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Original Research

Influence of meteorological factors and air pollution on the outbreak of severe acute respiratory syndrome

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Severe acute respiratory syndrome (SARS)

Summary *Objectives:* To understand the association between the outbreak of severe acute respiratory syndrome (SARS) and meteorological factors and air pollution.
Study design: An ecological study was conducted.
Methods: Three hundred and fifty primary probable SARS cases diagnosed in mainland China between 1 January and 31 May 2003, and their 6727 close contacts during the period of their clinical symptoms before admission, were included in this study. Of the 6727 close contacts, 135 (2.0%) later developed clinical symptoms and were diagnosed as probable SARS cases. The daily meteorological data and daily air pollution data during the same SARS outbreak period in mainland China were used in the data analysis. Logistic regression analyses were conducted to explore the association between the secondary attack rate of SARS and meteorological factors and air pollution.
Results: In univariate analyses, daily average temperature (DAT), daily average air pressure (DAAP), and daily average relative humidity (DARH) were inversely associated with secondary attack rate ($P<0.001$); a significant positive association was found for daily hours of sunshine (DHS) ($P<0.001$). In multivariate analyses, factors associated with secondary attack rate were DAAP (odds ratio (OR) = 0.53,

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95% confidence interval (CI): 0.42, 0.66), DARH (OR = 0.73, 95% CI: 0.53, 1.00), and daily average wind velocity (DAWV; OR = 0.81, 95% CI: 0.68, 0.96). Adjustment for the onset time of a primary case led to little change in the results. In addition, in Hebei Province, a major affected area in China, only DAWV (OR = 0.38, 95% CI: 0.20, 0.72) was a significant predictor of secondary attack rate with adjustment for the onset time of primary case. In Inner Mongolia, another major affected area in China, DAWV (OR = 0.50, 95% CI: 0.26, 0.94) and DHS (OR = 0.27, 95% CI: 0.09, 0.81) were significant predictors of secondary attack rate with adjustment for the onset time of primary case.

Conclusions: Our results suggest that the SARS outbreak was significantly associated with DAWV, and that DAAP, DARH and DHS may also have influenced the SARS outbreak to some extent. However, because of ecological fallacy and uncontrolled confounding effects that may have biased the results, the association between the SARS outbreak and these meteorological factors and air pollution deserve further investigation.

Introduction

More than two years after the severe acute respiratory syndrome (SARS) outbreak of 2003, the devastating impact of the spring 2003 emergence is still fresh in the minds of the public health authorities. As most established respiratory pathogens of human beings such as human coronavirus 229E and OC43 recur in wintertime,[1,2] it is an important public health issue whether SARS, which is a respiratory infectious disease caused by SARS-associated coronavirus (SARS-CoV), will follow the pattern of other respiratory viruses and reappear sometime. Furthermore, reports of four confirmed SARS cases in China's Guangdong Province in the winter of 2003–2004 prompted widespread speculation that SARS was making a seasonal resurgence.[1,3]

The potential sources of SARS resurgence include the natural animal reservoir, laboratory spillage, and an undetected low level of human infection.[4] Since some SARS cases shed detectable SARS-CoV RNA in their stools for at least nine weeks following recovery,[5] and the source or sources of the 2004 SARS viruses have not been definitively established,[1] recurrence of SARS from persistently shedding human or animal reservoirs is biologically plausible. If SARS behaves like newly emergent zoonotic diseases such as ebola or pandemic strains of influenza, it may be difficult to predict when, or if, it will re-emerge.[1] Therefore, an enhanced understanding of the determinants of the SARS outbreak, which will help public health officials to make better public health decisions to control a future outbreak, still assumes great importance.

Although there has been striking progress in the science of SARS, our understanding of the impact of weather or climate on a SARS outbreak remains fragmentary. In 2003, the SARS outbreaks in Vietnam and Guangzhou were brought under control earlier than in Hong Kong. The argument that Vietnam and Guangzhou controlled the outbreaks by better medical facilities and hygienic standards is unconvincing.[6] Anecdotal reports suggest that changes in temperature may have been a contributing factor. The wider use of heaters in Toronto and air conditioning in Hong Kong and Singapore, usually to keep the room temperature within 18–22 °C, may have contributed to the long-lasting outbreak in these developed cities.[6] There have been some studies reporting an association between the SARS outbreak and meteorological factors and air pollution.[3,7–12] However, these studies have largely been inconclusive. In fact, they use public data on SARS morbidity to obtain the daily reported number of probable SARS cases instead of the true daily onset number. Apparently, the results they obtained from the public data were doubtful due to time-delays and chaos in case reporting. In addition, as the designs in these studies focused on the relationship between the absolute daily number of SARS cases and meteorological factors, the results were greatly biased by the size of population in the affected areas. Therefore, no acceptable results up to now have been obtained concerning the association between the SARS outbreak and meteorological factors and air pollution.

