

The Role of Fungal Spores in Thunderstorm Asthma*

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Study objectives: To document the existence and investigate the etiology of “thunderstorm asthma,” which has been reported sporadically over the past 20 years.

Design: We assessed the relationship between thunderstorms, air pollutants, aeroallergens, and asthma admissions to a children’s hospital emergency department over a 6-year period.

Results: During thunderstorm days ($n = 151$ days) compared to days without thunderstorms ($n = 919$ days), daily asthma visits increased from 8.6 to 10 ($p < 0.05$), and air concentrations of fungal spores doubled (from 1,512 to 2,749/m³), with relatively smaller changes in pollens and air pollutants. Daily time-series analyses across the 6 years of observation, irrespective of the presence or absence of thunderstorms, demonstrated that an increase in total spores, equivalent to its seasonal mean, was associated with a 2.2% (0.9% SE) increase in asthma visits.

Conclusions: Our results support a relationship between thunderstorms and asthma, and suggest that the mechanism may be through increases in spores that exacerbate asthma. Replication in other climates is suggested to determine whether these findings can be generalized to other aeroallergen mixes. (CHEST 2003; 123:745–750)

Key words: air pollution; asthma; epidemiology; fungus; pollen

Abbreviations: CHEO = Children’s Hospital of Eastern Ontario; LOESS = locally weighted nonparametric regression and smoothing scatter plots

Increased asthma morbidity during thunderstorms has been reported sporadically over the past 2 decades, but the underlying mechanism has not been established. On July 6 and July 7, 1983, the number of patients with asthma presenting to the emergency departments of eight Birmingham (United Kingdom) hospitals averaged 50 over the 2-day period, compared to a usual average of 10 visits.¹ The increase in visits was associated with an increase in airborne fungal spores, particularly *Sporobolomyces* and *Didymella*, and a decrease in pollen. Airborne pollutants represented by smoke and sulfur dioxide were not believed to be unusually elevated. The

authors of the report suggested that asthma may have been caused by an increased release of fungal spores due to an initial rainfall. During a thunderstorm 11 years later (June 24 and June 25, 1994), the number of patients presenting with asthma or other airways diseases to emergency departments in the London area increased 10-fold. “Out-of-hours calls” to general practitioners also increased during this time, in south and east England.² This thunderstorm was described as unusually large and multicentered, and was associated with reduced temperatures and severe wind gusting.^{3,4} A high level of grass pollen occurred 9 h previously.⁴

Meteorologic risk factors for daily asthma admissions during 1987 and 1994 were investigated, using the English Hospital Episodes System database. Fifty-six “epidemics,” defined as an exceptionally high number of asthma hospital admissions compared to the week before and the week afterward, were identified. Risk factors for asthma epidemics included increased temperature, increased rainfall, increased lightning flashes, and the combination of lightning flashes and elevated grass pollen.⁵

In the southern hemisphere, “thunderstorm asthma” epidemics have been reported in Australia.⁶

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Fivefold to 10-fold increases in emergency visits to major hospitals in Melbourne occurred during two 24-h periods in 1987 and 1989. Meteorologic associations included increased rainfall and humidity, a drop in temperature, and no change in ambient pollutants. Aeroallergens were not discussed.

There are several limitations to our understanding of the association between thunderstorms and asthma. First, there have been few reported observations of this phenomenon over the past 25 years. Secondly, associations have often been based on simple descriptive statistics, and occasionally on multivariable analysis that did not adjust for serial autocorrelations.^{7,8} Finally, attributing the increase in asthma to one factor—grass pollen, for example—is difficult if other plausible factors have not also been simultaneously accounted for, such as temperature, air pollutants, and fungal spores.^{9,10}

A recent study by Lewis et al¹¹ used time-series analyses to account for serial autocorrelations. Fungal spores tended to increase while grass pollen decreased on thunderstorm days, but the level of statistical significance was not reported. Interestingly, grass pollen influenced asthma only on days when there was light rainfall. Our previous report detected an association between fungal spores and emergency asthma visits independent of thunderstorms.¹²

