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Research article

Meteorological parameters and hospital-acquired falls—A multicenter retrospective study based on 10 years of adverse events reporting system data

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ABSTRACT

Objective and rationale: Hospital-acquired falls are common and serious adverse events in medical institutions, with high incidence and injury rates. Studying the occurrence patterns of hospital-acquired falls is important for preventing falls in hospitalized patients. However, the effect of meteorological factors on hospital-acquired falls has not been elucidated. Therefore, this study explored the impact of meteorological parameters on hospital-acquired falls in Chongqing, China, and provided new ideas for the clinical prevention of falls in patients.
Methods: Correlation analysis and distributed lag nonlinear models were employed to analyze the relationship between 3890 cases of hospital-acquired falls and meteorological data in 13 hospitals in 11 districts and counties in Chongqing from January 2013 to April 2023.
Results: The number of hospital-acquired falls demonstrated a nonlinear correlation with the daily average relative humidity and negatively correlated with sunshine duration; however, temperature, air pressure, and wind speed were not correlated. Compared to the reference humidity (87 %), the immediate effects of daily average relative humidity (65–68 % and 90–97 %) increased the risk of hospital-acquired falls on the same day (relative risk [RR]:1.027–1.243). When the

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daily average relative humidity was 95–97 %, lags of 0–1 d and 8–12 d had greater effects on falls (RR:1.073–1.243). The daily average relative humidities of 62–74 % and 91–97 % were statistically significant at cumulative relative risk (CRR)of 4, 7, 10, and 14 d with a cumulative lag (CRR: 1.111–4.277). On sex and age stratification, the lag and cumulative effects of relative humidity more significantly impacted falls in women and patients aged ≥65 years.
Conclusion: Daily average relative humidity had a nonlinear correlation and lag effect on hospital-acquired falls; therefore, medical institutions should pay attention to the effect of relative humidity on hospital-acquired falls in patients, especially old and female patients.

1. Introduction

Hospital-acquired falls (HAFs), which are falls that occur in hospitalized patients, have emerged as one of the most common and serious adverse events in medical institutions [1,2].The incidence and injury rates of HAFs in foreign hospitals are 2.8 %–7.7 % [1] and 6.1 %–36.4 % [3–6], whereas in China, they are 1.9 %–17.1 % [7] and 49.01 %–69.12 % [8–10], respectively.

HAFs can not only lead to pain, bleeding, fractures, disabilities, and functional impairment [11–13], but also increase complications such as pulmonary infections, urinary tract infections, and deep vein thrombosis, causing psychological problems such as anxiety and fear, and even death [14–16] Moreover, HAFs can also prolong hospital stay and increase the economic burden in individuals, families, and society [17,18]. In Australia, HAFs result in an average increase in hospital stay of 8 days, increasing the average medical expenses by $6669; moreover the medical costs for patients with HAFs are twice of that of patients without falls [5]. In Germany, the length of hospital stay per fall patient increases by 6.3 days, and 30–35 % of HAFs result in injuries, increasing medical costs by more than $14,000 per fall [6]. Among patients with HAFs in China, the average length of hospital stay for patients with severe injuries increases by 14.73 days, and the total cost of treatment for HAFs reaches 680,000 yuan [19]. Based on the prevalence, harmfulness, and high cost of HAFs, effective prevention of HAFs has become an urgent patient safety issue [20]. Studying the occurrence patterns of HAFs is of great significance for preventing falls in hospitalized patients.

Climate change has become one of the most challenging issues of the 21st century and is directly related to public health [21]. Falls result from a combination of endogenous and exogenous factors [13,22,23], with meteorological factors being an important exogenous factor. With the advancement of research on the impact of global climate change on human health, some researchers have begun to pay attention to the impact of meteorological factors on falls [24–26]. By analyzing the relationship between the number of visits related to falls and meteorological factors, Gevitz K et al. [26] found a positive correlation between snowfall and the visit rate related to falls, which may be related to the increase in relative humidity and slippery road surface caused by snowfall. Clemson L et al. [24] believe that attention should be paid to the impact of high relative humidity weather on falls of elderly people in communities. Lin LW et al. [27] demonstrated relative humidity to be a relevant factor for falls by analyzing the meteorological data of the Taiwan province and the non accidental fall data of the Taipei Fire Department. Some researchers [28] suggest that meteorological factors should aid in the provision of specific guiding measures for fall intervention, including dehumidification threshold and humidity control standards, etc. Chow KP et al. [25] conducted a systematic review of 29 studies on falls and meteorological factors, and found that the relationship between meteorological factors and falls warrants further exploration. In the mainland area of China, few studies have been conducted on the relationship between climate change and falls [27–29]. Therefore, relevant research mainly has the following shortcomings: first, the research focuses mainly on the community, elderly, or whole population, without targeting the special population of hospitalized patients. However, hospitalized patients are a high-risk group for falls, with characteristics such as acute stage of the disease, complex condition, diverse medication use, and decreased self-care ability [20,30]. Studying the relationship between this group and meteorological factors is crucial for discovering meteorological related rules of HAFs and preventing falls; second, although meteorological factors were found to be associated with falls in the previous study, no in-depth analysis has been conducted [24–26]. Although studies suggest elevated relative humidity to be associated with falls, the relationship between different relative humidity levels and falls and the lag or cumulative effect of relative humidity levels on falls have not been investigated in detail.

In fact, relative humidity is an important physical indicator that reflects the water vapor content in the air, and plays an important role in health. Relative humidity can affect the human mucociliary clearance rate by affecting the rheological properties of water vapor in the air and changing its osmotic pressure [31]. In addition, relative humidity can indirectly affect the expression of ion channel protein of thermosensitive transient receptor potential [32] and regulate body fluids and temperature, affecting the core temperature [33], cold stress, heat stress [34], and hydration state of the human body [33]. Environmental epidemiological studies have shown that relative humidity can directly affect human comfort [35,36], and can also induce oxidative stress and inflammatory response [34,37,38], which is not only related to the occurrence and progression of immune system function [31,39–42], nervous system diseases [34,43,44], mental diseases [36,45,46], emotional regulation [36,46], and skin diseases [39,43,47,48], but also related to the all-cause mortality and incidence rate of cardiovascular diseases and respiratory diseases [21,38,49,50].

Based on these findings, we hypothesized a relationship between meteorological factors and HAFs. Therefore, this study aimed to use a retrospective analysis to explore the correlation between HAFs and meteorological factors in Chongqing from 2013 to 2023 to provide new ideas for the clinical prevention of falls in patients.