From the epidemiological triangle, the agent must be capable of infecting the host for infection to develop and this depends on whether the environment is favourable for its survival and transmission, and it also depends on the susceptibility of the host.[13] Meteorological factors and air pollution may have influenced the trends of the SARS outbreak by changing the host susceptibility and the survival time of SARS-CoV in vitro.[1,14–16] Therefore, changes in meteorological factors and air pollution may be reflected in the variation of the secondary attack rate before admission of the primary SARS cases.

In this paper, the actual onset data of SARS were used to explore the association between secondary attack rate before admission of the primary SARS cases and meteorological factors and air pollution. This will help us to understand the roles that meteorological factors and air pollution played in the 2003 SARS outbreak and thus provide significant information for the prevention and control of any future SARS outbreak.

Methods

A total of 365 primary probable SARS cases diagnosed in mainland China between 1 January and 31 May 2003, and their 7357 close contacts during the period of their clinical symptoms before admission, were initially identified and screened. This was carried out using individual survey databases of probable SARS cases and close contacts, main transmission chains of SARS in important affected areas, and the medical records of SARS cases in some designated hospitals. The criteria for SARS diagnosis were consistent with the criteria from the Ministry of Health of the People's Republic of China for diagnosing infectious atypical pneumonia. The definition of SARS close contacts conformed to the Ministry of Health of the People's Republic of China criteria for determining close contacts of infectious atypical pneumonia. The histories of close contacts were confirmed by telephone interviews. All interviews were tape-recorded and checked by quality control staff to monitor the quality of the interview data. Of the 365 primary probable SARS cases, 15 cases (4.1%) were excluded from the present study due to unreliable information, and 350 cases (95.9%) and their 6727 close contacts during the periods of their clinical symptoms before admission were included. There were no significant differences in age and gender between the excluded and included primary cases.

All included primary cases were statistically independent. Of the 6727 close contacts, 135 (2.0%) later developed clinical symptoms and were diagnosed as probable SARS cases. The secondary attack rate of each primary case before admission was estimated by dividing the number of secondary cases that were generated by the primary case before admission, by the number of close contacts before admission of the primary case. In this study, as no active intervention measures against the primary cases such as case isolation were taken before admission, the variation of secondary attack rate before admission of the primary case may have resulted from impact of the meteorological factors and air pollution on the SARS outbreak. Therefore, this type of secondary attack rate was used as a dependent variable in the data analysis.

For each primary case, corresponding average values for meteorological variables and the air pollution variable between onset date and admission date were computed by means of arithmetic mean and used in the data analysis. The daily meteorological data, including daily average temperature (DAT), daily average relative humidity (DARH), daily average air pressure (DAAP), daily average wind velocity (DAWV), and daily hours of sunshine (DHS), were obtained from the National Meteorological Centre of China. The daily air pollution data were provided by the Chinese National Environmental Protection Agency (CNEPA). Air pollution was evaluated by the air pollution index (API).[17,18] CNEPA calculates individual pollution indices for five major air pollutants, including particulate matter, sulphur dioxide, nitrogen dioxide, ground-level ozone, and carbon monoxide. The maximal individual pollution index was set as the comprehensive API for the monitoring area. In most monitoring areas, particulate matter was considered as a major pollutant.

Logistic regression analyses were conducted to explore the association between secondary attack rate before admission of the primary case and the meteorological factors and air pollution. Univariate logistic regression models were initially used to identify potential risk factors for the SARS outbreak in these data. Factors assessed included DAT, DARH, DAAP, DAWV, DHS, and API. The multivariate logistic regression model included all above-mentioned factors.

During a calendar year, meteorological conditions are correlated with time. Knowledge of SARS increased over time during the year, and therefore individuals and communities may have taken more effective action to protect themselves, even if they were not specifically quarantined. Thus, the time variable, i.e. the onset time of a primary case, was a potential confounding factor and was further included in multivariate analyses. Since 21 April 2003 was an important date for the control of the SARS outbreak in China, when the State Council began to disseminate daily epidemic information and many major intervention measures were commenced in order to control the outbreak, we used it as a cut-off point. In multivariate analyses, the time variable took a value of 1 when onset date of a primary case was after 21 April 2003, and 0 otherwise.

