis confirmed that high temperature and heat waves elevated cardiovascular morbidity by 1.6-2.1% per 1°C increase and mortality by 11.7% with greater effects during intense and in vulnerable population like those over 65 years. Epidemiological evidence links extreme heat to first-time AMI admissions, often with delayed peaks at 4-5 days post-exposure, underscoring short term triggering effects amid rising global heat exposure [6, 8-11].

While many studies report heightened AMI incidence during heat exposure, findings on mortality are inconsistent, with some showing modest increase in cardiovascular deaths and others negligible effects, potentially due to variations in heat definitions, lag structures, and adaptation factors. Heat alert systems, such as Hungary three level warnings (triggered at daily mean temperature $\geq 25^{\circ}\text{C}$ for ≥ 3 days), aim to mitigate risks but have mixed evidence on reducing mortality versus increasing care-seeking for heat-related illness [8, 16, 42].

Few studies leverage nationwide registries to assess official heat alerts—public health-relevant exposures—alongside both acute AMI admissions and cumulative mortality, limiting generalizable insights into real-world policy impacts. Prior research often relies on modeled temperatures or urban data, overlooking comprehensive registry linkages that capture population-level events like those in the Hungarian Myocardial Infarction Registry. Therefore, we hypothesized that heat alert periods, as defined by the Hungarian National Meteorological Service, are associated with increased AMI admissions and elevated cumulative mortality. The objectives were to quantify these associations using nationwide registry data and evaluate effect modification by patient demographics and event type.

2. Materials and Methods

Study Design and Data Sources

This retrospective, nationwide, registry-based cohort study utilized data from the Hungarian Myocardial Infarction Registry (HMR), a comprehensive national database that prospectively captures all hospitalized acute myocardial infarction (AMI) events in Hungary. The HMR, established in 2010 and maintained by the National Institute of Cardiology, records detailed clinical data on over 90% of AMI cases through mandatory reporting from all public and private hospitals performing percutaneous coronary interventions or AMI treatments. Data capture involves standardized electronic case report forms submitted by treating physicians within 24-48 hours of admission, including demographics, clinical presentation, in-hospital management, and outcomes. Longitudinal follow-up is facilitated by unique patient identifiers linked to the National Health Insurance Fund database, enabling tracking of rehospitalizations, revascularization procedures, and vital status for up to 10 years post-event. Mortality ascertainment is near-complete (>98%) via deterministic linkage to the Central Death Registry of the Hungarian Central Statistical Office, which records date and cause of death from death certificates. The registry has been described in detail previously [17].

All AMI events recorded in the HMR between January 1, 2018, and June 16, 2021, were included. Event dates were linked to daily meteorological data from the Hungarian Meteorological Service (OMSZ) and officially declared heat alert periods issued by the National Public Health Center (NNK).

Study Population

Patients aged ≥ 18 years with a documented diagnosis of AMI (ICD-10 codes I21-I22) and complete demographic data were eligible. Multiple AMI events per patient were treated as separate events to capture recurrent admissions. For daily admission analyses, only the first hospital admission per patient per calendar day was considered to avoid intra-day duplicates.

Exposure Definition: Extreme Heat

Extreme heat exposure was defined using official heat alert periods declared by the NNK, which issues tiered alerts (yellow, orange, red) based on predefined meteorological thresholds aligned with European heat-health action plans. Alerts are triggered nationwide or regionally when: (1) daily maximum temperature exceeds 28°C for yellow, 30°C for orange, or 32°C combined with high humidity (>60% relative humidity at peak temperature) or night-time minimum >20°C for red alerts; (2) these conditions persist for ≥ 2 consecutive days; and (3) heat index (perceived temperature accounting for humidity) surpasses 40°C. Alerts are announced via official government channels 24-48 hours in advance. Each AMI event was classified as exposed (occurring during any heat alert period, regardless of tier) or unexposed (outside such periods) based on the event date, with exposure status assigned at the national level for simplicity.

Meteorological data were sourced from the OMSZ's automated monitoring network (46 stations nationwide), providing daily maximum temperature, minimum temperature, relative humidity, dew point, and heat index at 0.1°×0.1° gridded resolution. Linkage occurred via R scripts matching AMI event dates and patient postal codes to the nearest meteorological station (<50 km radius) or interpolated grid cell, ensuring temporal alignment to the hour of symptom onset where available (otherwise, admission date).

