

**Key Points:**

- Although heat is closely linked to death, disease, or injury, only few studies have analyzed the effect of heat on the working population
- Heat exposure is closely linked to death, infectious, cardiocerebrovascular diseases, and injuries or accidents among workers
- The maximum temperature was more significantly related to workers' health outcomes than did the average temperature or heat index

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## Risk of Heat-Related Mortality, Disease, Accident, and Injury Among Korean Workers: A National Representative Study From 2002 to 2015

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**Abstract** Many studies have shown that heat waves can cause both death and disease. Considering the adverse health effects of heat waves on vulnerable groups, this study highlights their impact on workers. The present study thus investigated the association between heat exposure and the likelihood of hospitalization and death, and further identified the risk of heat-related diseases or death according to types of heat and dose-response modeling with heat threshold. Workers were selected from the Korean National Health Insurance Service-National Sample Cohort 2002–2015, and regional data measured by the Korea Meteorological Administration were used for weather information. The relationship between hospitalization attributable to disease and weather variables was analyzed by applying a generalized additional model. Using the Akaike information criterion, we selected a model that presented the optimal threshold. Maximum daily temperature (MaxT) was associated with an increased risk of death and outdoor mortality. The association between death outdoors and MaxT had a threshold of 31.2°C with a day zero lag effect. History of medical facility visits due to the health effects of heat waves was evident in certain infectious and parasitic diseases (A and B), cardio and cerebrovascular diseases (I20–25 and I60–69), injury, poisoning, and other consequences of external causes (S, T). The study demonstrated that heat exposure is a risk factor for death and infectious, cardio-cerebrovascular, and genitourinary diseases, as well as injuries or accidents among workers. The finding that heat exposure affects workers' health has future implications for decision makers and researchers.

**Plain Language Summary** Exposure to heat can cause diseases and even death. Avoiding heat is one of the best ways to prevent the adverse health effects of heat. Some groups have difficulty avoiding heat. That is the worker. They find it difficult to choose a place and time to work in their duties. In this study, the health effects of heat exposure were investigated among workers. The medical facility visit history, death status, and risk were estimated according to the ambient temperature characteristics. The analysis showed that the daily maximum temperature was strongly associated with the death of workers. This association was statistically significant from the highest temperature of 31.2°C. Additionally, outdoor deaths among workers were also closely related to the daily maximum temperature. It was reported that exposure to heat was closely linked to the status of visits to hospitals among workers. There was a significantly increased risk of medical facility visits due to infectious diseases, cardiac and cerebrovascular diseases, injuries and accidents related heat exposure among workers. In this study, we found that heat exposure is closely related to various diseases and death in workers. We hope that the findings of the study can be applied to protect workers' health and safety.

### 1. Introduction

During the past 130 years, the average temperature has increased by approximately 0.85°C worldwide due to climate changes (J. Lee et al., 2021). Global warming is an aggregative heat exposure status that affects life through desertification, loss of biodiversity, degradation of ecosystems, acidification of the oceans, and the disruption and depletion of stratospheric ozone (Rossati, 2017). Increased heat exposure can also cause severe health problems in humans. Exposure to heat might increase the burden of homeostasis, both physiologically and emotionally; moreover, it could induce oxidative stress, fluid imbalance, respiratory or circulatory burden, and loss of

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concentration (J. Lee et al., 2021). Previous studies have reported that heat exposure could increase the risk of disease or death in vulnerable populations (Johnson & Wilson, 2009; White-Newsome et al., 2012). In addition, exposure to heat is closely related to increased mortality, incidence of accidents or injuries, and various diseases in the general population (Fuhrmann et al., 2016; Lin et al., 2009).

In epidemiological studies, workers were not considered a vulnerable population in most cases of diseases and death due to the healthy worker effect, which could increase the error (commonly decreasing) of hazard estimation because only healthy workers could survive as working population (Yasmeen et al., 2020). In the case of heat exposure, workers could be considered a vulnerable population for heat-related diseases and injuries, since they do not have the power to choose working time or place, which is a basic response to protect human health from heat exposure, even under extreme heat conditions in most industries under labor contracts (Phanprasit et al., 2021). There has been limited quantitative analysis of heat exposure and worker health. Some studies have highlighted the vulnerability of heat-related diseases among workers, including deaths, accidents or injuries, diseases of the urinary and reproductive systems, and psychological effects (Hamerezaee et al., 2018; J. Lee et al., 2021; Schulte et al., 2016; Spector et al., 2016; Xiang et al., 2014). Although some studies have reported the risk of heat-related diseases among workers, they have focused only on specific occupations or diseases, such as literature review design, or a small part of heat characteristics. There are limited studies that have attempted to investigate the effect of heat exposure on workers' health with the whole working population and various definitions of heat exposure.