As cases of a directly transmitted infectious disease are clustered in space as well as time, and meteorological variables are also clustered in space and time, the space variable, i.e. affected area that a primary case was from, was also a potential confounding factor. Therefore, we further selected two major affected areas in China, Hebei Province and Inner Mongolia, to perform multivariate logistic regression analyses.

The regression models included all meteorological variables and the API variable with adjustment for the time variable. A P-value of less than 0.05 was considered significant. All P-values were two-sided. Statistical analyses were performed using SAS version 8.1 software (SAS Institute, Inc., Cary, North Carolina, USA).

Results

A total of 350 primary SARS cases from 22 Chinese provinces were included in this study. Table 1 presents the descriptive statistics of their corresponding meteorological variables and the air pollution variable.

Univariate logistic regression results are presented in Table 2. DAT (odds ratio (OR) = 0.71, 95% confidence interval (CI): 0.60, 0.86; $P<0.001$), DAAP (OR = 0.57, 95% CI: 0.50, 0.65; $P<0.001$), and DARH (OR = 0.60, 95% CI: 0.50, 0.71; $P<0.001$) were inversely significantly associated with secondary attack rate. In addition, a significant positive association was found for DHS (OR = 1.38, 95% CI: 1.15, 1.64; $P<0.001$).

In multivariate logistic regression analysis (Table 3), factors independently associated with secondary attack rate were DAAP (OR = 0.53, 95% CI: 0.42, 0.66; $P<0.001$), DARH (OR = 0.73, 95% CI: 0.53, 1.00; $P = 0.047$), and DAWV (OR = 0.81, 95% CI: 0.68, 0.96; $P = 0.014$). The time variable, i.e. onset time of a primary case, was considered as a potential confounding factor. Adjustment for the time variable led to little change in the results.

The space variable, i.e. affected area that a primary case was from, was also considered as a potential confounding factor. To avoid the potential confounding effect from the space variable, we further selected two major affected areas in China, Hebei Province and Inner Mongolia, to repeat the multivariate logistic regression analyses. The regression models included all meteorological variables and API variable with adjustment for the time variable (Table 4).

In Hebei Province, a total of 135 primary probable SARS cases and their 2856 close contacts during the period of their clinical symptoms before admission were included in the data analysis. Of the 2856 close contacts, 44 (1.5%) later developed clinical symptoms and were diagnosed as probable SARS cases. Only DAWV (OR = 0.38, 95% CI: 0.20, 0.72; $P = 0.003$) was found to be a significant predictor of secondary attack rate with adjustment for the time variable.

In Inner Mongolia, a total of 65 primary probable SARS cases and their 698 close contacts during

Table 1 Descriptive statistics of the meteorological variables and air pollution variable for 350 primary SARS cases included in this study; People's Republic of China, 2003.

Variable	Mean (SD)	Minimum	Maximum
Daily average temperature (DAT, °C)	17.47 (4.56)	3.73	29.20
Daily average air pressure (DAAP, kPa)	96.54 (5.11)	80.55	102.09
Daily average relative humidity (DARH, %)	61.11 (18.01)	22.00	96.80
Daily average wind velocity (DAWV, m/s)	2.13 (0.89)	0	7.00
Daily hours of sunshine (DHS, h)	6.12 (3.31)	0	12.40
Air pollution index (API)	87.90 (25.26)	34.33	260.25

SD, standard deviation.

Table 2 Univariate logistic regression results for the association between secondary attack rate before admission and meteorological factors and air pollution; People's Republic of China, 2003.

Risk factor	OR	95% CI	*P*-value
Daily average temperature (DAT)	0.71	0.60, 0.86	<0.001
Daily average air pressure (DAAP)	0.57	0.50, 0.65	<0.001
Daily average relative humidity (DARH)	0.60	0.50, 0.71	<0.001
Daily average wind velocity (DAWV)	0.91	0.77, 1.07	0.267
Daily hours of sunshine (DHS)	1.38	1.15, 1.64	<0.001
Air pollution index (API)	0.99	0.85, 1.17	0.949

OR, odds ratio; CI, confidence interval.