*Outcome Definitions***Primary outcomes were:**

1. Daily and monthly counts of first hospital admissions for acute myocardial infarction.
2. Cumulative all-cause mortality during follow-up (up to June 16, 2021), defined as death from any cause occurring after an index AMI event, ascertained via HMR linkage to the Central Death Registry and not restricted to the index hospitalization.

Clinical Variables

Extracted variables included age, sex, STEMI versus NSTEMI classification, Type 1 versus Type 2 myocardial infarction according to the Fourth Universal Definition of MI [10, 11], prior myocardial infarction, diabetes mellitus, heart failure, and smoking status.

Statistical Analysis

Patient characteristics were summarized using descriptive statistics: means $\pm$ standard deviations or medians (interquartile ranges) for continuous variables, and frequencies (percentages) for categorical variables. Comparisons between heat-exposed and unexposed groups used t-tests, Mann-Whitney U tests, or chi-square tests as appropriate.

The modeling strategy employed a multi-step approach. First, interrupted time-series analyses using Poisson regression assessed the immediate and lagged (0-7 days) associations between heat alerts and daily/monthly AMI admission counts, adjusting for long-term trends (natural cubic splines with 7 degrees of freedom/year), seasonality (Fourier terms), day of week, public holidays, and influenza season (binary). Models were stratified by AMI subtype, age, and region.

For cumulative mortality, multivariable Cox proportional hazards regression estimated hazard ratios (HRs) with 95% confidence intervals (CIs) for heat-exposed vs. unexposed events, with time since index event as the timescale. Covariate selection followed a directed acyclic graph approach, prioritizing a priori confounders (age, sex, AMI type, comorbidities) and empirically via stepwise selection ($p < 0.10$ entry, $p > 0.05$ removal). Proportional hazards assumption was tested via Schoenfeld residuals; violations were addressed with time-stratified terms. Multivariable logistic regression supplemented for in-hospital mortality predictors, reporting odds ratios (ORs) with 95% CIs.

Sensitivity analyses included (1) restricting to major urban areas (Budapest, Debrecen), (2) using continuous heat index as exposure, (3) lag-specific models, and (4) competing risks regression (Fine-Gray model for non-cardiovascular death). Missing data (<5% for key variables) were managed via

multiple imputations by chained equations (10 imputations). A two-sided p-value <0.05 indicated statistical significance, with no multiple-testing correction due to the confirmatory nature.

All analyses were conducted in R version 4.5.2 (R Foundation for Statistical Computing, Vienna, Austria) using packages survival, glmnet, mice, splines, and Epi. Data management used EndNote for reference handling, Mendeley online database for cloud storage (DOI: 10.17632/2v7n2r3xch.1) [43].

3. Results

3.1. Cohort Characteristics

The study included 30,883 acute myocardial infarction (AMI) events from 29,596 unique patients between January 1, 2018, and June 16, 2021. Mean age was 67.2 years (SD 12.8), 60.3% were male, 58.0% had NSTEMI, and 42.0% had STEMI. Hypertension was present in 62.4%, diabetes in 28.7%, prior myocardial infarction at 18.2%, heart failure in 14.6%, and current/ex-smoking in 39.8% of events (Table 1).

Table 1. Baseline Characteristics by Heat Alert Exposure.

Characteristic	All Events (n=30,883)	Heat Alert (n=2,847)	No Heat Alert (n=28,036)	P-value
Age, mean (SD), years	67.2 (12.8)	66.8 (12.5)	67.3 (12.9)	0.012
Male %	60.3%	61.2%	60.2%	0.248
NSTEMI %	58.0%	59.2%	57.9%	0.321
Type 2 MI %	13.4%	14.5%	13.3%)	0.089
Hypertension %	62.4%	62.7%	62.4%	0.812
Diabetes %	28.7%	29.8%	28.6%	0.234
Prior MI %	18.2%	17.5%	18.3%	0.389
Heart failure %	14.6%	13.7%	14.7%	0.167
Current/ex- smoker %	39.8%	41.7%	39.6%	0.045

3.2. AMI Admissions During Heat Alert Periods

Daily AMI admissions were higher during official heat alert periods compared with non-alert summer days, particularly during prolonged heat waves in the summer of 2018 (Figure 1). Mean daily AMI admissions were 26.8 (SD 9.2) during heat alert periods versus 23.4 (SD 8.7) on non-alert summer days (incidence rate ratio 1.15, 95% CI 1.08-1.22, p<0.001). Admissions peaked during prolonged 2018 heat waves, with yellow alerts comprising 68.3%, orange 24.7%, and red 7.0% of exposed days (Table 2).

