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Relationship between RSV-hospitalized children and meteorological factors: a time series analysis from 2017 to 2023

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Abstract

Objectives: Respiratory syncytial virus (RSV) is a leading cause of hospitalization for lower respiratory tract infections amongst infants under 1 year, posing a significant global health challenge. The incidence of RSV exhibits marked seasonality and is influenced by various meteorological factors, which vary across regions and climates. This study aimed to analyze seasonal trends in RSV-related hospitalization in Tianjin, a region with a semi-arid and semi-humid monsoon climate, and to explore the relationship between these trends and meteorological factors. This research intends to inform RSV prevention strategies, optimize public health policies and medical resource allocation while also promoting vaccine and therapeutic drug development.

Methods: This study analyzed data from a cohort of 6222 children hospitalized with RSV-related infections. Meteorological data were collected from the Tianjin Binhai International Airport meteorological station, encompassing temperature (℃), air pressure (mmHg), wind speed (m/s), humidity (%), and precipitation (mm). We employed seasonal ARIMA and GAM models to investigate the association between meteorological factors and RSV-related hospitalizations.

Results: The SARIMA (1,0,0) (0,1,2)12 model effectively predicted RSV-related hospital admissions. Spearman correlation and GAM analysis revealed a significant negative association between the monthly average temperature and RSV hospitalizations.

Conclusions: Our findings indicated that meteorological factors influence RSV infection-related hospital admissions, with higher monthly average temperatures associated with fewer hospitalizations. The predictive capabilities of the SARIMA model bolster the formulation of targeted RSV prevention strategies, enhancing public health policy and medical resource allocation. Furthermore, continued research into vaccines and therapeutic drugs remains indispensable for augmenting public health outcomes.

Keywords: Respiratory syncytial virus (RSV), SARIMA model, GAM model, Meteorological factors

Introduction

Respiratory syncytial virus (RSV), as a highly contagious pathogen, poses a particularly severe challenge in the field of pediatric health. Nearly all children under the age of two are infected, and it is also considered the main reason for hospitalization of children under 1 year due to acute lower respiratory tract infections [1, 2]. This group is particularly susceptible to RSV, because their immune system has not yet developed completely, and their illness is often severe after infection. Furthermore, RSV is the second leading cause of infant death, highlighting its non-negligible mortality risk [2]. This sobering reality is evident and worldwide, with an estimated 3 million RSV-related hospitalizations and 60,000 deaths among children under 5 years every year [3]. Respiratory syncytial virus infection usually causes acute lower respiratory tract infection, which is mainly characterized by bronchiolitis or pneumonia [4]. These acute infections not only cause immediate acute damage to the lungs but also have long-term health effects. Studies have shown that RSV is an important factor in the development of recurrent wheezing, asthma, or lung function impairment in young children [5]. This means that children who experience RSV infection may have more respiratory health problems later in life.

Meteorological factors play a critical role in the epidemic of respiratory viruses. By affecting the epidemiology and population immunity status of the virus, it can affect the transmission and infection of respiratory viruses [3]. This phenomenon is observed globally but varies significantly across regions. In recent years, several studies have explored the complex interplay between temperature, an environmental factor, and RSV prevalence, revealing that the relationship between them is not a simple linear correlation but shows the characteristics of regional specificity and dynamic changes [4–6]. For example, lower temperature and higher relative humidity may prolong the survival of the virus in the environment while reducing the defense function of the human respiratory mucosa, making it easier for the virus to enter the body. The prevalence of RSV has distinct seasonal characteristics, usually peaking in winter and early spring [7]. This seasonal trend may be affected by a variety of meteorological factors, such as temperature, air pressure, precipitation, wind speed, relative humidity, etc. The Spanish study not only confirmed the close association between RSV hospitalization peak and seasonal transition but also suggested the importance of considering seasonal preventive measures in the formulation of public health policies [7]. The study by Zhang et al. further refined the effect of temperature on RSV activity, highlighting the key role of viral biological characteristics such as lipid encapsulation in environmental adaptation [8, 9]. This finding provides a scientific basis for developing RSV prevention and control strategies that account for environmental factors. It is worth noting that the differences in meteorological factors in different regions and climatic conditions lead to the diversity of RSV epidemic characteristics. The reported inverse relationship between temperature and RSV activity in the subtropical region may reflect reduced viral survival in hot environments and greater social distancing due to increased outdoor activity among the population. However, in tropical regions, due to the complexity and diversity of climate conditions, the relationship between meteorological factors and RSV prevalence may be disturbed by more unknown variables, showing variability and unpredictability [10]. Therefore, detailed epidemiological and meteorological studies in specific areas, combined with big data analysis and model prediction, are the key to accurately formulating RSV prevention