2. Materials and methods

2.1. Study area

Chongqing is located on the eastern edge of the Sichuan Basin in southwestern China (105°11′-110°12′E, 28°10′-32°15′N), with a total area of 82,400 km^2. It has a subtropical monsoon humid climate with hot and humid summers and warm and relatively dry winters. The spring and autumn seasons are short, and the annual precipitation is abundant [51].

2.2. Research objective

This study focused on HAF cases in Chongqing from January 2013 to April 2023. The data covered 11 districts and counties, including the main urban areas of Chongqing, urban clusters of the Three Gorges Reservoir Area in the northeast of Chongqing, and urban clusters of the Wuling Mountains area in the southeast of Chongqing, with 13 hospitals at or above the second level. The inclusion criteria were as follows: (1) second-level and higher public comprehensive hospitals: Hospitals that comply with the "Hospital Grading Management Measures" issued by the former Ministry of Health of the People's Republic of China and the "Medical Institution Evaluation Measures" issued by the National Health Commission of the People's Republic of China for the management and evaluation standards of second level and higher public comprehensive hospitals [52,53]; (2) presence of a sound adverse event reporting and management mechanism; and (3) presence of a relatively complete adverse event reporting and analysis information system. The exclusion criteria for hospitals were as follows: (1) military hospitals, (2) specialized hospitals, and (3) private hospitals. Case inclusion criteria were as follows: (1) patients aged ≥18 years old; (2) falls occurred during hospitalization, and (3) complete relevant information (kindly refer to 2.3.1 Fall Data for further details). This study included 3890 cases of HAFs.

2.3. Data collection

2.3.1. Fall data

The researchers formulated a data extraction manual and sent it to all the participating units. Through the Adverse Events Reporting System (AERS), the participating units exported the data of patients with HAFs who met the inclusion criteria. Data included hospitalization number, sex, age, diagnosis, fall time, fall location, fall status, fall position, injury grade, injury description, and event level.

2.3.2. Meteorological data

Meteorological data were collected between January 2013 and April 2023 from the China Meteorological Science Data Center website (http://data.cma.cn/site/index.html). These data included daily minimum temperature (°C), maximum temperature (°C), average temperature (°C), maximum air pressure (hPa), minimum air pressure (hPa), average air pressure (hPa), daily average relative humidity (%), minimum daily relative humidity (%), precipitation (mm), average wind speed (m/s), maximum wind speed (m/s), sunshine duration (h), and daily average visibility (m). Relative humidity refers to the ratio of the actual water vapor pressure in air to the saturated water vapor pressure at a given temperature [54].

2.4. Statistical analysis

Spearman rank correlation analysis was used to analyze the simple correlation between the meteorological factors and number of daily falls. The distributed lag nonlinear model (DLNM) was used to investigate the relationship between relative humidity and HAFs, and estimate the relative risk (RR) and cumulative relative risk (CRR) associated with different daily average relative humidities. Upon considering the number of daily fall cases as the dependent variable and selecting a quasi-Poisson distribution, a cross-basis function of daily average relative humidity was established to correct for the effects of daily average temperature, sunshine duration, daily precipitation, long-term trend of time, seasonal trend, and day of the week. The fitting model was as follows:

$$log[E(Y_t)] = a + \beta Humidness_{t,l} + NS(Temp, v) + NS(ds, v) + NS(rf, v) + NS(time, v) + QTR + DOW \quad (1)$$

Y_t represents the number of daily fall cases; α represents the intercept; $Humidness_{t,l}$ represents the cross basis of daily average relative humidity and lag time; β represents the $Humidness_{t,l}$ coefficient; NS represents the natural cubic spline function; ν represents the degree of freedom; Temp represents the daily average temperature; Ds represents the sunshine duration; Rf represents the daily precipitation; Time represents the time variable; QTR represents the seasonal trend; and DOW represents the day of the week effect. In this study, P75 of the daily average relative humidity was used as the reference humidity, which was 87 %. The maximum delay time was set to 14 d. According to the quasi-likelihood of Akaike's information criterion (Q-AIC), the degrees of freedom for sunshine duration, daily average relative humidity, and daily precipitation were determined to be 2, whereas the annual degrees of freedom for the time trend variable were 7. DLNM was implemented using the "dlnm" package in R4.0.3 (version 2.4.2), whereas the rest were implemented in SAS9.4 (9.4). Statistical significance was set at $P < 0.05$.

3. Results

3.1. HAFs cases

A total of 3890 cases of HAFs were included with patients aged 18–100 years (average age, 68.44 ± 17.44 years), comprising 1927 men, 1963 women, 2537 cases with individuals aged<65 years old, and 1353 cases with individuals aged ≥65 years old. There were 615, 506, 486, 442, and 1841 cases of circulatory system, respiratory, neurological, mental, and other systemic diseases. Although the number of fall cases increased every year, no obvious pattern was observed (Fig. 1).

3.2. Distribution of meteorological factors in Chongqing

The daily average relative humidity in Chongqing from January 2013 to April 2023 ranged from 37.76 % to 97.61 % (average, 78.19 ± 11.19 %). The daily maximum temperature ranged from 2.35 °C to 41.83 °C (average, 22.15 ± 8.93 °C). The daily minimum temperature range was −2.08°C-31.19 °C (average, 15.10 ± 7.10 °C). The daily average temperature range was 1.29–36.15 °C (average, 17.96 ± 7.79 °C). The average sunshine duration was 3.38 ± 3.74h, and the average precipitation was 3.37 ± 7.43 mm (Table 1).

3.3. Correlation between HAFs and meteorological factors

The number of HAFs was positively correlated with the daily average relative humidity (r = 0.046, P < 0.01) and negatively correlated with sunshine duration (r = −0.033, P < 0.05) (Table 2).

3.4. Effects of daily average relative humidity on HAFs

A non-linear relationship was observed between the daily average relative humidity and the number of HAFs (Fig. 2 (A)). Compared with the reference humidity (87 %), a daily average relative humidity of 95 %–97 % had the greatest effect on falls, with a lag of 0–1 day and 8–12 days, and the RR ranged from 1.073 to 1.243. Among them, the effect of a daily average relative humidity of 97 % with a lag of 0 day was the largest, with an RR of 1.243 (95 % confidence interval [CI] = 1.033–1.495). This indicates that the risk of HAFs increased by 24.3 % on days when the daily average relative humidity was 97 % (Fig. 2 (B)).

Compared to the reference relative humidity (87 %), the daily average relative humidity of 65%–68 % and 90–97 % at 0 day lag (RR: 1.027–1.243), 80–83 % at 7 days lag (RR: 1.020–1.031), and 76–85 % at 10 days lag (RR: 1.012–1.047) were risk factors for HAFs, with a statistically significant lag effect (Fig. 3 (A–E)). The CRR of the daily average relative humidity of 62–74 % and 91–97 % with cumulative lags of 4, 7, 10, and 14 days had statistical significance (CRR:1.111–4.277) (Fig. 3 (F–J)).