This study characterized the association between heat (as an ambient condition) exposure and the risk of hospitalization and death in the Korean working population using a nationally representative data set spanning from 2002 to 2015. Furthermore, the risk of heat-related diseases or death according to the types of heat and dose-response modeling with the heat threshold was explored.

## 2. Materials and Methods

### 2.1. Study Population

The health data used in this study were obtained from the Korean National Health Insurance Service (KNHIS) database. These administrative data are population-based cohorts established by a single compulsory health insurance system, including insurance eligibility, disease diagnosis, prescription, treatment procedure, and socio-demographic status from 2002 to 2015. The KNHIS data covered the following five types of insurance: NHIS employee subscriber, NHIS employee dependent, NHIS district subscriber, NHIS district dependent, and medical aid. We defined workers as NHIS employee subscribers in KNHIS data. Some workers, such as nonpaid familial workers or self-employed workers, had different types of insurance, and we focused on most paid workers who were included among NHIS employee subscribers. The total person-years of workers from the KNHIS data were 85,954,378 during the follow-up period. Previous studies used the same definition of workers; this definition had consensus in occupational medicine under Korean cultural and economic circumstances (S. Lee, Choi, et al., 2020; W. Lee, Kang, et al., 2020). The study included only workers, and variables were obtained for the date of hospital visit and the International Classification of Diseases (ICD-10). The outcome variable, health effects, used the main category of ICD-10 codes, which was a system of one letter, flowed by a number and grouped by each system of the body (<https://icd.who.int/browse10/2019/en>). In addition, the T67.0–T67.9 (effects of heat and light) codes from “XIX Injury, poisoning, and certain other consequences of external causes” in the ICD-10 major category were selected to determine the health effects associated with heat waves.

Data on deaths, a serious health impact, were confirmed by the Korean National Statistical Office during the same period. These data were aggregated for all reported deaths in the country and classified as a cause of death by ICD-10. Only workers with information regarding their jobs available at the time of death were included in the analysis, and deaths were divided into total and outdoor using death location information from the death certification record.

## 2.2. Ethical Statement

Data from the KNHIS were collected using written informed consent from all participants, and the information was anonymized. The study was approved by the Institutional Review Board of Gachon University Gil Medical Center (IRB No. GCIRB2020-256).

## 2.3. Statistical Analysis

We used the disease and death data of nationwide workers from 2002 to 2015 and the aforementioned weather data. In the analysis, the health results were matched with the weather in the same administrative region. The average annual temperature in Korea was found to be 12.4°C–13.4°C during the study period, and there was no statistically significant year-trend effect.

The weather data were based on regional weather monitoring stations operated by the Korea Meteorological Administration. There are 105 monitoring stations operating across the country, and all of them work simultaneously using automatically synchronized observation systems. Major weather observation factors include average temperature, highest temperature, average wind speed, relative humidity, and daylight hours. Heat exposure was defined as maximum daily temperature (MaxT) (°C), average daily temperature (AvgT) (°C), and heat index (HI) (°C). Considering that the weather information was collected based on the monitoring station, the results of each monitoring station in the same administrative area (city) were averaged and applied as representative values for analysis as health effects.

### 2.3.1. Generalized Additive Model

There were differences in monthly temperatures depending on the geographical location. The model also includes humidity, wind, time of sunlight, and the amount of clouds that affect the weather. The analysis period was from 1 June to 30 September during follow-up period, and due to the nonlinear nature of the weather information, the model was fitted through the generalized additive model (GAM).

$$g(\text{Health event}_t) = \beta_0 + f_1(\text{Heat exposure}_{t-1}) + f_2(\text{Months}_t) + f_3(\text{Weeks}_t) + f_4(\text{Humidity}_t) + f_5(\text{Cloud amount}_t) + f_6(\text{Sunlight time}_t) + f_7(\text{Wind}_t) + f_8(\text{Region}_t) + \epsilon_t,$$

where  $g(Y)$  is the link function, and  $f_s(x_t) = \sum_{i=1}^k b_i(x_t)\beta_i$  is a nonparametric smoothing function of the covariates  $x_t$ .