and control strategies and optimizing resource allocation. In addition, attention should be paid to the possible long-term effects of climate change on the prevalence patterns of respiratory viruses to prepare for possible public health challenges in the future.

Since the number of hospitalized children caused by RSV infection showed significant seasonal fluctuations, we used the seasonal autoregressive moving average (SARIMA) model to analyze its autocorrelation and construct a prediction model. The ARIMA (Autoregressive Integrated Moving Average) model is a powerful statistical tool for analyzing and forecasting time series data. It integrates three core components: autoregressive (AR), which uses past values to predict future ones; integrated (I), which addresses non-stationarity by differencing the data to make it stationary; and moving average (MA), which models the relationship between an observation and residual errors from past observations. The SARIMA model can more accurately capture the seasonal components in the time series, making the prediction more accurate. In addition, the generalized linear model has limitations when dealing with non-linear meteorological factors. Therefore, we used the generalized additive model (GAM) to analyze the relationship between meteorological factors and the number of hospitalizations associated with RSV infection. GAM has an outstanding ability to solve nonlinear and non-monotonic relationships between response variables and predictors. Combining the above two models makes our results more accurate and reliable.

The climate type of Tianjin is a warm zone semi-arid semi-humid monsoon climate. According to the Koppen climate classification, Tianjin has four distinct seasons, with rain and heat in the same season, warm and humid in summer, and cold and dry in winter.

We aimed to examine the seasonal variations in the number of hospitalizations associated with RSV infection in Tianjin, a warm-zone city in China. SARIMA and GAM models were used to explore the relationship between the number of RSV infection-related hospitalizations and meteorological factors (monthly average temperature, monthly average pressure, monthly average relative humidity, monthly average precipitation, and monthly average wind speed). This study provides a scientific reference for the prevention and control of RSV in Tianjin and beyond, fostering a broader understanding and application. It serves as a catalyst for the refinement of public health policies and the judicious allocation of medical resources. We hope to reveal the epidemic pattern and risk factors of RSV-related hospitalization to promote the research and development of related vaccines and therapeutic drugs, ultimately enhancing public health outcomes.

Results

During 7 years from 2017 to 2023, a total of 6222 children were hospitalized for RSV-associated infections. The number of RSV-related hospitalizations was lowest in summer and late spring, increased from autumn, and peaked in winter or early spring. During the period from 2017 to 2022, the average wind speed and temperature peaked in July each year, and the number of RSV-related hospitalized children peaked in January of the next year, with a lag coefficient of about June. As for 2023, the first epidemic peak occurred in May when the mean monthly temperature was 21.1 ℃, and the second peak occurred in December when the mean monthly temperature was − 3.1 ℃. The lag coefficients of the effects of precipitation and humidity

on the number of RSV-related hospitalized children were both from April to May. The peak of air pressure and the number of hospitalized children associated with RSV infection seemed to be synchronized, with both trends mirroring each other throughout the year (Figs. 1, 2, 3, 4, 5).