Compared to the reference relative humidity (87 %), the daily average relative humidity of 62 % (P10) with a lag of 1–3 days, 71 % (P25) with a lag of 1–2 days, 80 % (P50) with a lag of 7–11 days, 85 % with a lag of 8–12 days, and 91 % (P90) with a lag of 0–1 days were risk factors for HAFs, and the lag effect was statistically significant (Fig. 4 (A–E)). Among them, the daily average relative humidity of 62 % at 1 day lag, 71 % at 2 days lag, 80 % at 10 days lag, 85 % at 10 days lag, and 91 % (P90) at 0 day lag had the largest effect, and the RR values and 95%CI were 1.073 (1.018–1.131), 1.057 (1.011–1.105), 1.045 (1.008–1.082), 1.012 (1.002–1.023) and 1.044 (1.007–1.083), respectively. The CRR of the daily average relative humidity of 62 % with cumulative lags of 1–10 days and 13–14 days had statistical significance (CRR: 1.168–1.461) (Fig. 4 F). The CRR of the daily average relative humidity of 71 % and 91 % with 1–14 days of accumulation had statistical significance (CRR: 1.074–1.578) (Fig. 4 G and J). The CRR of the daily average relative humidity of 80 % with cumulative lags of 10–14 days had statistical significance (CRR: 1.307–1.498) (Fig. 4H). The CRR of the daily average relative humidity of 85 % within 14 days of accumulation was not statistically significant (Fig. 4 I).

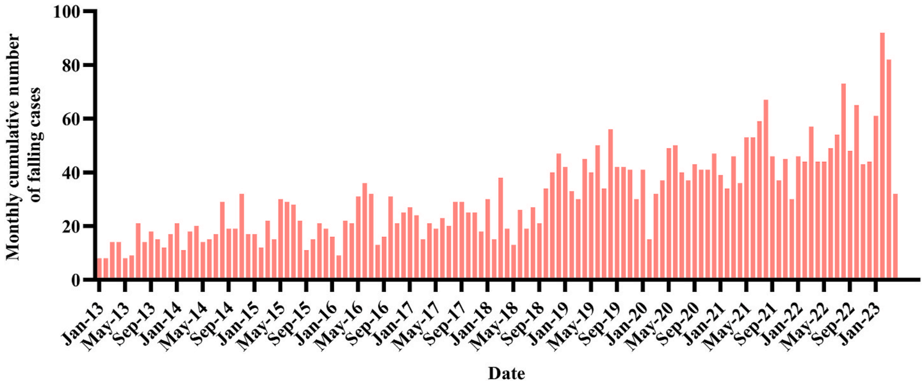

Fig. 1. Bar chart of cumulative monthly fall cases from January 2013 to April 2023.

Table 1
Distribution of meteorological factors in Chongqing from January 2013 to April 2023.

Variables	Mean value	Standard deviation	Minimum value	P10	P25	P50	P75	P90	Maximum value
Daily maximum temperature (°C)	22.15	8.93	2.35	10.25	14.35	22.27	29.43	34.55	41.83
Daily minimum temperature (°C)	15.10	7.10	−2.08	5.65	8.81	15.22	20.90	24.44	31.19
Daily average temperature (°C)	17.96	7.79	1.29	7.76	10.82	17.95	24.24	28.63	36.15
Daily average relative humidity (%)	78.19	11.19	37.76	62.00	71.09	80.13	86.95	91.35	97.61
Daily precipitation (mm)	3.37	7.43	0.00	0.00	0.00	0.27	3.21	10.41	79.60
Sunshine duration (h)	3.38	3.74	0.00	0.00	0.09	1.73	6.19	9.65	14.08

Table 2
Results of Spearman rank correlation coefficient analysis between meteorological factors and HAFs.

Variables	Daily maximum temperature (°C)	Daily minimum temperature (°C)	Daily average temperature (°C)	Daily average relative humidity (%)	Daily precipitation (mm)	Sunshine duration (h)
Daily maximum temperature (°C)	1					
Daily minimum temperature (°C)	0.929[c]	1				
Daily average temperature (°C)	0.980[c]	0.981[c]	1			
Daily average relative humidity (%)	−0.476[c]	−0.238[c]	−0.370[c]	1		
Daily precipitation (mm)	−0.013	0.198[c]	0.079[c]	0.602[c]	1	
Sunshine duration (h)	0.666[c]	0.423[c]	0.557[c]	−0.718[c]	−0.426[c]	1
Number of daily fall cases	0.015	0.026	0.021	0.046[b]	0.027	−0.033[a]

Note.
[a] $P < 0.05$.
[b] $P < 0.01$.
[c] $P < 0.001$.

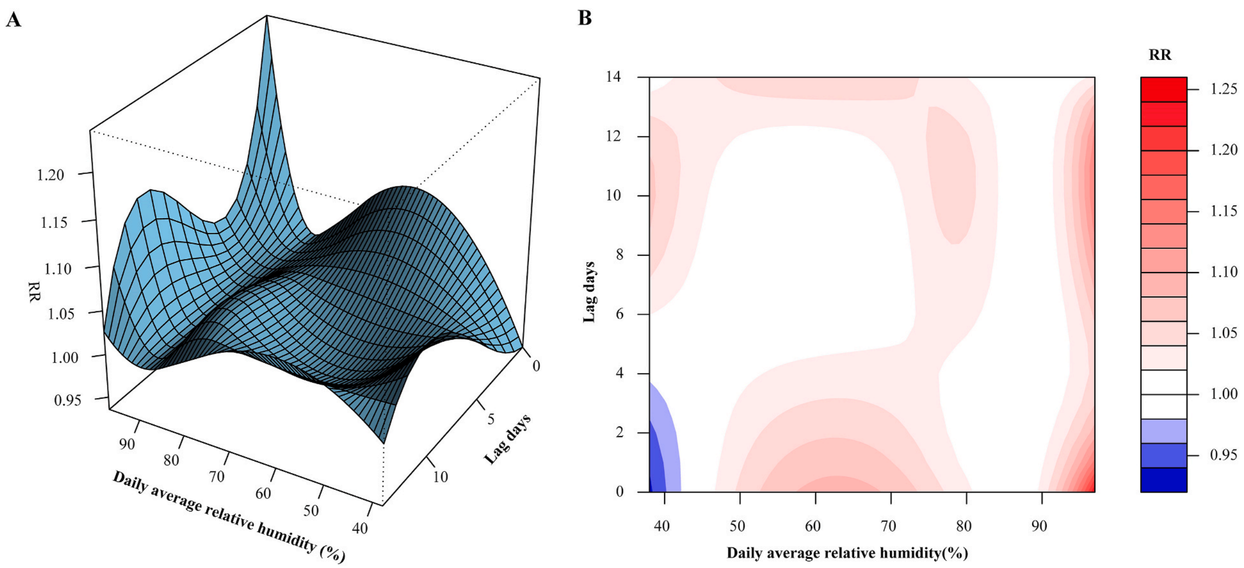

Fig. 2. Effect of daily average relative humidity on HAFs in Chongqing with different lag times three-dimensional correlation map (A) and heat map (B) (reference daily average relative humidity: 87 %).