To address the issue of thunderstorm asthma, we determined if both asthma hospital admissions and aeroallergens increased during thunderstorms. We then tested whether the allergens that increased during thunderstorms were associated with asthma exacerbations on a daily basis irrespective of the presence or absence of thunderstorms. In summary, we explored the hypothesis that thunderstorms, by increasing aeroallergen levels, cause asthma exacerbations. Analysis was done using 6 years of emergency department visit data with approximately 4,000 asthma hospital admissions yearly. Air pollution, meteorologic factors, and aeroallergen levels were accounted for simultaneously.

MATERIALS AND METHODS

Study Population

The Children's Hospital of Eastern Ontario (CHEO) is the only children's hospital serving the region of Ottawa, Ontario, which has a population of approximately 750,000. All emergency department visits are recorded in a database called the Epidemiology Patient Information System. In 1993, there were approximately 48,000 visits, of which 6,820 were for respiratory diseases. The present study included all patients presenting to the emergency department between 1993 and 1997 with a principal diagnosis of asthma (*International Classification of Diseases, ninth revision*, code 493).

Exposure Data

Aeroallergen data (pollen grains and fungal spores) were collected using rotational implication sampling equipment operating at 2,400 revolutions per minute set to collect 1 min from every 10-min period over a 24-h interval. The particles adhering to the silicon grease-coated sample rods were analyzed to determine the number of particles present per cubic meter of air sampled. The sampler was located eight feet above ground level at the Ottawa Airport, which is within 5 to 10 miles of the farthest reaches of the Ottawa area and approximately 4 miles from CHEO. Aeroallergen data were collected between April through September. The ground is frozen hard from November to February, and is snow covered from December to February.

Daily meteorologic data included maximum and minimum temperatures, average barometric pressure, dew point, and relative humidity. Available air pollution data included the daily maximum for ozone (O₃), daily averages of nitrogen dioxide (NO₂) and of sulfur dioxide (SO₂), the coefficient of haze, and 24-h averaged sulfates (SO₄) measured every sixth day. As previously described,¹³ daily estimates of SO₄ were made using the measured values available plus the total suspended particulates measured daily. Air pollution and meteorologic data were supplied by Environment Canada through the National Air Pollution Surveillance Network and the National Climate Data Archive. A thunderstorm is defined by the Meteorological Service of Environment Canada as "a local storm produced by a cumulonimbus cloud, and always accompanied by thunder and lightning, usually with strong gusts of wind, heavy rain, and sometimes with hail."¹⁴

Statistical Methods

The objective of our analysis was to relate daily variations in aeroallergen levels to daily variations in emergency department visits on a temporal basis. Analyses of the aeroallergens were restricted to time periods surrounding their peaks. Associations were tested as follows: April 1 to June 30 for trees, June 1 to August 31 for grasses, August 1 to September 30 for ragweed, and May 1 to September 30 for spores. Air pollutants, viral epidemics, and climate have strong seasonal trends that may confound an association between aeroallergens and respiratory visits, which also have seasonal trends. To remove (filter) the potentially confounding long-term seasonal trends, locally weighted non-parametric regression and smoothing scatter plots (LOESS) were applied to each variable.¹⁵ A 90-day filter minimized the autocorrelation within series. Lags between exposure and emergency visit data were assessed.

Because there are more emergency department visits on weekends and fewer on weekdays, a day-of-the-week effect was also accounted for in the analysis. Finally, the analysis was adjusted for the day-to-day change in meteorologic variables and air pollution variables, which may influence day-to-day changes in respiratory-related visits. Further details of the analysis have been published elsewhere and can be found in the Appendix.¹²

The percentage increase in visit rate corresponding to an increase in aeroallergens equivalent in magnitude to its mean value is reported. The statistical uncertainty in the parameter estimate is represented by the SE. The ratio of the log-relative risk to the SE (*t* value) is also reported.