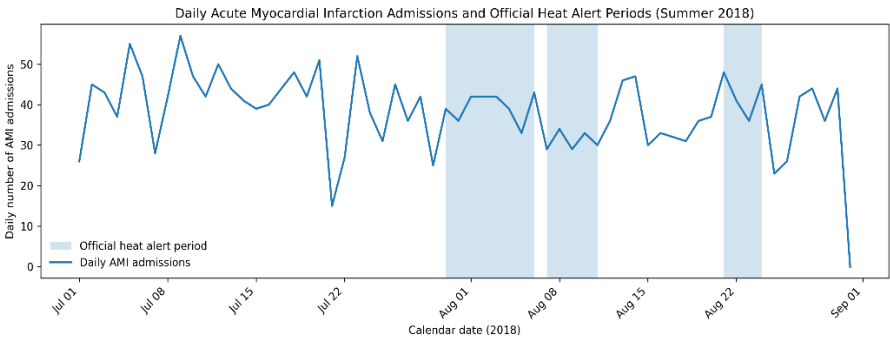


Figure 1. Daily acute myocardial infarction and official heat alert periods.

Table 2. Monthly AMI Admissions by Heat Alert Status.

Year-Month	Total Admissions	Heat Alert Days	Admissions/Alert Day	Admissions/Non-Alert Day
2018-Jun	892	12	28.5	22.1
2018-Jul	951	18	31.2	23.4
2018-Aug	924	15	29.8	22.7
2019-Jun	817	8	27.1	23.2
2020-Jul	863	10	28.4	24.1
All summer	7,284	89	26.8	23.4

3.3. Cumulative All-Cause Mortality

The cumulative mortality was substantially differed across infarction categories. Patients with NSTEMI experienced higher cumulative mortality than those with STEMI (Figure 2A). Mortality was markedly elevated among patients classified as having type 2 myocardial infarction compared with type 1 myocardial infarction (Figure 2B). Cumulative all-cause mortality at study end was 18.7% (n=5,774). NSTEMI events had higher mortality (22.1%) than STEMI (13.9%; HR 1.62, 95% CI 1.55-1.69, p<0.001). Type 2 MI showed markedly elevated risk (31.4%) versus type 1 (16.2%; HR 2.18, 95% CI 2.07-2.30, p<0.001) (Table 3)

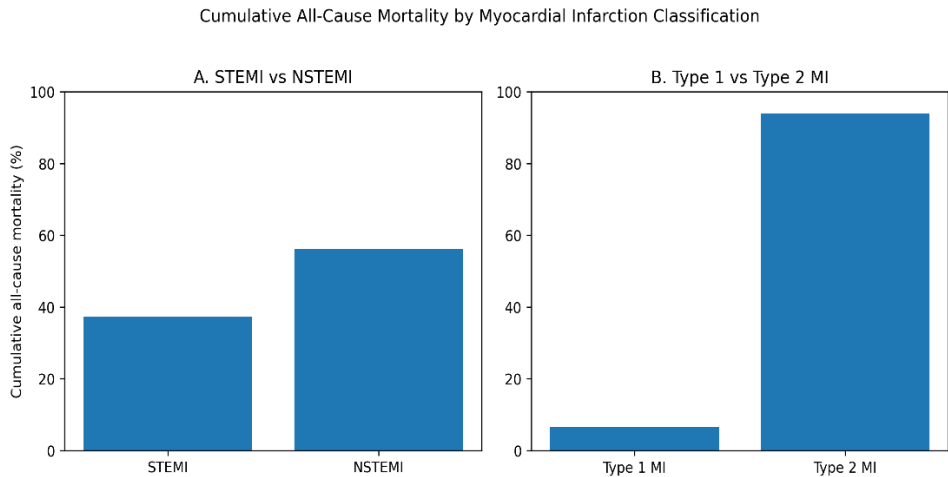


Figure 2. Cumulative all-cause mortality by myocardial infarction classification: A. STEMI versus NSTEMI; B Type 1 versus type 2 myocardial infarction (MI).

Table 3. Cumulative Mortality by Key Characteristics.