### 2.3.2. Distributed Lag Nonlinear Model

If the model was significant, a lag time effect analysis was conducted to calculate the duration of the effects of heat on health, and since it could have a nonlinear model, the effect was estimated by applying a distributed lag nonlinear model. Months and weeks are time series confounding factors, so every step of model building was simulated by the degree of freedom (df) from 2 to 100 in the generalized linear mode. In that simulation, minimal values of the Akaike information criterion (AIC) were used to fit the model.

### 2.3.3. Dose-Response Relationship Analysis

Consequently, through the dose-response relationship, a polynomial function with heat exposure and outcome was established, and the appropriate model was selected by applying AIC to present the optimal threshold for model fitting. All statistical analyses were conducted using the R program (version 4.0; R Foundation for Statistical Computing, Vienna, Austria).

## 3. Results

Table 1 summarizes the climate characteristics during the summer (June–September) in Korea (2002–2015). The average MaxT, HI, and humidity were 26.6°C, 22.2°C, and 66.8%, respectively.

Table 2 demonstrates the effect, calculated by GAM, of heat exposure on mortality, disease, accidents, and injuries among workers during the follow-up periods. Overall, there were 4,735,892 deaths, of which 836,189 occurred outdoors. MaxT was closely linked to an increased risk of both death and outdoor death. The medical facility visit history was significantly increased by 0.042636 visit cases owing to infectious and parasitic diseases (A and B); 0.003127 from cardio and cerebrovascular diseases (I20–25 and I60–69); 0.001260 from diseases of

**Table 1**  
*Summary of Summer Season (June–September) Climate Characteristics in Korea (2002–2015)*

| Characteristic                 | Minimum | 25th percentile | Median | 75th percentile | Maximum | Mean (standard deviation) |
|--------------------------------|---------|-----------------|--------|-----------------|---------|---------------------------|
| Maximum daily temperature (°C) | 9.8     | 23.7            | 26.6   | 29.1            | 35.3    | 26.3 (4.0)                |
| Average daily temperature (°C) | 5.3     | 18.0            | 21.5   | 24.3            | 29.9    | 21.0 (4.3)                |
| Minimum daily temperature (°C) | −0.5    | 12.7            | 17.4   | 20.8            | 25.9    | 16.6 (5.2)                |
| Humidity (%)                   | 21.0    | 56.7            | 66.8   | 76.1            | 99.4    | 66.3 (13.7)               |
| Heat index (°C)                | 3.2     | 18.6            | 22.2   | 24.9            | 34.9    | 21.7 (5.0)                |

the genitourinary system (N); 0.003097 arising from injury, poisoning, and certain other consequences of external causes (S and T); and 0.024075 from the effects of heat and light (T67) by 1°C elevated MaxT. In AvgT, there was a significantly related risk to the effects of heat and light (T67). HI was associated with injury, poisoning, and certain other consequences of external causes (S and T), as well as the effects of heat and light (T67).