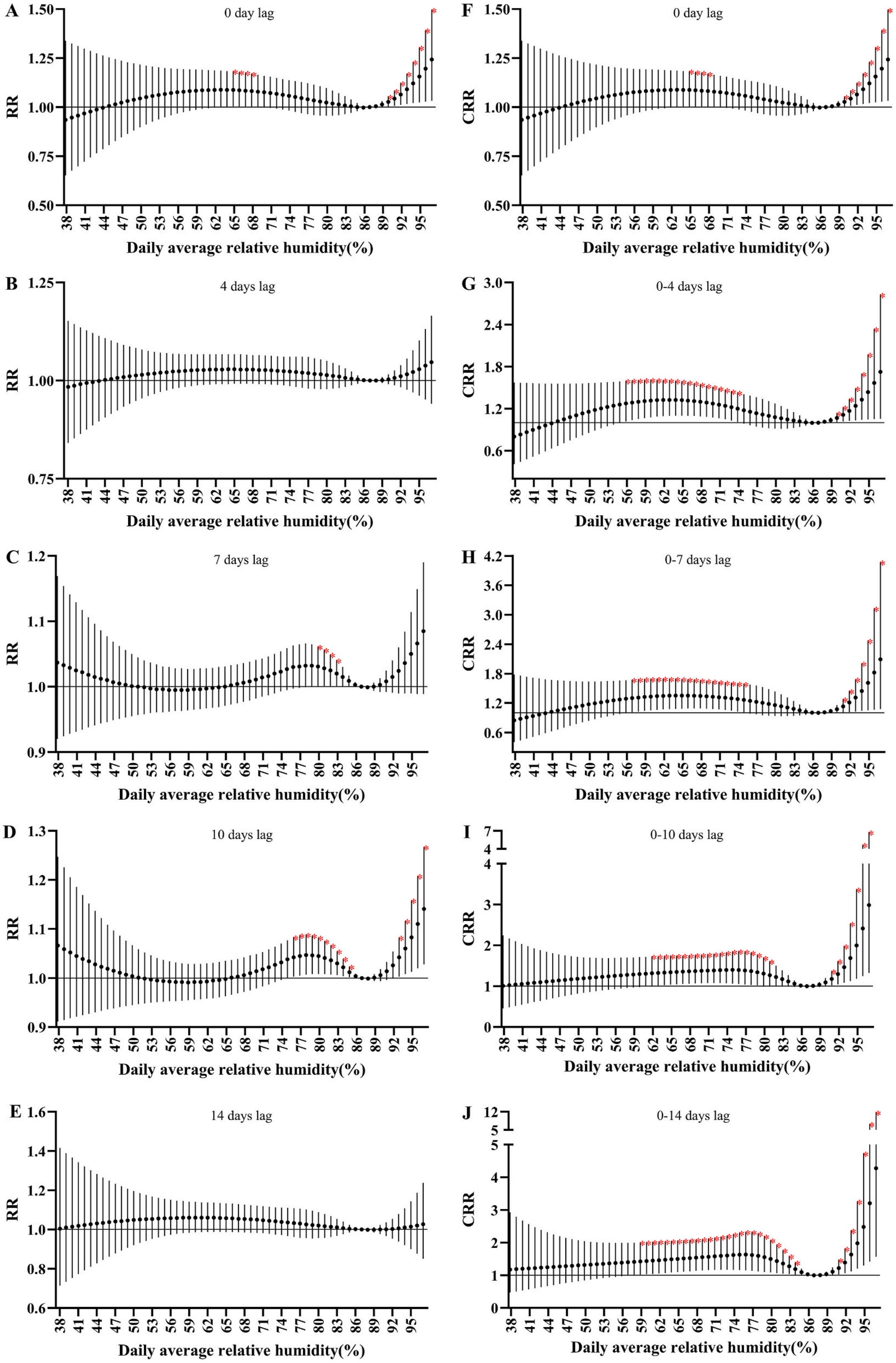

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Fig. 3. Effect of daily average relative humidity on the risk of HAFs with a lag of 0–14 days (compared with reference relative humidity 87 %, *P < 0.05)
A–E: RR on 0, 4, 7,10 and 14 days lag, respectively;
F–J: CRR on 0, 4, 7,10 and 14 days lag, respectively.
RR, relative risk; CRR, cumulative relative risk.

3.5. Hierarchical analysis

The results of sex stratification demonstrated that the influence of daily average relative humidity was statistically significant. Daily average relative humidities of 62 % (RR = 1.153, 95 % CI = 1.020–1.304), 71 % (RR = 1.148, 95 % CI = 1.035–1.273), and 91 % (RR = 1.058, 95 % CI = 1.006–1.112) increased the risk of HAFs in female patients with a lag of 0 day, whereas that of 80 % (RR = 1.051, 95 % CI = 1.001–1.104) increased the risk of HAFs with a 10-day lag. The CRRs of 62 % and 71 % of daily average relative humidity were statistically significant (CRR:1.148–2.159) over the cumulative 14-day periods.

The age stratification results showed that, among the population aged <65 years, 91 % of the daily average relative humidity alone increased the risk of falls at a lag of 0 day (RR = 1.049, 95 % CI = 1.003–1.096). The daily average relative humidity of 71 % at a lag of 10 days (RR = 1.063, 95 % CI = 1.0020–1.127), 80 % at a lag of 7 days (RR = 1.057, 95 % CI = 1.006–1.111) and 10 days (RR = 1.104, 95 % CI = 1.040–1.171), 85 % at a lag of 10 days (RR = 1.028, 95 % CI = 1.011–1.047), and 91 % at a lag of 4 days (RR = 1.039, 95 % CI = 1.008–1.071) and 7 days (RR = 1.035, 95 % CI = 1.008–1.062) could increase the risk of HAFs in patients aged ≥65 years. The daily average relative humidity of 62 % at cumulative 4 and 7 days (CRR: 1.443–1.468), 71 % at cumulative 10 and 14 days (CRR: 1.610–2.032), 80 % and 85 % at cumulative 14 days (CRR: 1.177–1.977), and 91 % at cumulative 4 7, and 10 days (CRR: 1.199–1.431) were found to be statistically significant (Table 3).