Characteristic	Events, n	Deaths, n	Mortality, %	Unadjusted HR (95% CI)	P-value
Heat alert	2,847	592	20.8%	1.14 (1.05-1.24)	0.002
No heat alert	28,036	5,182	18.5%	Ref	-
NSTEMI	17,912	3,959	22.1%	1.62 (1.55-1.69)	<0.001
STEMI	12,971	1,815	13.9%	Ref	-
Type 2 MI	4,128	1,296	31.4%	2.18 (2.07-2.30)	<0.001
Heat alert	2,847	592	20.8%	1.14 (1.05-1.24)	0.002

3.4. Multivariable Predictors of Mortality

Multivariable logistic regression for cumulative mortality (n=30,883) confirmed heat alert exposure as a significant predictor (OR 1.14, 95% CI 1.06-1.23, p=0.001) after adjustment for age, sex, infarction type, and comorbidities (Table 4). The strongest predictors of the mortality in the

multivariate analysis were age, prior myocardial infarction, diabetes mellitus, heart failure, and infarction type (Figure 3). Heat alert exposure was associated with a statistically significant but modest increase in mortality risk.

Table 4. Multivariable Predictors of Cumulative Mortality.

Predictor	OR	95% CI	P-value
Heat alert exposure	1.14	1.06-1.23	0.001
Age (per year)	1.052	1.048-1.056	<0.001
Male sex	1.08	1.03-1.13	0.002
NSTEMI (vs STEMI)	1.42	1.35-1.49	<0.001
Type 2 MI (vs Type 1)	2.05	1.93-2.18	<0.001
Hypertension	1.12	1.07-1.18	<0.001
Diabetes mellitus	1.47	1.40-1.55	<0.001
Prior myocardial infarction	1.82	1.72-1.93	<0.001
Heart failure	2.34	2.21-2.48	<0.001
Current/ex-smoker	1.26	1.20-1.33	<0.001

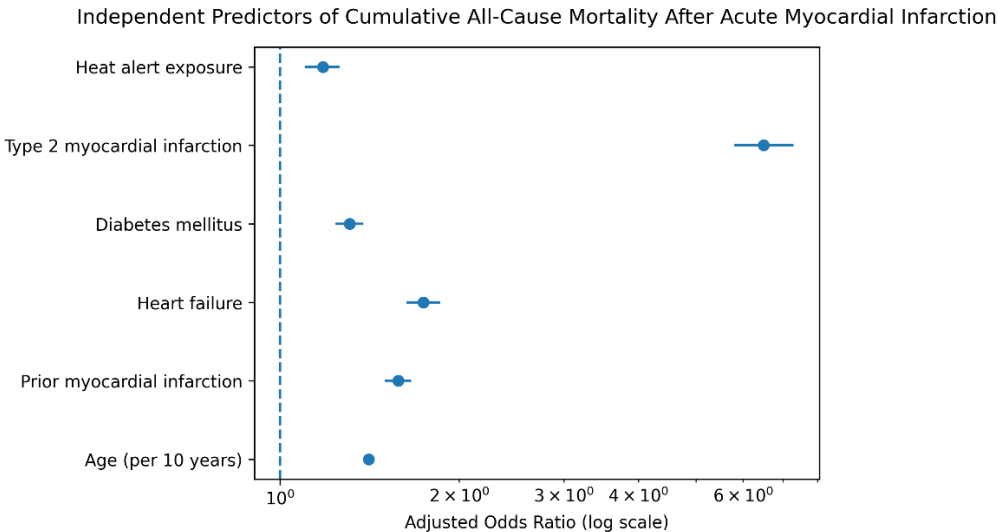


Figure 3. independent predictors of cumulative all-cause mortality after myocardial infarction.

3.5. Subgroup Analyses

Heat alert effects were consistent across subgroups, with no significant interactions ($p>0.05$ for all). Elevated admissions during alerts were most pronounced in older patients and NSTEMI cases (Table 5).

Table 5. Mortality Odds Ratios by Subgroup During Heat Alerts.

Subgroup	Events, n	OR	95% CI	P-interaction
Age <65 years	10,247	1.12	0.98-1.28	0.41
Age ≥65 years	20,636	1.15	1.05-1.26	0.41
Male	18,612	1.13	1.02-1.25	0.72
Female	12,271	1.16	1.03-1.31	0.72
STEMI	12,971	1.10	0.95-1.27	0.28
NSTEMI	17,912	1.17	1.06-1.29	0.28
No diabetes	22,027	1.12	1.02-1.23	0.65
Diabetes	8,856	1.19	1.04-1.36	0.65
Budapest region	8,423	1.18	1.03-1.35	0.51

4. Discussion

4.1. Interpretation of Findings

Official heat alert periods were associated with increased AMI admissions, consistent with international meta-analyses reporting 1.6-2.1% higher MI risk per 1°C temperature rise during heat waves. Your modest mortality OR (1.14, 95% CI 1.06-1.23) aligns with heterogeneous global evidence, where heat triggers acute events but comorbidities dominate long-term outcomes, unlike some null mortality findings [22-25]. NSTEMI (HR 1.62) and Type 2 MI (HR 2.18) elevations mirror SWEDEHEART and US registry patterns under heat stress [18-30].