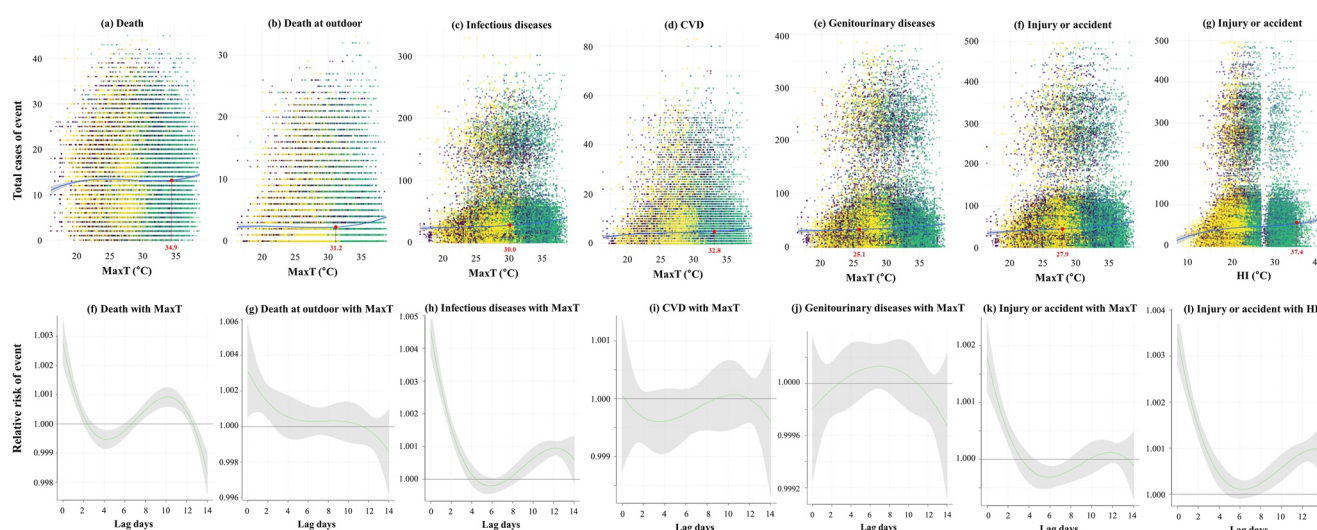
In Figures 1a–1g, the results of distributed lag nonlinear model between heat exposure and death, disease, and injury or accident with the threshold of effect, which was estimated by the least AIC of model fitting, excluded nonsignificant results from GAM and the effects of heat and light, (T67) given the small number of cases. The association between (a) death or (b) death outdoors and MaxT had a threshold of 34.9°C and 31.2°C, respectively. The lowest MaxT threshold was found in panel (e) diseases of the genitourinary system (N) (25.1°C). The threshold of HI was calculated at 37.4°C in (g) injury, poisoning and certain other consequences of external causes (S and T).

Figures 1f–1i show the lag effect of heat exposure on health focused on the relationship described in Figures 1a–1g. Day zero showed the highest effect of heat exposure on most diseases. There was no significant lag effect of

**Table 2**  
*Summary Statistics of Heat-Related Mortality, Diseases, Accident, and Injury Among Workers From the Generalized Additive Model During the Summer Season (June–September) in Korea (2002–2015)*

| Characteristics                                                      | Total no.  | Estimate of risk × associated with a unit increase in heat |                 |                 |
|----------------------------------------------------------------------|------------|------------------------------------------------------------|-----------------|-----------------|
|                                                                      |            | MaxT                                                       | AvgT            | HI              |
| Death records                                                        |            |                                                            |                 |                 |
| Total deaths                                                         | 4,735,892  | <b>0.008517</b>                                            | 0.027840        | 0.013360        |
| Deaths outdoors                                                      | 836,189    | <b>0.004663</b>                                            | 0.019885        | 0.021332        |
| National Health Insurance Service data                               |            |                                                            |                 |                 |
| Certain infectious and parasitic diseases                            | 7,947,675  | <b>0.005423</b>                                            | 0.041042        | 0.030610        |
| Endocrine, nutritional, and metabolic diseases                       | 7,593,852  | 0.002868                                                   | 0.033938        | 0.024494        |
| Mental and behavioral disorders                                      | 3,176,853  | 0.002090                                                   | 0.021500        | 0.010513        |
| Diseases of the circulatory system                                   | 4,203,093  | 0.001026                                                   | 0.033650        | 0.025384        |
| Cardio and cerebrovascular diseases                                  | 432,453    | <b>0.003127</b>                                            | 0.035945        | 0.045452        |
| Diseases of the respiratory system                                   | 37,462,821 | 0.002871                                                   | 0.036351        | 0.026423        |
| Diseases of the digestive system                                     | 12,989,765 | 0.001645                                                   | 0.034621        | 0.018466        |
| Diseases of the skin and subcutaneous tissue                         | 15,440,482 | 0.001026                                                   | 0.021975        | 0.021994        |
| Diseases of the musculoskeletal system and connective tissue         | 28,609,277 | 0.001281                                                   | 0.033064        | 0.023131        |
| Diseases of the genitourinary system                                 | 11,800,634 | <b>0.001260</b>                                            | 0.036039        | 0.025347        |
| Injury, poisoning, and certain other consequences of external causes | 14,888,037 | <b>0.003097</b>                                            | 0.038120        | <b>0.002821</b> |
| Effects of heat and light                                            | 5,342      | <b>0.024075</b>                                            | <b>0.060677</b> | <b>0.049862</b> |

*Note.* MaxT, maximum daily temperature (°C); AvgT, average daily temperature (AvgT) (°C); HI, heat index (°C). Risks were estimated using the generalized additive model with monthly and weekly trends, humidity, cloud amount, sunlight time, average wind speed, and region. Bold indicates statistically significant association ( $P < 0.05$ ).