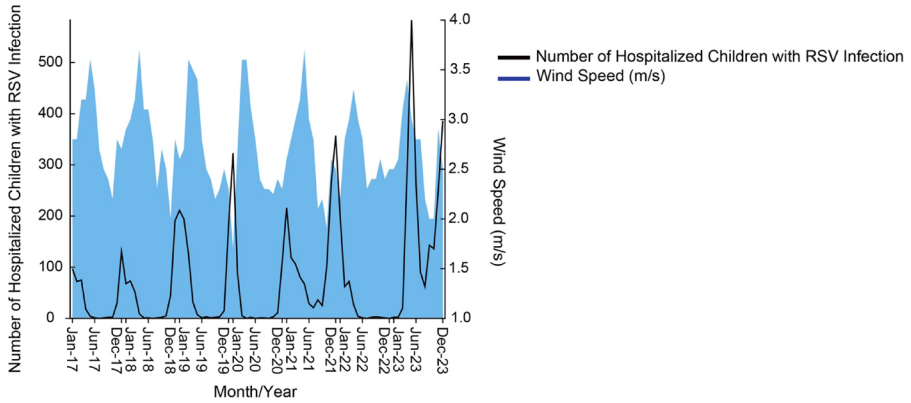

Fig. 1 Relationship between RSV-related hospital admissions and wind speed

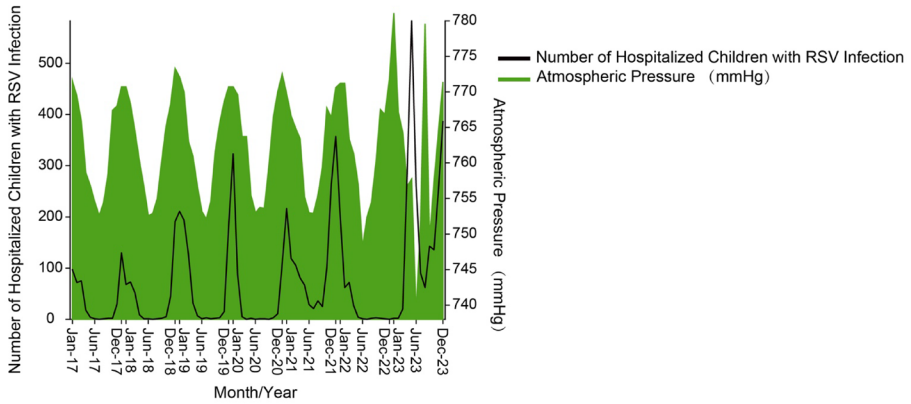

Fig. 2 Relationship between RSV-related hospital admissions and atmospheric pressure