Table 3 Multivariate logistic regression results for the association between secondary attack rate before admission and meteorological factors and air pollution; People's Republic of China, 2003.

Risk factor	OR	95% CI	Time variable adjusted OR	95% CI
Daily average temperature (DAT)	1.03	0.82, 1.30	1.20	0.91, 1.58
Daily average air pressure (DAAP)	0.53	0.42, 0.66	0.50	0.40, 0.64
Daily average relative humidity (DARH)	0.73	0.53, 1.00	0.71	0.51, 0.97
Daily average wind velocity (DAWV)	0.81	0.68, 0.96	0.80	0.67, 0.95
Daily hours of sunshine (DHS)	0.83	0.62, 1.12	0.80	0.59, 1.09
Air pollution index (API)	0.88	0.76, 1.02	0.88	0.76, 1.01

OR, odds ratio; CI, confidence interval.

Table 4 Multivariate logistic regression results for the association between secondary attack rate before admission and meteorological factors and air pollution in Hebei Province and Inner Mongolia; People's Republic of China, 2003.

Affected area	Risk factor	Time variable adjusted OR	95% CI	*P*-value
Hebei Province	Daily average temperature (DAT)	1.43	0.67, 3.04	0.355
	Daily average air pressure (DAAP)	0.48	0.21, 1.10	0.082
	Daily average relative humidity (DARH)	1.29	0.58, 2.89	0.529
	Daily average wind velocity (DAWV)	0.38	0.20, 0.72	0.003
	Daily hours of sunshine (DHS)	1.38	0.74, 2.58	0.306
	Air pollution index (API)	0.96	0.57, 1.63	0.890
Inner Mongolia	Daily average temperature (DAT)	1.42	0.41, 4.96	0.582
	Daily average air pressure (DAAP)	0.49	0.15, 1.61	0.240
	Daily average relative humidity (DARH)	0.26	0.06, 1.03	0.055
	Daily average wind velocity (DAWV)	0.50	0.26, 0.94	0.031
	Daily hours of sunshine (DHS)	0.27	0.09, 0.81	0.019
	Air pollution index (API)	0.79	0.27, 2.27	0.655

OR, odds ratio; CI, confidence interval.

the period of their clinical symptoms before admission were included in the data analysis. Of the 698 close contacts, 48 (6.9%) later developed clinical symptoms and were diagnosed as probable SARS cases. The multivariate analysis results showed that DAWV (OR = 0.50, 95% CI: 0.26, 0.94; $P = 0.031$) and DHS (OR = 0.27, 95% CI: 0.09, 0.81; $P = 0.019$) were significant predictors of secondary attack rate with adjustment for the time variable.

Discussion

In view of the fact that most established respiratory pathogens of human beings such as human coronavirus 229E and OC43 are seasonal,[1,2] and the 2003 SARS outbreak waned when the weather turned warmer, it is commonly speculated that meteorological conditions may have influenced the 2003 SARS outbreak. However, it is not clear to what extent this is true. Previous attempts to explore the association between the SARS outbreak and meteorological factors and air pollution have largely been inconclusive.[3,7–12]

In the present study, the secondary attack rate before admission of the primary case, whose variation may have resulted from the impact of meteorological factors and air pollution, was used as a dependent variable instead of the daily reported number of SARS cases. Further, the actual onset data rather than the reported data were used to explore the association between secondary attack rate before admission of the primary SARS cases and the meteorological factors and air pollution. The results of this study indicate that secondary attack rate before admission of the primary case was significantly inversely associated with DAWV, and that DAAP, DARH and DHS may also influence the SARS outbreak to some extent. We believe that our results should be of sufficient reliability.

A report from the World Health Organization maintains that short distance droplet transmission is the main transmission route of SARS.[19] When a contagious individual coughs or sneezes, sputum droplets containing infectious particles (SARS-CoV) are released. On average, droplets are about 3 microns in diameter and, when inhaled, are capable of bypassing the protective mechanisms of the upper respiratory tract, causing infection. Droplets of 3 microns in size can stay in the air for 3 h.[20] Wind is an important environmental parameter with respect to the suspending time of droplets in the air. In the outdoor environment, high wind velocity facilitates dilution and removal of the droplets and shortens their suspending time in the air, thus reducing the transmission potential. In the indoor environment, higher wind velocity usually means better ventilation for the same room. During the Toronto outbreaks of SARS, SARS-CoV RNA was detected in air samples that were obtained from the room occupied by a patient with SARS.[21] The viral load of the room air could be affected by ventilation. When ventilation was good, the number of infected people became smaller, and the infection rate became lower.[22] Our results are consistent with these findings. In this study, we found that higher DAWV corresponded to a lower secondary attack rate before admission of the primary case. All the findings suggest that ventilation may be an effective intervention measure on the prevention and control of a SARS outbreak.