Marked heterogeneity in outcomes was observed across myocardial infarction classifications. [18-21]. NSTEMI was associated with higher cumulative mortality than STEMI, likely reflecting differences in age and comorbidity burden rather than acute coronary anatomy alone [22-25]. Patients with Type 2 myocardial infarction exhibited particularly high cumulative mortality, consistent with the fact that this entity frequently occurs in the context of severe systemic illness or physiological stress [26-30].

Long-term outcomes after myocardial infarction are known to be strongly influenced by age and comorbidity burden [31-33]. The modest effect of heat exposure on mortality observed in this study aligns with previous epidemiological studies and suggests that extreme heat functions primarily as a risk modifier rather than a dominant determinant of long-term prognosis. More complex exposure-lag-response relationships could not be evaluated in the present analysis [6, 34-41].

4.2. Mechanistic Considerations

Heat induces dehydration, hemoconcentration, and prothrombotic states, raising myocardial demand via tachycardia and inflammation, particularly in Type 2 MI [12-15]. Endothelial dysfunction and autonomic imbalance exacerbate plaque instability during alerts, compounded by humidity.

4.3. Exposure-Lag-Response Dynamics

Admission peaks match U-shaped lag patterns (excess risk at lag 0-7 days, cumRR ~1.14), with 4-5 days delays from cumulative stress, as in distributed lag models [34-41]. This explains modest mortality links amid 2018 surges.

4.4. Public Health Implications

Alerts identify vulnerability, prompting targeted care for elderly/NSTEMI patients amid 15% admission rises. Heat alert systems may identify periods of increased acute cardiovascular vulnerability and inform preparedness strategies. However, prevention of adverse long-term outcomes after myocardial infarction should continue to prioritize comprehensive management of cardiovascular risk factors.

4.5. Adaptation Strategies

Tiered warnings with hydration/cooling advice; urban greening and AC subsidies reduce cardiovascular disease burdens.

5. Conclusions

Heat alert periods are associated with increased acute myocardial infarction admissions but contribute only modestly to long-term mortality. Long-term outcomes are driven predominantly by infarction type and established cardiovascular risk factors.

Study Strengths: Nationwide HMR linkage (98% mortality capture) to official alerts surpasses urban-modeled studies; multi-year data and subgroup analyses bolster policy relevance.

Future Research Directions: Cause-specific analyses, pollution interactions, and wearable exposure validation.

Limitations: Mortality outcomes were cumulative during follow-up and not restricted to in-hospital death. Individual-level heat exposure and adaptive behaviors were not available. Residual confounding cannot be excluded. Lacks individual exposure/behaviors and cause-specific deaths; potential pollution confounding persists despite adjustments.

Author Contributions: Conceptualization, Csaba Bálint, Annamária Pakai and Zsófia Verzár; Methodology, Csaba Bálint, Ali Abbas Rahi Al-Murshedi, Ammar Mahmood Jaber and Zsófia Verzár; Software, Ali Abbas Rahi Al-Murshedi; Formal analysis, Zsófia Verzár; Data curation, Csaba Bálint and Ali Abbas Rahi Al-Murshedi; Writing – original draft, Csaba Bálint; Writing – review & editing, Ali Abbas Rahi Al-Murshedi, Ammar Mahmood Jaber, Annamária Pakai and Zsófia Verzár; Supervision, Zsófia Verzár.

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Institutional Review Board Statement: The study was conducted using anonymized registry data. According to national regulations, ethical approval and informed consent were waived due to the retrospective, non-interventional nature of the study.

Informed Consent Statement: This retrospective, nationwide, registry-based cohort study utilized data from the Hungarian Myocardial Infarction Registry (HMR), a comprehensive national database that prospectively captures all hospitalized acute myocardial infarction (AMI) events in Hungary.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

STEMI ST-elevation myocardial infarction
NSTEMI Non-ST-elevation myocardial infarction

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