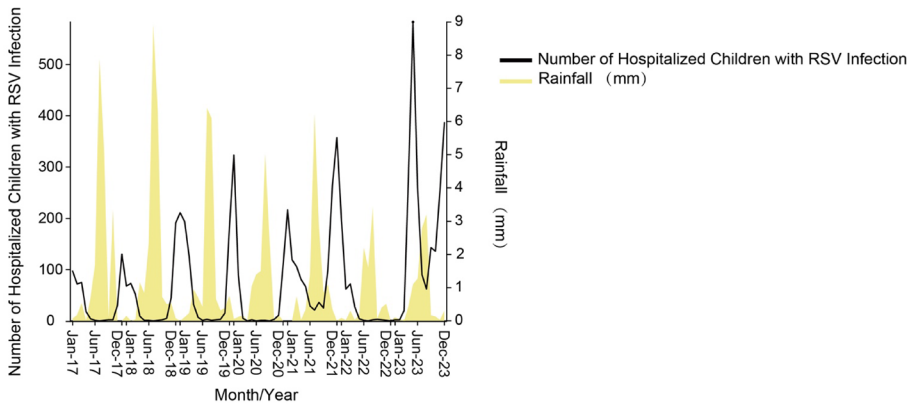

Fig. 3 Relationship between RSV-related hospital admissions and rainfall

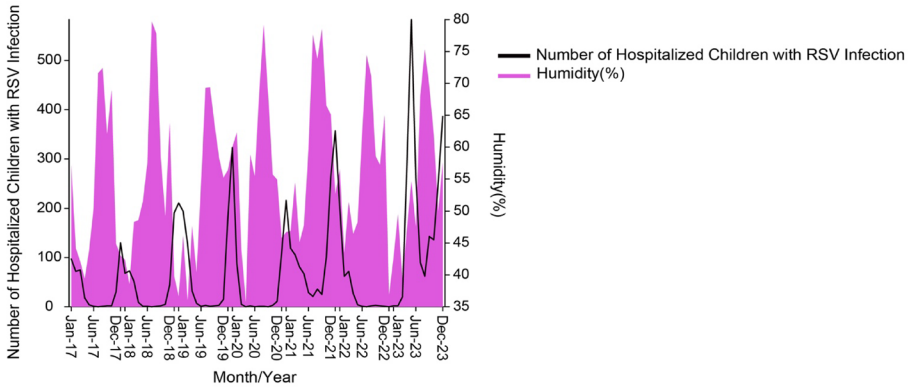

Fig. 4 Relationship between RSV-related hospital admissions and humidity

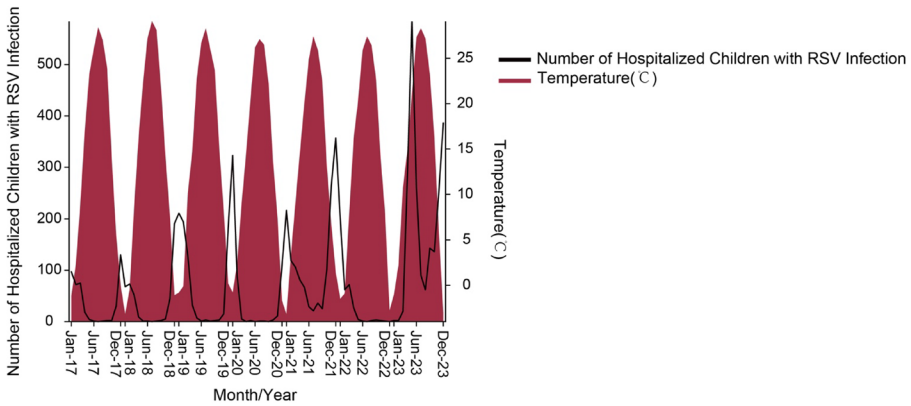

Fig. 5 Relationship between RSV-related hospital admissions and temperature

ARIMA model

The ARIMA model is a robust statistical tool designed for time-series forecasting, enabling predictive modeling based on empirical data. Its seasonal counterpart, SARIMA, incorporates seasonal factors to better capture periodic patterns in the data. By applying first-order seasonal differencing, we achieved a notable stabilization of variability in the data set. The final parameters of the ARIMA (1,1,1) (0,1,0) 12 model were determined using the auto.arima function in R and further refined through manual adjustments informed by the autocorrelation function (ACF) and partial autocorrelation function (PACF) diagrams. This model achieved an $R2$ value of 0.723 and a root mean square error (RMSE) of 27.169. Importantly, the model's projections for pediatric RSV-associated hospitalizations from 2018 to 2023 closely aligned with observed data, validating its predictive accuracy and reliability. As a practical consideration, when predicted values were less than zero, they were rounded to zero to reflect the non-negativity constraint of hospitalization counts (Fig. 6).

Spearman test

A Spearman correlation test was conducted to investigate the association between various meteorological factors and the incidence of RSV-related pediatric hospitalizations.