4. Discussion

4.1. High relative humidity increased the risk of HAFs

Falls were divided into three types: predictable physiological falls (78 % of all falls), unpredictable physiological falls (8 %), and unexpected falls (14 %) [55]. Regardless of the type, the risk factors for falls generally included two categories: internal and external factors [13,22,23]. Diseases are important internal factors that are closely related to predictable and unpredictable physiological falls [55], whereas relative humidity was an important external factor.

The suitable range of relative humidity for the human body is 25–65 % [32]. This study found that when the relative humidity exceeds the comfortable range of the human body, it may increase the risk of HAFs. The impact of environmental changes, such as relative humidity, on the human body is immediate [56]. When the relative humidity suddenly exceeds the suitable range of the human body, the human body may experience stress reactions to adapt to the changes in the relative humidity [56], including increased body temperature and blood pressure [57], accelerated heart rate [57], mental tension [41], decreased attention [58], fatigue and headaches [41]. Moreover, if the relative humidity exceeds the suitable range of the human body, it may cause serious imbalances in cardiovascular function [21,31,35,50,59], neurological function [43,44], emotional regulation [36,46], and immune function [31,39,41], which may increase the risk of HAFs.

A relative humidity ≤40 % was considered low relative humidity; >40 % to ≤60 %, medium relative humidity; and, >60 %, high relative humidity. At a certain pressure and temperature, the relative humidity ≥90 % was near-saturation relative humidity [32]. High relative humidity, especially near-saturation relative humidity, contributed to diseases such as pneumonia, asthma, chronic obstructive pulmonary disease, and emphysema [38,49,59,60]. High relative humidity not only contributes to mold growth, virus transmission and survival, but also increase the load of allergens, causing lung infections and airway hyperresponsiveness [31,49,50,59,60]. Moreover, high relative humidity decreases the blood oxygen saturation, limits sweat evaporation, reduces the mucociliary clearance rate, and indirectly affects the expression of thermosensitive transient receptor potential ion channel proteins, leading to impaired regulation of body fluids and body temperature, resulting in a physiological increase in respiratory frequency and leading to a series of respiratory system diseases [32,50,59,60]. Various diseases induced or exacerbated by high relative humidity and near-saturation relative humidity are often accompanied by decreased lung function, which can cause insufficient oxygenation in the body and result in chest tightness, fatigue, dizziness, and respiratory failure and distress, leading to HAFs [61,62].

High relative humidity can reduce the efficiency of metabolic heat transmission, resulting in an increase in the core temperature and a decrease in the hydration levels, which are closely related to various cardiovascular and cerebrovascular diseases, such as ischemic heart disease, arrhythmia, angina, heart failure, and stroke [37,38,46,49,50]. Decreased blood flow perfusion, insufficient oxygen supply, decreased vascular wall elasticity, decreased baroreceptor sensitivity, and abnormal white matter information in the deep brain caused by cardiovascular and cerebrovascular diseases [63,64] can lead to weakened muscle strength, decreased balance function, abnormal posture and gait, decreased mobility, and cognitive dysfunction, thereby increasing the risk of HAFs [64–67].

High relative humidity can also cause neurotransmitter imbalance, leading to irritability, lack of concentration, decreased motivation, and low mood, exacerbating the symptoms of various mental disorders, such as emotional disorders, behavioral disorders, depression, and anxiety [36,46]. Psychological emotions and mental illness symptoms are important factors affecting falls and may be related to poor activity coordination, weakened muscle strength, negative emotions, and cognitive abnormalities [61,68].

Especially when the relative humidity is close to saturation, it will directly weaken the skin-atmosphere moisture gradient, inhibit