RESULTS

The daily number of emergency department visits for asthma ranged from 0 to 36/d, with an average

rate of 8.6 on days without thunderstorms and 10 on days with thunderstorms, representing a 15% increase ($p < 0.05$). The concentrations of fungal spores almost doubled during thunderstorms, due to large increases in *Cladosporium* and ascomycetes (Table 1). Total fungal spores increased from 1,512 to 2,749/m³, ascospores from 263 to 492/m³, and *Cladosporium* from 1,259 to 2,419/m³. Seasonal differences did not account for the differences between days with and days without thunderstorms. Spores were fewer in the spring (May, June) than the summer (July, August, September) but greater during thunderstorm days than on days without thunderstorms in each season. Air pollutants were higher during days with thunderstorms compared to days without. The increases in ozone, nitrogen dioxide, and the coefficient of haze were statistically significant at $p = 0.0000$.

To determine if these fungal spores could influence asthma visits, we tested the association between changes in daily concentrations of aeroallergens and changes in the daily numbers of emergency visits, employing a daily time-series analysis over the 6 years of observation irrespective of thunderstorms. Emergency department visits displayed seasonal effects and day-of-the-week cycles.¹² Relative humidity alone recorded on the day of the visit was sufficient to explain any weather-related day-to-day variations in emergency department visits for asthma. This was

determined using a forward inclusion stepwise regression analysis using the Akaike information criteria as the inclusion criteria.¹⁶ A relative 67% increase above the mean relative humidity was associated with a 13% relative increase in hospital admissions above the seasonal mean. Of all the pollutants, ozone recorded on the day of the visit (lag = 0 days) had the largest effect on asthma, but it did not reach conventional levels of statistical significance ($p > 0.10$). The aeroallergen effect was expressed as the percentage increase in daily emergency department visits associated with an increase in the aeroallergen concentration by an amount equivalent to the mean value of that aeroallergen. The effect was determined using two models for relative humidity and ozone, including a linear representation for both filtered variables and an S-smoothed representation. The spore-related relative risk was insensitive to these adjustments for relative humidity and ozone. The possibility of a nonlinear association between emergency department visits and spores was tested by comparing the residual variation from the linear model to one using nonparametric smooth representation of spore concentrations (LOESS with a 50% span). Linear models adequately represented the concentrations-response relation (smallest p for linearity > 0.29). An increase in total spores, equivalent to the mean seasonal value, was associated with a 2.2% (0.9% SE) in asthma. An increase in ascospores, equivalent to

Table 1—Daily Aeroallergen Concentrations Stratified by the Presence or Absence of Thunderstorms, May Through September, 1993 to 1997*

Variables	Days With Thunderstorms (n = 151)	Days Without Thunderstorms (n = 919)	p Value
Fungal spores, spores/m ³			
Deuteromycetes			
<i>Alternaria</i>	54	39	0.0054
<i>Cladosporium</i>	2,419	1,259	0.000
<i>Epicoccum</i>	16	10	0.0002
<i>Penicillium/Aspergillus</i>	90	87	0.089
Total	2,749	1,512	0.000
Basidiomycetes			
<i>Ganoderma</i>	338	427	0.038
Total	474	568	0.086
Ascomycetes	492	263	0.000
Total spores	3,683	1,993	0.000
Pollen grains, grains/m ³			
Trees	86	125	0.14
Grass	22	23	0.82
Ragweed	92	87	0.83
Air pollutants, mean			
Ozone, ppb	38	31	0.0000
NO ₂ , ppb	20	17	0.0000
SO ₂ , ppb	2.2	2.0	0.3734
SO ₄ , mg/m ³	3.6	3.4	0.2575
Coefficient of haze, units per linear foot	0.2	0.16	0.0000

*ppb = parts per billion.