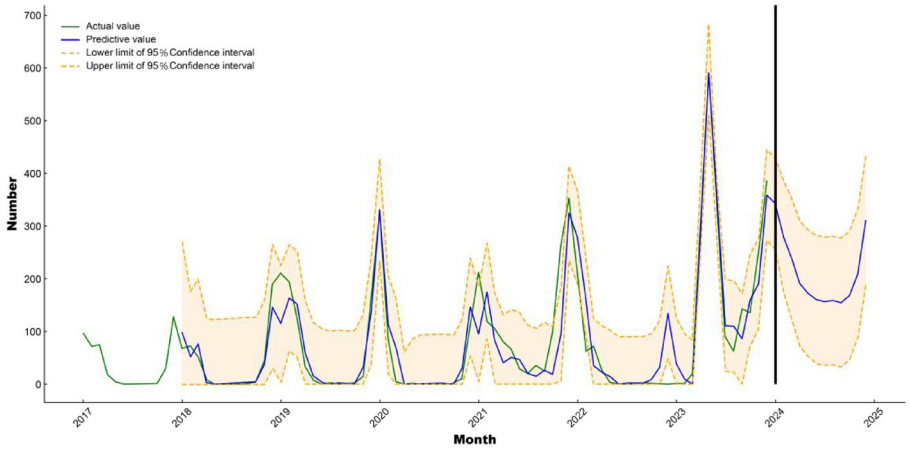

Fig. 6 ARIMA modeling of the number of hospitalized children infected with RSV from 2018 to 2023

Table 1 Spearman test

	Lag0	Lag1	Lag2	Lag3	Lag4
Pressure (mmHg)	0.450*	0.499*	0.364*	0.189	− 0.048
Humidity (%)	− 0.304*	− 0.189	0.040	0.217	− 0.344
Wind Speed (m/s)	0.035	− 0.207	− 0.426*	− 0.513*	− 0.469*
Temperature (℃)	− 0.549*	− 0.508*	− 0.329*	− 0.075	− 0.201
Precipitation (mm)	− 0.431*	− 0.406*	− 0.203	− 0.029	− 0.196

Lag0–4: The "Lag" values represent the time delay (in months) between the meteorological variables and the RSV-related hospitalizations. Specifically, "Lag0" refers to the current month's data, while "Lag1," "Lag2," "Lag3," and "Lag4" correspond to data from the previous 1, 2, 3, and 4 months

* Correlation is significant at the 0.01 level (two-tailed)

The results revealed that all meteorological variables exhibited a significant relationship with the number of RSV-associated pediatric admissions. Specifically, monthly mean relative humidity, monthly mean temperature, and monthly mean precipitation demonstrated a synchronized pattern with the number of RSV-related hospitalizations. All meteorological factors appeared to be associated with the number of children hospitalized with RSV infection. Monthly mean relative humidity, monthly mean temperature, and monthly mean precipitation were synchronized with the number of children admitted to the hospital related to RSV. The monthly mean air pressure with a month lag and monthly mean wind speed with a month lag showed a close correlation with the number of children hospitalized with RSV. A comprehensive analysis of all meteorological factors at Lag0 indicated that, apart from monthly mean wind speed, which showed no discernible correlation, the other meteorological variables displayed a strong correlation with the number of RSV-related inpatients, with substantial correlation coefficients (Table 1).

GAM model

Utilizing Spearman's test to evaluate the optimal lagged month values, we identified Lag0 as the most appropriate. GAM analysis was performed under the Lag0 condition. The univariate analysis revealed a certain degree of correlation between the monthly

average pressure, temperature, and precipitation and the number of RSV-related hospitalizations. However,

However, upon conducting a multivariate analysis, only the monthly average temperature emerged as a significant predictor of the number of RSV-related hospitalizations, suggesting potential collinearity among the other factors (Table 2).

Discussion

In this study, we used two time-series models and Sperman's test with different lag coefficients to examine the association between meteorological factors and hospitalizations associated with RSV infection. The generalized additive model (GAM) combined with Spearman test data revealed a significant negative correlation between seasonal RSV prevalence and temperature. This finding implies that hospitalization rates due to RSV infection showed an increasing trend with decreasing temperatures, further supporting the hypothesis that cold environments may act as one of the drivers of RSV transmission and increased disease severity. It is particularly noteworthy that this negative correlation peaked when we set the lag coefficient to 0, that is when we examined the immediate relationship between meteorological factors and the number of hospitalizations of children with RSV infection. This result emphasizes the critical role of immediate meteorological conditions, especially temperature, in predicting and controlling seasonal RSV epidemics.