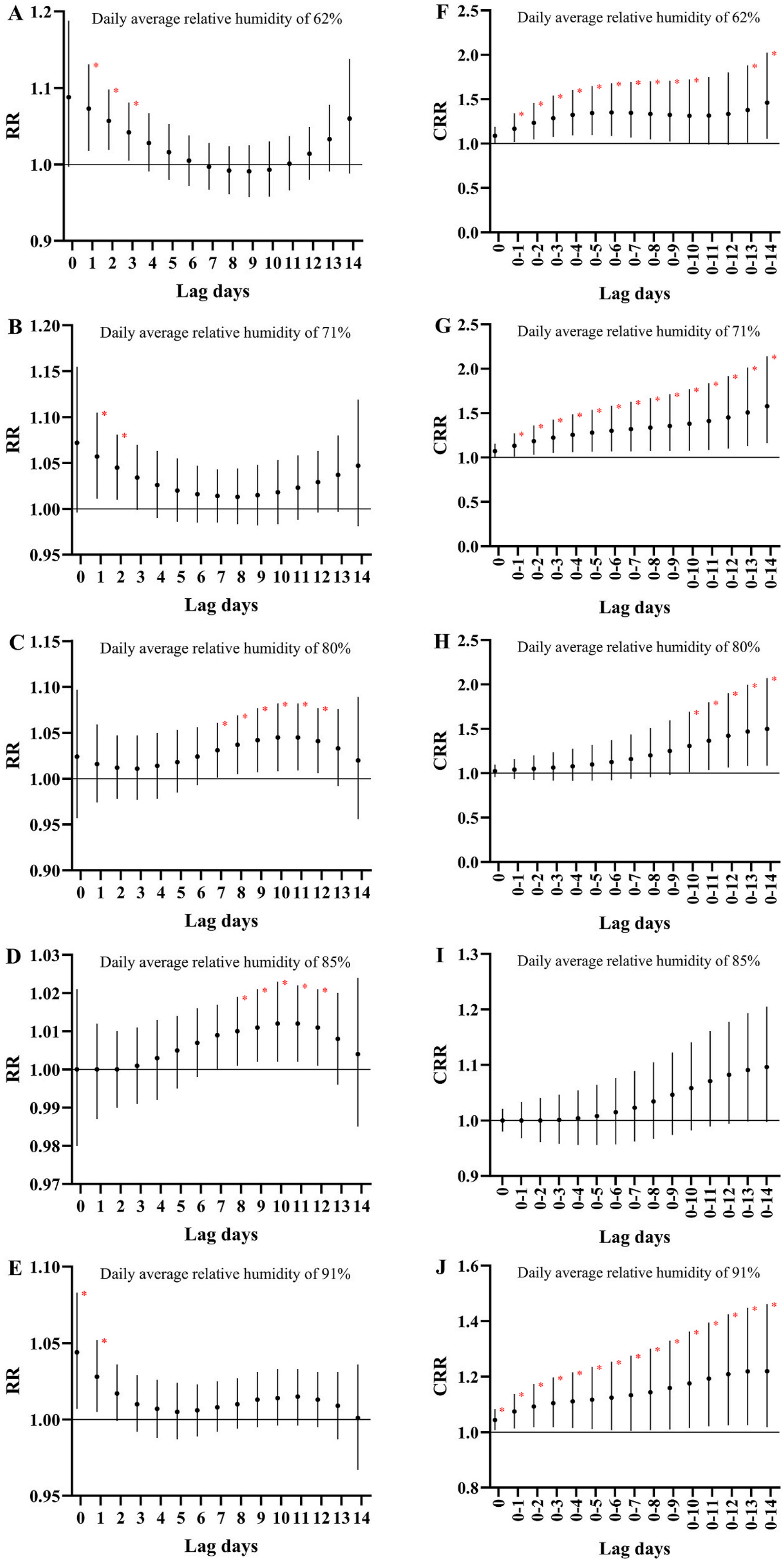

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Fig. 4. Effect of different daily average relative humidity lag days on HAFs risk (compared to reference relative humidity of 87 %, *P < 0.05)
A–E: RR on daily average relative humidity of 62 %, 71 %, 80 %, 85 % and 91 %, respectively;
F–J: CRR on daily average relative humidity of 62 %, 71 %, 80 %, 85 % and 91 %, respectively.
RR, relative risk; CRR, cumulative relative risk.

Table 3
Relationship between the daily average relative humidity of different days and the risk effect of hospital-acquired falls on different lag days (reference relative humidity: 87 %).

Daily average relative humidity(%)	Lag 0 day	Lag 4 days	Lag 7 days	Lag 10 days	Lag 14 days
RR					
Men (n=1927)					
62 (P_{10})	1.012(0.894,1.145)	1.017(0.967,1.070)	0.989(0.949,1.032)	0.977(0.930,1.028)	1.055(0.955,1.165)
71 (P_{25})	0.985(0.887,1.093)	1.018(0.970,1.069)	1.002(0.963,1.042)	0.988(0.942,1.037)	1.033(0.943,1.133)
80 (P_{50})	0.976(0.886,1.076)	0.994(0.946,1.044)	1.016(0.976,1.059)	1.028(0.979,1.080)	0.998(0.910,1.095)
85	0.990(0.961,1.019)	0.996(0.982,1.011)	1.005(0.993,1.017)	1.008(0.994,1.023)	0.996(0.968,1.024)
91 (P_{90})	1.032(0.980,1.087)	1.008(0.982,1.035)	1.007(0.985,1.030)	1.014(0.988,1.040)	1.022(0.974,1.073)
Women (n=1963)					
62 (P_{10})	1.153(1.020,1.304)[a]	1.041(0.989,1.096)	1.011(0.969,1.054)	1.016(0.967,1.069)	1.076(0.975,1.188)
71 (P_{25})	1.148(1.035,1.273)[a]	1.028(0.979,1.080)	1.024(0.984,1.066)	1.047(0.998,1.099)	1.056(0.963,1.158)
80 (P_{50})	1.060(0.963,1.166)	1.022(0.973,1.073)	1.035(0.994,1.078)	1.051(1.001,1.104)[a]	1.022(0.933,1.120)
85	1.007(0.978,1.037)	1.005(0.991,1.020)	1.010(0.998,1.022)	1.013(0.998,1.027)	1.007(0.980,1.035)
91 (P_{90})	1.058(1.006,1.112)[a]	1.004(0.979,1.031)	1.008(0.986,1.031)	1.016(0.990,1.042)	0.980(0.932,1.029)
<65 years old (n=2537)					
62 (P_{10})	1.047(0.942,1.165)	1.029(0.984,1.076)	0.996(0.960,1.033)	0.989(0.947,1.033)	1.089(1.000,1.186)
71 (P_{25})	1.040(0.951,1.138)	1.031(0.988,1.076)	1.006(0.972,1.042)	0.998(0.957,1.040)	1.060(0.979,1.147)
80 (P_{50})	1.022(0.941,1.109)	1.017(0.975,1.062)	1.016(0.980,1.052)	1.016(0.974,1.060)	1.021(0.943,1.104)
85	1.000(0.976,1.026)	1.006(0.993,1.018)	1.006(0.995,1.016)	1.004(0.992,1.017)	1.002(0.978,1.026)
91 (P_{90})	1.049(1.003,1.096)[a]	0.986(0.963,1.009)	0.990(0.971,1.010)	1.012(0.989,1.035)	1.024(0.983,1.067)
≥65 years old (n=1353)					
62 (P_{10})	1.146(0.985,1.332)	1.025(0.962,1.091)	1.001(0.950,1.054)	1.008(0.947,1.073)	1.034(0.915,1.167)
71 (P_{25})	1.123(0.990,1.275)	1.014(0.956,1.076)	1.028(0.980,1.080)	1.063(1.002,1.127)[a]	1.042(0.930,1.166)
Daily average relative humidity(%)	Lag 0 day	Lag 4 days	Lag 7 days	Lag 10 days	Lag 14 days
80 (P_{50})	1.037(0.923,1.165)	1.003(0.945,1.064)	1.057(1.006,1.111)[a]	1.104(1.040,1.171)[a]	1.021(0.914,1.141)
85	1.003(0.968,1.039)	0.996(0.979,1.014)	1.014(0.999,1.028)	1.028(1.011,1.047)[a]	1.010(0.977,1.044)
91 (P_{90})	1.034(0.972,1.100)	1.039(1.008,1.071)[a]	1.035(1.008,1.062)[a]	1.015(0.984,1.046)	0.952(0.894,1.013)
CRR					
Men (n=1927)					
62 (P_{10})	1.012(0.894,1.145)	1.104(0.849,1.436)	1.099(0.810,1.492)	1.031(0.723,1.469)	1.088(0.717,1.651)
71 (P_{25})	0.985(0.887,1.093)	1.037(0.824,1.304)	1.063(0.804,1.405)	1.036(0.747,1.437)	1.069(0.722,1.583)
80 (P_{50})	0.976(0.886,1.076)	0.919(0.730,1.157)	0.944(0.704,1.266)	1.019(0.718,1.447)	1.081(0.701,1.667)
85	0.990(0.961,1.019)	0.962(0.899,1.030)	0.968(0.888,1.054)	0.990(0.894,1.097)	1.000(0.882,1.135)
91 (P_{90})	1.032(0.980,1.087)	1.093(0.963,1.240)	1.115(0.947,1.313)	1.153(0.945,1.406)	1.246(0.979,1.584)
Women (n=1963)					
62 (P_{10})	1.153(1.020,1.304)[a]	1.544(1.184,2.013)[a]	1.628(1.191,2.226)[a]	1.687(1.171,2.433)[a]	2.044(1.323,3.157)[a]
71 (P_{25})	1.148(1.035,1.273)[a]	1.442(1.143,1.820)[a]	1.540(1.155,2.054)[a]	1.727(1.228,2.427)[a]	2.159(1.427,3.265)[a]
80 (P_{50})	1.060(0.963,1.166)	1.185(0.943,1.490)	1.294(0.965,1.735)	1.485(1.045,2.111)[a]	1.738(1.120,2.696)[a]
85	1.007(0.978,1.037)	1.027(0.960,1.099)	1.052(0.966,1.146)	1.090(0.985,1.207)	1.137(1.001,1.291)[a]
91 (P_{90})	1.058(1.006,1.112)[a]	1.130(1.000,1.277)	1.149(0.979,1.349)	1.199(0.985,1.460)	1.197(0.939,1.525)
<65 years old (n=2537)					
62 (P_{10})	1.047(0.942,1.165)	1.233(0.978,1.554)	1.257(0.955,1.654)	1.211(0.877,1.674)	1.403(0.955,2.059)
71 (P_{25})	1.040(0.951,1.138)	1.211(0.990,1.482)	1.265(0.985,1.625)	1.259(0.936,1.693)	1.401(0.979,2.006)
80 (P_{50})	1.022(0.941,1.109)	1.100(0.902,1.343)	1.154(0.893,1.492)	1.209(0.888,1.647)	1.301(0.885,1.912)
85	1.000(0.976,1.026)	1.018(0.960,1.079)	1.036(0.961,1.116)	1.051(0.961,1.149)	1.061(0.949,1.187)
91 (P_{90})	1.049(1.003,1.096)[a]	1.053(0.944,1.175)	1.012(0.875,1.169)	1.024(0.857,1.224)	1.121(0.902,1.394)
Daily average relative humidity(%)	Lag 0 day	Lag 4 days	Lag 7 days	Lag 10 days	Lag 14 days
≥65 years old (n=1353)					
62 (P_{10})	1.146(0.985,1.332)	1.443(1.044,1.995)[a]	1.468(1.005,2.144)[a]	1.485(0.954,2.313)	1.632(0.957,2.784)
71 (P_{25})	1.123(0.990,1.275)	1.304(0.985,1.726)	1.384(0.982,1.951)	1.610(1.073,2.416)[a]	2.032(1.236,3.340)[a]
80 (P_{50})	1.037(0.923,1.165)	1.040(0.790,1.371)	1.160(0.816,1.649)	1.509(0.989,2.302)	1.977(1.166,3.352)[a]
85	1.003(0.968,1.039)	0.983(0.906,1.066)	1.004(0.906,1.113)	1.080(0.955,1.222)	1.177(1.010,1.373)[a]
91 (P_{90})	1.034(0.972,1.100)	1.199(1.032,1.393)[a]	1.337(1.102,1.623)[a]	1.431(1.128,1.814)[a]	1.314(0.978,1.765)