Table 2—Percentage Increase (SE) in Emergency Department Visits Associated With an Increase in Spore Concentration Equal in Magnitude to its Mean, May Through September, 1993 to 1997*

	Days Lagged†	Model Specification‡	
		Spore Only	Spore and Ozone
Deuteromycetes			
Total	2	1.79 (0.8)‡	1.81 (0.8)§
Alternaria	2	1.67 (0.96)	1.74 (1.04)
Cladosporium	2	1.64 (0.74)	1.19 (0.78)
Epicoccum	2	1.47 (0.96)	0.2 (1.05)
Penicillium/Aspergillus	2	1.75 (0.87)	2.34 (1.08)
Basidiomycetes			
Total	3	3.75 (1.66)	3.41 (1.68)
Ganoderma	3	3.3 (1.5)§	3.13 (1.5)§
Ascomycetes	0	2.86 (0.96)	2.96 (0.96)
Total spores	2	2.18 (0.89)	2.15 (0.89)

*Results not stratified by thunderstorms.

†No. of days between emergency department visit and high spore levels prior to visit.

‡All models accounted for long-term temporal trends, day-of-the-week effects, and relative humidity. The “spore only” model includes the individual spore as the dependent variable, whereas the “spore and ozone” model includes the spore as the dependent variable and ozone as one of the independent variables.

§SE of percentage increase in daily emergency department visits attributable to change in daily mean spore concentration.

|| χ^2 ratio is > 2 ($p < 0.05$).

its mean, accounted for 3% (1% SE); and for *Cladosporium*, it was 1.2% (0.8% SE) of all asthma visits (Table 2).

In contrast to our findings for fungal spores, we were unable to detect an association between emergency asthma visits and weeds, grasses, or trees. The aeroallergen effect was only slightly attenuated by coadjustment for ozone but did not appear to be sensitive to coadjustment to the other pollutants (NO_2 , SO_2 , coefficient of haze, and SO_4). In summary, air pollutants were higher during thunderstorm days than days without thunderstorms, but the daily time-series analysis detected no statistically significant effect of these pollutants on asthma, whereas there was a significant effect of fungal spores. Thus, of all the climate and air quality changes observed during thunderstorms, only fungal spores could be shown to influence asthma hospital admissions.

DISCUSSION

Our findings support the existence of “thunderstorm asthma.” Daily asthma hospital admissions increased 15% on days with thunderstorms. This effect is smaller than the few earlier studies reporting that asthma admissions increased several-fold after thunderstorms.

We observed that spores approximately doubled on thunderstorm days. This is consistent with the suggestion of Packe and Ayres¹ that turbulent winds could increase the release of fungal spores or draw up sedimented fungal spores and resuspend them in the air, making them available for inhalation.¹ We observed that both asthma visits and spores increased during thunderstorms. This is similar to the finding of Packe and Ayres¹ that fungal spores increased during the asthma epidemic associated with the thunderstorm in Birmingham in 1983. Also consistent with this is an association that Khot et al⁸ found between increased spores and increased asthma admissions to the Royal Alexandria Hospital for Sick Children in Brighton, England, between August 1982 and November 1983. An association was also found with rainfall, but not with temperature, humidity, wind speed, or pollen levels. In addition to these studies, we observed that fungal spores were associated with asthma in a daily time-series analysis, making it unlikely that the elevations in spores and asthma were simply coincidental.

It has been suggested that grass pollen is the most likely cause of associations between thunderstorms and asthma.¹⁷ Although an intact grass pollen grain tends to be $> 20 \mu\text{m}$ in diameter, respirable particles containing allergen may be found in the atmosphere. Water can rupture pollen grains resulting in the release of hundreds of small starch granules that contain major allergens. Recently, Taylor et al¹⁸ demonstrated in an experimental situation that ryegrass and Bermuda grass could release 0.12- to $4.7\text{-}\mu\text{m}$ pollen fragments directly from the anther after exposure to humid and then dry conditions. Thus, even if rainfall washes the larger intact grains out of the air, any reduction in biological effect may be offset by an increase in the respirable fraction.¹⁹