Respiratory syncytial virus (RSV) is one of the leading pathogens of acute lower respiratory tract infection in children, and its epidemiological characteristics are significantly affected by seasonal variation. Specifically, in subtropical regions, the peak of RSV epidemics often follows cold climates in winter or early spring, a finding that strongly suggests that lower temperatures may be one of the important factors promoting the transmission and prevalence of RSV in these regions [7, 8]. These studies pointed out the negative relationship between temperature and RSV prevalence through statistical analysis, that is, as the temperature decreased, the RSV infection rate increased, which is consistent with the phenomenon observed in this study in a specific period, such as 2017–2022 [11, 12]. In the tropics, RSV epidemic patterns no longer simply follow a unidirectional effect of temperature because of relatively small temperature variations throughout the year. Studies in these regions have shown that there may be a more complex interaction between RSV activity and temperature, including but not limited to

Table 2 Respiratory syncytial virus detection rate according to meteorological factors using generalized additive models (Lag0)

Variable	Univariate analysis			Multivariate analysis		
	df (freedom)	*F*	*P*	df (freedom)	*F*	*P*
Monthly average atmospheric pressure (mmHg)	6.447	3.05	0.00862	2.291	2.657	0.056344
Monthly average relative humidity (%)	2.148	2.035	0.139			
Monthly average wind speed (m/s)	4.588	1.387	0.276			
Monthly average air temperature (°C)	1.344	13.05	0.000369	1.000	12.212	0.000782
Average monthly precipitation (mm)	1	6.441	0.013	1.000	0.067	0.796697

df: degrees of freedom; *F*: test statistic for the analysis of variance (ANOVA); *P*: significance level

the combined effects of other meteorological factors, such as temperature fluctuation, humidity, rainfall, etc., which makes the peak of RSV epidemic no longer limited to a specific temperature range, but shows a diversified time distribution [13]. In this study, the prevalence of RSV from 2017 to 2022 peaked in January, and there was only one peak in the whole year, but there were two peaks in 2023. This finding not only challenges the previous understanding of the single relationship between temperature and RSV epidemic but also suggests that in addition to temperature, other underrecognized factors (such as virus mutation, changes in population immune status, and adjustment in social behavior patterns, etc.) may play an important role in the epidemic of RSV. In particular, the occurrence of the May peak in a relatively warm environment with a mean monthly temperature of 21.1℃, further emphasizes the complexity and variability of the relationship between temperature and RSV prevalence. In addition, similar research results have been reported in the literature, that is, in some years or regions, the prevalence of RSV will show two or more peaks in different periods of the year, corresponding to different temperature levels [10]. These findings together point to an important conclusion that the relationship between temperature and RSV prevalence is far from static or unidirectional but is regulated by a variety of environmental, ecological, and social factors. More detailed and comprehensive monitoring and research are needed to reveal the dynamic changes.

In the univariate analysis of the time series model GAM (generalized additive model), the monthly average rainfall, as one of the important meteorological variables, showed a significant correlation with the prevalence of RSV. This finding further enriches our understanding of the drivers of RSV epidemics, particularly in terms of how meteorological conditions affect virus transmission and disease occurrence in natural Settings. At present, many studies have focused on the association between acute lower respiratory tract infections, including infections caused by RSV and precipitation. These studies generally pointed out that changes in precipitation can directly or indirectly affect air humidity, dust suspension, population activity patterns, and other aspects, thus affecting the incidence of respiratory infections [14]. Studies in several tropical regions have consistently shown that increased precipitation in these regions is often accompanied by an increase in RSV prevalence, showing a significant positive relationship [15, 16]. This may be due to precipitation promoting virus survival and spread in the environment or indirectly promoting virus spread through changes in population behavior, such as increased indoor activity. However, humidity, another meteorological factor closely related to precipitation, has shown a more complex and unclear relationship in affecting RSV prevalence. In temperate climates, higher humidity is generally considered to be beneficial for RSV survival and transmission and thus positively correlated with RSV prevalence [17], but in tropical and subtropical regions, the effect of humidity appears to be more variable. Some studies have shown that the prevalence of RSV increases with the increase in humidity, while others have come to the opposite conclusion or found no significant correlation between them [18, 19]. This difference may result from the difference in the range of humidity variation in different climate regions, the difference in the adaptability of the population to humidity variation, and the complex interaction between humidity and other meteorological factors, such as temperature and wind speed.