Notes: Compared with the reference relative humidity 87 %.
[a] P < 0.05; RR, relative risk; CRR, cumulative relative risk。.

the heat dissipation of the skin surface, lead to insufficient cooling of the body and various organs [37], and damage multiple organ functions, causing the above effects to be more pronounced [34,37,38,46,49,59], further increasing the risk of HAFs.

In addition, high relative humidity and near-saturation related humidity have a lag and cumulative effect on HAFs, which may be related to the short-term and long-term effects of relative humidity on physiology and psychology. Lepeule J et al. found that high relative humidity leads to decreased lung function within 6 days after relative humidity increase [59]. Lam HC et al. also found that high relative humidity (>82 %) was associated with an increased incidence of pneumonia with a lag of 0–10 days, and the incidence rate of respiratory diseases increased significantly [69]. The effect of increased relative humidity on mental illness is greatest when high relative humidity lags for 0–9 days and lasts for 13 days [46]. The impact of relative humidity on infectious diseases, such as influenza, malaria and dengue fever, may be delayed by 1 month [49]. Zeng et al. found that the effect of high relative humidity on the burden of cardiovascular disease mortality has a lag of 0–21 days [34]. Deng et al. found that the effect of high relative humidity on the mortality rate of cardiovascular disease and stroke typically lasts for a longer period of time [37]. Moreover, Huynh D et al. thought that the visit rate associated with falls increased by 5 % 5–7 days after the onset of high relative humidity weather [70]. These studies indicate that after reaching high relative humidity for a certain period of time, it can still cause lag and cumulative effects, further inducing or exacerbating various diseases, such as respiratory, cardiovascular, infectious diseases and mental disorders, causing discomfort and negative emotions in the human body [36–38,59,60], which may increase the risk of HAFs.

4.2. High relative humidity increased the risk of HAFs in female and older patients

Owing to factors such as physiological structure, the ability to adapt to climate change, and social and economic status, women are more affected by increased relative humidity than men [21,50,71], leading to the occurrence and progression of various diseases mediated by high relative humidity [21,46,50], thereby increasing the risk of HAFs in women. Women are more prone to gait instability owing to weak muscle strength, poor posture control ability, and longer reaction time while walking. In addition, decreased postmenopausal estrogen levels, accelerated bone loss, and intensified osteoporosis resulting in a higher incidence of falls in women than that in men by 1.131–1.4 times [68,72]. When changes in relative humidity are combined with multiple fall risk factors, they may further increase the risk of falls in women.

Older patients aged ≥65 years are at a high risk of falls [13,22,23], which are associated with physiological decline, frailty, coexistence of multiple diseases, decreased mobility and balance ability, cognitive dysfunction, foot diseases, and multiple medications [13,22,23,64–68]. In addition, older hospitalized patients have a weakened response speed, intensity, and ability to respond to external stimuli owing to reduced environmental adaptability, weakened physiological regulation function, and decreased metabolic activity [21], making them more susceptible to changes in high relative humidity environments and inducing or exacerbating multiple diseases [21,38,46,49,50,59], sequentially leading to an increased risk of HAFs. In summary, for clinical fall prevention, medical staff should pay more attention to the impact of high relative humidity environments on HAFs in female and older patients. Health education on preventing HAFs in these two types of patients should be strengthened, and vigilance in preventing falls in high relative humidity weather should be improved.