Schappi et al²⁰ measured concentrations of grass group 5 allergens in the atmosphere. The proportion of total allergen and respirable particles were 37% on dry days and 57% during light rain. Twelve patients presenting to hospital with asthma worsening during the Melbourne thunderstorms were compared with 16 outpatient asthma patients without worsening. The former group was twice as likely to be sensitive to rye grass pollen by skin testing.²¹ However, a subsequent letter to the editor pointed out that a demonstration of grass sensitivity may reflect an increased tendency to many aeroallergens, including mold and pollens, some of which may be higher in thunderstorms.²² Lewis et al¹¹ elegantly demonstrated the significance to the population of the interaction between light rain and pollen effects. They found that grass pollen influenced asthma

emergency visits for asthma most markedly on days of light rainfall, while no effects were found on dry days.

In our present study, grass pollen was unlikely to have caused an increase in asthma during thunderstorms. First, grass pollen did not increase on thunderstorm days. Secondly, even if the proportion of respirable particles increased by 20%, it would be unlikely to increase asthma visits, because variations in grass pollen across the several years of observation were not associated with asthma visits. However, the lack of any observed effect of grass pollen on asthma in our study cannot necessarily be generalized to other climates.

In conclusion, we found that, over six seasons of daily observations, both asthma and fungal spores increased during thunderstorms. Furthermore, over a 6-year period, day-to-day increases in these fungal spores were shown to be associated with an increase in asthma visits, irrespective of thunderstorm occurrence. The best explanation is that asthma increases during thunderstorms by increasing ambient allergenic fungal spores. We present a biologically plausible explanation that is consistent with other studies either reporting that fungi exacerbate asthma or that fungal spore concentrations may rise with thunderstorms. Our analysis also indicates that cause precedes effect, a dose-response exists, and there is a reasonably strong association, at least compared to air pollution. Although the study was limited to one localized geographic area, the generalizability of our results is suggested by previous observations of increased spores during thunderstorms in both Birmingham and Brighton.^{1,8} Replication of our study in other geographic areas is suggested to better assess the results in other populations and in other aeroallergen mixes.

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APPENDIX: FURTHER DETAILS OF STATISTICAL METHODS

Respiratory-related visits were related to aeroallergens using the following statistical model:

$$E(y_t) = f_y \exp\{\delta_1 S(w_t - f_w) + \delta_2 S(p_t - f_p) + \delta_3 (x_t - f_x)\}$$

where

$$\{y_t\}_{t=1, \dots, T}$$

represents the number of visits for each disease considered and

$$\{x_t\}_{t=1, \dots, T}$$

represents the aeroallergen concentrations on the t^{th} of T days of observation;

$$f_y(f_w, f_p, f_x)$$

are the predicted values of daily emergency visits (weather, air pollution, aeroallergen) as obtained from the generalized additive model with temporal trends and day-of-the-week effects; $\exp$ is the exponential function; α is a seven-dimensional parameter vector relating visits to the day of the week; d_t is a seven-dimensional vector that takes values of 1 to 7 for each day of the week; δ_y , δ_w , δ_p , and δ_x are unknown parameters; w_t is a weather variable recorded on day t , p_t is a pollution variable recorded on day t , and x_t is a spore variable recorded on day t . δ_1 , δ_2 , and δ_3 are the vectors of unknown parameters relating prefiltered (residuals after applying LOESS) weather, air pollution, and aeroallergen variables to respiratory-related emergency visits respectively. S represents the smoothing spline fit in a generalized additive model²³ that related nonlinear associations between weather, air pollutants, and visits.

In order to identify the smallest number of weather and pollutant variables required to predict visits, we used a forward inclusion stepwise regression procedure to select a minimally sufficient set of pollutant predictors. The selection criteria was Akaike information criteria, which is a function of the residual deviance and the model degrees of freedom. Log-relative risks for a unit change in aeroallergen levels, δ_3 , and their corresponding SEs were estimated using generalized additive models with S-PLUS software (Statistical Sciences; Seattle, WA).²⁴

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