Relative humidity is defined as the ratio of the water vapour content of the air to its total capacity at a given temperature. It is generally believed that the survival of enveloped viruses on inanimate surfaces is favoured when relative humidity levels are below 50%.[23] Since SARS-CoV is an enveloped virus,[24] it may be more stable in dry air. In this study, both univariate analysis and multivariate analysis showed that DARH was inversely associated with secondary attack rate. The results indicate that lower DARH corresponds to a higher secondary attack rate, which is consistent with our speculation. In addition, a high relative humidity level may shorten the suspending time of SARS-CoV in the air, as well as high wind velocity. However, after adjustment for affected area, we found that DARH did not appear to have played a role in SARS-CoV transmission. As this finding results from investigations in only two affected areas, further studies need to be conducted.

As with wind velocity and relative humidity, high air pressure may shorten the suspending time of SARS-CoV in the air. Thus, we infer that high DAAP may reduce the potential for SARS-CoV transmission. However, evidence from this study is sparse and equivocal: both univariate analysis and multivariate analysis show that DAAP is inversely associated with secondary attack rate, but the relationship does not occur after adjustment for affected area; further investigations are necessary.

There is some literature relating the infectivity of SARS-CoV and ultraviolet light irradiation.[25,26] Ultraviolet light irradiation for 60 min on the virus in culture medium resulted in the destruction of viral infectivity at an undetectable level.[25] Therefore, in the outdoor environment, more DHS corresponding to more hours of ultraviolet irradiation may reduce the potential for SARS-CoV transmission. However, in this study, after adjustment for onset time of primary case and affected area, only in Inner Mongolia was it observed that DHS was inversely associated with secondary attack rate. This may be because SARS-CoV transmission mainly occurs by close contact in the indoor environment, where DHS has relatively little influence.

Air temperature is an important factor influencing survival of microorganisms in the external environment. There have been studies reporting that SARS-CoV is sensitive to temperature and relatively stable at low temperatures.[14–16] However, some experimental evidence has shown that SARS-CoV remains stable at 4 °C, at room temperature (20 °C) and at 37 °C for at least 2 h without remarkable change in the infectious ability of cells, but is converted to a non-infectious state after 90-, 60-, and 30-min exposure at 56 °C, at 67 °C, and at 75 °C, respectively.[25] Therefore, air temperature may not have affected SARS-CoV transmission. The results of this study show that there is no relationship between DAT and secondary attack rate. This finding is confirmed by the experimental study,[25,26] but is not consistent with other reports.[3,27] Further investigations are necessary to verify this finding.

Cui et al. pointed out that air pollution may influence the prognosis of SARS.[18] However, there have been no reliable studies documenting the correlation between air pollution and the SARS outbreak. The results of this study failed to disclose a correlation between air pollution and the SARS outbreak. Theoretically, air pollution should not affect survival of SARS-CoV in vitro, though it may exert its effect by influencing local resistance of the host. Further investigations are also necessary.

Although this study overcame some of the disadvantages of other similar studies and obtained comparably reliable results, there may still be some limitations. Firstly, the present study used an ecological study design and may therefore produce ecological fallacy. In addition, it is impossible for us to make an estimate of the direction and magnitude of possible bias because of a lack of more detailed data. Secondly, the results of this study may have been influenced by some social factors and other natural factors. Although we used secondary attack rate before admission of the primary case as a dependent variable to minimize the influence of social factors on the results, a confounding bias of the present study is possible due to a lack of data on the joint distribution between other potential confounding factors and the meteorological factors studied. Finally, we used data from 673 meteorological observation stations in this study in an attempt to best reflect the exposure level of the study areas. In the process of making use of these data, we assumed that the exposures of each affected area and the corresponding observation station were homogenous, which may lead to exposure misclassification to some extent.

Despite these possible biases, we believe that the results of this study are reliable and to some extent answer questions concerning seasonal transmission of SARS. Also, our results provide scientific references for the research of SARS prevention and control, and of transmission dynamics.

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