**Figure 1.** Results of an analysis with distributed lag nonlinear model between heat exposure and death, diseases, and injury or accident with threshold and lag effect of heat exposure on each health outcome. Purple dots, June; Blue dots, July; Green dots, August; Yellow dots, September.

heat exposure on (i) cardio and cerebrovascular diseases (I20–25 and I60–69) and (j) diseases of the genitourinary system (N) with MaxT.

## 4. Discussion

This study aimed to investigate the relationship between heat exposure and worker health. These findings indicate a close association between heat exposure and various health outcomes. In terms of health outcomes, heat exposure was significantly related to death, death outdoors, infectious, cardio and cerebrovascular, and genitourinary diseases, as well as injuries or accidents. The most significant relationship in the definition of heat was MaxT. These findings may help us to understand the effect of heat on workers' health.

Extreme heat has been reported to be a risk factor for all-cause mortality. Comprehensive review articles, totaling almost 50 until the early 2000s, have highlighted that various types of heat exposure are related to the risk of mortality (Basu & Samet, 2002). These relationships have been elucidated in various study designs, including time-series analysis, register-based cohort, and case-crossover studies. The dose-response model also showed a strong causal relationship between heat exposure and mortality (Díaz et al., 2002). Such serious relationships have been tested in various regions across a wide range of longitudes; hence, the association between heat waves and mortality has been accepted as a general phenomenon beyond any particular region (Kalkstein & Greene, 1997; Mirabelli & Richardson, 2005; Ostro et al., 2009). Heat exposure can trigger organ damage due to ischemia, heat cytotoxicity, inflammatory response, disseminated intravascular coagulation, or rhabdomyolysis (Mora et al., 2017). These physiological mechanisms are closely related to cell death.

Furthermore, heat waves contribute both directly and indirectly to disease processes. Research has shown that it increases the hospitalization rate of fluid and electrolyte-related diseases or kidney disease or raises the risk of coagulation or heart disease in the vulnerable general population (Bobb et al., 2014). It has also been accepted that older adults are more likely to experience cardiovascular reactions to heat stress (Gravel et al., 2021).

These health effects have also been well studied among workers. We performed a systematic review of the health of workers and their heat exposure (J. Lee et al., 2021). For workers, the risk ratio of heat-related mortality was 1.37 (95% confidence interval [CI] 0.99–1.90) when the average summer temperature rose by 1°F (Mirabelli & Richardson, 2005; Morabito et al., 2014). In addition, three consecutive days of high temperature increased the risk of damage by 15% (95% CI 1.01–1.30) (McInnes et al., 2018). In Canada, the incidence rate ratio of the number of disaster compensations for damage was 1.002 (95% CI 1.002–1.003) (Adam-Poupart et al., 2015). Workers are likely to suffer from various diseases, similar to those in the general population. A downward change in eGFR was observed in workers with high exposure to rising temperatures and intense work (García-Trabanino

et al., 2015). Moreover, there is a high risk of cumulative incidence of chronic kidney disease in acute kidney injury (Butler-Dawson et al., 2019; Moyce et al., 2017). The risk of hyperlipidemia also increased significantly in workers exposed to heat, with increased levels of total cholesterol and low-density lipoprotein cholesterol (Vangelova et al., 2006).

These phenomena can be explained using mechanistic studies. One explanation is that heat exposure represents an unsafe environment and the other is that a stressful environment aggravates human homeostasis. A well-known heat-related disease mechanism is non-compensable thermoregulation, which is an important function of an automatic system that responds to heat and cold stress in the body. It is controlled by autonomic reactions that dissipate and produce heat to maintain cellular activity. Extreme heat and high humidity slow evaporation, and the body needs to work harder to maintain a normal body temperature. When the core temperature rises beyond the body's control, cell anoxia occurs and inflammatory reactions such as a systematic inflammatory response system are activated, leading to multiorgan dysfunction (Bouchama & Knochel, 2002). In addition to these mechanisms, there is a possibility that many natural disasters, such as storms, have occurred, thus increasing the risk of death and damage. The rise in the highest temperature and the occurrence of outdoor deaths might also be related to our results.