The transmission and spread of RSV are deeply affected by the complex and changeable natural environment, such as meteorological factors, and is also closely related to the implementation of human-made strategies, such as non-pharmaceutical interventions. Due to the characteristics of respiratory syncytial virus itself, it is easier to survive, replicate, and spread in lower temperature conditions. Lower temperatures promote the stability and survival time of viral particles, which in turn accelerates transmission in susceptible populations. In addition to temperature, humidity, and precipitation were also key factors affecting the epidemic pattern of RSV. Moderately increased humidity may promote the suspension time of virus particles in the air, while frequent precipitation may indirectly affect the efficiency of virus transmission by changing population behavior and aggregation patterns. The epidemic trend in 2023 was inconsistent with the previous data, and the implementation of nonpharmaceutical interventions in 2023 May have had some impact. For example, wearing masks, maintaining social distancing, and strengthening personal hygiene practices can significantly reduce the risk of virus exposure in the population, thereby changing the epidemic trajectory of the virus. Meteorological factors and non-pharmaceutical interventions have a particularly significant impact on children. As a high-risk group for RSV infection, children's immune system is still in the development stage, and their resistance to the virus is relatively weak. At the same time, children's activity patterns and social behaviors make it easier for them to congregate in group Settings, further increasing the risk of virus transmission. Therefore, changes in meteorological conditions and the implementation of non-pharmaceutical interventions not only directly affect the health status of children but also may indirectly regulate the prevalence of RSV by regulating the response-ability and behavior pattern of their immune system.

Palivizumab is currently approved for the prevention of respiratory syncytial virus in high-risk children (e.g., children with congenital heart disease and preterm birth < 29 weeks) [20, 21]. This move significantly reduced the risk of RSV-associated severe lower respiratory tract illness, such as bronchiolitis and pneumonia, in this susceptible group of children, thereby improving their health outcomes and quality of life. However, it is worth noting that although the international acceptance and application of palivizumab has made significant progress, this drug has not yet been approved for clinical use in China, which to some extent limits the access of high-risk children in China to this effective preventive tool. At the same time, although several candidate vaccines against RSV are under intense research and development and clinical trials worldwide, aiming to fundamentally prevent RSV infection through immunization, no vaccine can fill this gap, including those vaccines that have been approved for use in foreign countries have not yet been licensed in the Chinese market [22]. Therefore, more efforts have to be focused on non-pharmaceutical interventions to contain the spread of RSV. These measures include but are not limited to strengthening public health education to improve the awareness and prevention of RSV infection. Environmental cleaning and disinfection should be strengthened, especially in medical institutions, kindergartens, families, and other places, where susceptible populations gather. Implement effective infection control measures, such as wearing masks, hand washing, and social distancing, to reduce the chance of transmission of the virus. For patients with confirmed or

suspected RSV infection, the strategy of timely isolation and treatment should be taken to control the spread of the epidemic.