4.3. Reduced sunshine duration increased the risk of HAFs

The risk of HAFs and sunshine duration were negatively correlated, which is consistent with the findings of Mazzuccchelli R [73]. Kang et al. also found that reduced sunshine duration significantly increased the risk of fractures after falls [74]. Reduced sunshine duration not only reduces vision, but also directly affects the vitamin D and parathyroid hormone levels and has medium-to long-term effects on bone metabolism, which can lead to osteoporosis and bone softening [73,74]. Moreover, sunshine duration is closely related to psychology and emotions. Decrease in sunshine duration can generate or exacerbate negative emotions, such as anxiety and depression, leading to an increased risk of HAFs [36,46].

4.4. Clinical significance of this study

Falls are one of the most common inpatient safety incidents. Although fall-related factors, fall prevention, fall hazards and other issues are still the focus of attention at home and abroad, few reports exist on the impact of meteorological factors on HAFs. This study analyzed fall data and meteorological data from 13 s-level and higher public comprehensive hospitals in Chongqing for over 10 years, and found a non-linear relationship between relative humidity and HAFs, with a significant lag effect between a relative humidity of 65 %–68 % and ≥90 %. Meanwhile, when the relative humidity ranged from 90 % to 97 %, the association with HAFs was strongest at a lag of 0 d. When the relative humidity was within this range, the risk of HAFs on the same day in hospitalized patients increased significantly. Moreover, the increase in relative humidity had a greater impact on female and older patients aged ≥65 years. This finding has significant clinical significance.

First, fall prevention requires combined efforts of individuals, families and society to enhance public health knowledge through health education, improve patients' awareness of fall prevention, and reduce or eliminate environmental risk factors, which can effectively reduce the incidence of falls [24]. Meteorological warnings are essential in public health planning and preventive healthcare [28]. Canada has developed a heat-health watch and warning system that provides alerts of adverse weather in advance, effectively reducing heat-related mortality [75]. Researchers have found that weather warnings can reduce the incidence of fall-related injuries in the elderly [28]. Therefore, public health institutions should pay attention to the impact of meteorological factors, such as relative humidity on falls, improve the public's awareness of meteorological early warning, enhance the ability of public health institutions to respond to meteorological changes, make early use of early warning information to timely launch fall prevention strategies and allocate medical and health resources rationally.

Second, With the development of artificial intelligence, intelligent fall prevention assistance technologies, such as wearable devices and fall warning systems, have provided new tools for fall prevention [22,76]. However, few studies have focused on the importance of humidity in preventing falls. This study suggests that in the future, intelligent fall prevention assistive technology can be equipped with humidity monitoring sensors to monitor humidity in real-time and provide timely warning, helping medical staff to take targeted fall prevention measures early, achieving dynamic and real-time risk warning, which may help reduce the impact of humidity on falls and protect patient safety.

Third, the results of this study suggest that in clinical practice, when relative humidity reaches the above range, medical staff should strengthen the approaches for prevention of falls and pay close attention to the health education of patients and caregivers, especially for female and older patients. Hospitals in the future should set up humidity meters in wards, especially in wards with older people, to improve clinical attention to the effect of relative humidity on falls.

Finally, although guidelines indicating the need to pay attention to environment on falls exist, they have not been specified [22,23]. This study may provide reference for the development of fall intervention guidelines and public health policies.

4.5. Strengths and limitations

Our study has the following strengths: first, meteorological data were obtained from the China Meteorological Science Data Center, which has high authority and credibility. Fall data were collected from 13 hospitals at or above the second level for more than 10 years, covering 11 districts and counties in Chongqing. The volume of data was large and representative to a certain extent. Second, relatively few studies in China, especially a lack of research in Chongqing have focused on the relationship between meteorological factors and HAFs. Our findings may provide a reference for protecting high-risk populations from HAFs and making reasonable public health decisions.

However, our study has some limitations. First, this study directly used the data released by meteorological monitoring stations; thus, measurement errors were inevitable. Second, the patients' underlying diseases may alter their sensitivity to climate change. However, because diseases were not classified according to single diseases in the early preparation of data collection standards, and the data span was long and had uneven levels of information technology across the different hospitals, the lack of relevant data made it impossible to conduct an in-depth subgroup analysis. In addition, DLNM used in this study mainly describes the lagged association between the outcome variable (fall) and exposure factor (daily average relative humidity), that is, the association between the outcome variable y at time t and exposure factor x in the period before time t, and this association can be non-linear. Due to the model limitations, we did not take into account the daytime humidity span and completely exclude the association between daily relative humidity. Finally, although multiple relative humidity ranges were correlated with HAFs under high relative humidity, it was inferred that relative humidity may induce or aggravate related diseases, thereby leading to HAFs, the accuracy of this inference and the mechanism of influence of different relative humidity ranges on HAFs still require further clinical in-depth research.

5. Conclusions

A correlation between hospital-acquired falls and meteorological parameters in the Chongqing area was observed, with the daily average relative humidity being an important factor. In addition, there was a non-linear correlation and lag effect on the occurrence of falls, as well as sex and age differences. Exposure to high relative humidity, particularly near-saturation relative humidity, significantly increased the risk of hospital-acquired falls. All medical institutions should consider fall-related relative humidity changes while formulating fall prevention strategies and implement targeted measures to protect high-risk groups to reduce the incidence of hospital-acquired falls.

Ethics statement

This study was reviewed and approved by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University with the approval number: 2022 Research Ethics [2022-K367], dated August 23, 2022.

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Data availability statement

Data associated with this study have not been deposited into a publicly available repository, since the study participants did not give their permission to make their data publicly available. Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Yuanyuan Ren: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Jinyan Li:** Writing – review & editing, Resources, Data curation. **Jun Yang:** Writing – review & editing, Data curation. **Lei Hu:** Writing – review & editing, Data curation. **Zhihui Xu:** Writing – review & editing, Data curation. **Rongjuan Fu:** Writing – review & editing, Data curation. **Kaihui Wu:** Writing – review & editing, Data curation. **Min Guo:** Writing – review & editing, Data curation. **Mei Hu:** Writing – review & editing, Data curation. **Liu Ran:** Writing – review & editing, Data curation. **Xia Li:** Writing – review & editing, Data curation. **Huicheng Qiu:** Writing – review & editing, Data curation. **Lianmei Liao:** Writing – review & editing, Data curation. **Mengmeng Zhang:** Writing – review & editing, Data curation. **Yetao Luo:** Writing – review & editing, Methodology. **Sumei Zhou:** Writing – review & editing, Supervision, Resources. **Fu Ding:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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