The thermoregulation mechanism can also be applied to various diseases. Similar mechanisms derived from thermoregulation can be applied to a range of diseases. Among them, those related to kidney disease are well known, and dehydration or rhabdomyolysis caused by heat is associated with the development of acute kidney injury (Hansen et al., 2008; Knowlton et al., 2009). Vasopressin is produced by repeated high serum osmolarity and this oxidative stress causes chronic kidney disease (de Lorenzo & Liaño, 2017). In the cardiovascular system, blood vessels dilate in the skin, redistribute blood flow to organs, and increase cardiac output. It also increases sympathetic nervous activity, causing hypertension and vascular diseases (Gorman & Proppe, 1984; Gravel et al., 2021; Liu et al., 2015).

In addition, many injuries are caused by a decline in cognitive function. Long-term exposure to stressful conditions of temperature leads to a decline in the performance of complex tasks (Hancock & Vasmatazidis, 2003; Ramsey & Kwon, 1992). A heat-related environment can be regarded as a job stressor (Dehghan et al., 2016), which increases the risk of injury by almost three-fold (Clouser et al., 2018).

Workers' health and safety have been linked to weather information. Our study did not include all related factors, such as workers' working characteristics or socio-economic factors, but it has the advantage of being able to link with workers' health and weather information even under limited conditions. The International Labor Organization has also created interventions that provide criteria for limiting occupational heat exposure. It is about getting enough water on the job, working during cooler hours, reducing physical demands during hot hours, ensuring breaks, and wearing the right clothes (Department of Health and Human Services, Centers for Disease Control and Prevention, & National Institute for Occupational Safety and Health, 2018). In addition, considering that the weather forecast may differ from the actual weather conditions according to the characteristics of the work site, it may be necessary to take measures for the local weather conditions where the work is being done.

Workers who have insufficient job control and job authority cannot regulate their heat exposure during working hours; hence, the vulnerability to heat exposure is an issue beyond individual education and decisions. In our study, high peak temperatures and continuous heat can deteriorate health; therefore, scenarios should be established considering working conditions and a response system should be developed accordingly. Moreover, the political implication of how to control heat exposure in workers is an especially important issue to prevent heat-related mortality, as our current study highlighted. Therefore, we hope our current scientific results support policy changes to protect workers' health. We could explore potential weather effects on workers' health during the summer season. Further research into the effect of low temperatures on workers during the winter season is strongly recommended.

This study also has the following limitations: the first is the lack of data on local weather conditions. In this study, we used information based on the national representative weather information of Korea, which was collected from a total of 105 regional weather monitoring stations. This could be a slightly different condition between reported and local worksite weather. It is necessary to conduct an analysis of the effect of heat on workers' health considering workplace weather conditions. Uncontrolled potential confounders, such as occupational and sociodemographic characteristics, remained in the final analysis due to the limited nature of the data. The type of

medical facility visit information (emergency or planned visit, inpatient or outpatient, or nursing hospital) is also an important characteristic of the effect of heat exposure. Future studies should consider these factors.

Finally, although death information from the Korean National Statistical Office had few errors regarding health outcomes, diseases or injury information, which were defined as medical facility admission histories, might have a misclassification error due to the national health insurance system in Korea. Nevertheless, it is meaningful in that it preemptively considers the association between workers among the whole population by using representative data established by the government. Moreover, it is imperative to conduct comprehensive studies, such as physiological and epidemiological.

## 5. Conclusions

The current study revealed that heat exposure is a risk factor for death (including death outdoors), infectious, cardio and cerebrovascular, and genitourinary diseases, as well as injuries or accidents among workers. MaxT was more significantly related to workers' health outcomes than did AvgT or HI. Since heat exposure could be a critical environmental risk factor among workers, it is necessary to further explore the effect of environmental heat exposure on occupational health.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Data of current work was not open to the public because the full authority of the data set of the current work belonged to the KNHIS, authors' authority of data has been terminated at the end of this study. The study participants and medical facility visit data can be requested from the National Health Insurance Sharing Service of Korea (<https://nhiss.nhiss.or.kr>), regional weather monitoring data were obtained from the Korea Meteorological Administration (<https://data.kma.go.kr>).

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