Based on the analysis of the number of children admitted to the hospital due to meteorological factors and RSV-related infection from 2017 to 2023 in Tianjin, China, we found that the seasonality of children admitted to the hospital due to RSV-related infection was closely related to temperature. With the change of season, especially when the temperature dropped to lower levels, the hospitalization rate due to RSV infection increased significantly, indicating that a low-temperature environment may be one of the important factors promoting the transmission of RSV and aggravating the disease. The SARIMA model constructed in this study can provide prospective data support for medical staff, hospital administrators, and public health authorities to help them plan and adjust their response strategies in advance to ensure that they can respond quickly in periods of high incidence of RSV infection, effectively relieve the pressure on the medical system, and ensure that children receive timely and effective treatment.

Limitation

This study has certain limitations. Children hospitalized for RSV-related infection in Tianjin Children's Hospital from 2017 to 2023 were selected in this study. During this period, economic conditions, family living environment, and educational level of children were recognized as important factors that can significantly affect access to medical care resources and the spread of RSV infection [23]. Non-pharmaceutical interventions due to the spread of SARS-COV-19 in 2023 also had a notable impact on the transmission of RSV. These measures effectively restricted the movement and aggregation of people, thereby objectively blocking the main transmission route of respiratory viruses, such as RSV, which adds complexity to the interpretation of our results. In addition, studies have shown that air pollution has a certain impact on the prevalence of RSV [24]. However, air pollution in Tianjin was relatively controllable during the sample collection period and did not reach the level that significantly affected the transmission of RSV. Therefore, air pollution was not included in the analysis framework as a core variable at the beginning of the design of this study. While this decision was grounded in real-world data, it also suggests that this study may have a limited scope in exploring the multifaceted mechanisms underlying RSV infections.

Materials and methods

Study population

The cohort for this study included hospitalized children for RSV-related diseases in Tianjin Children's Hospital from January 1, 2017 to December 31, 2023. Inclusion criteria: 1: nasopharyngeal swab RSV antigen test positive; 2. age: 0–18 years.

Data collection

We collected the Tianjin Binhai International Airport (Tianjin Binhai International Airport, IATA: it passes, ICAO: ZBTJ) (north latitude, 39.126976 and 117.362141 east longitude) weather stations. Data on temperature (℃), air pressure (mmHg), wind speed (m/s), humidity (%), and precipitation (mm) were downloaded from http://rp5.ru.com.

Statistical analysis

To account for potential non-linear relationships between meteorological factors and RSV-related hospitalizations, we employed the Generalized Additive Model (GAM). For the smoothing function and associated parameters, we used the default settings from the "mgcv" package in R. These defaults are widely adopted in similar analyses and are well-suited for capturing non-linear relationships in the data. Variable selection was based on a prior Spearman correlation analysis, which identified variables significantly correlated with RSV-related hospitalizations. The degrees of freedom for the smooth terms were also set using the default options in "mgcv," a common approach in similar studies. This choice was made to ensure the robustness of the model, as these default settings are designed to strike a balance between model complexity and fit. In addition, this approach serves as a simple sensitivity analysis, ensuring that the results are not unduly influenced by specific model parameters. Monthly meteorological factors, including mean temperature (°C), air pressure (mmHg), wind speed (m/s), relative humidity (%), and precipitation (mm), were included as independent variables in the models. The analysis was performed using the ARIMA model to assess seasonal changes in hospitalizations, along with Spearman's test and both univariate and multivariate GAM analyses to account for potential non-linear effects of meteorological factors on RSV-related hospitalizations. All data analyses were conducted using SPSS 27.0 and R 2023.12.1 software.

Author contributions

S. W. wrote the first draft. Y. W. analyzed and interpreted the patient data. Y. Z. and C. Y. was major contributors in reviewing and editing the manuscript. All authors gave final approval of the version to be submitted and any revised version.

Funding

This study was funded by Tianjin Municipal Health Commission Key Discipline Special Fund (TJWJ2022XK038) and Tianjin Key Medical Discipline (Specialty) Construction Project (No.TJYXZDXK-040A).

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethic Committee of the Tianjin Children's Hospital (No. 022-LXKY-004). All procedures performed in the studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 31 October 2024 Accepted: 20 January 2025
Published online: 05 February 2025

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