

Review

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Thunderstorm asthma: an overview of the evidence base and implications for public health advice

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Summary

Thunderstorm asthma is a term used to describe an observed increase in acute bronchospasm cases following the occurrence of thunderstorms in the local vicinity. The roles of accompanying meteorological features and aeroallergens, such as pollen grains and fungal spores, have been studied in an effort to explain why thunderstorm asthma does not accompany all thunderstorms. Despite published evidence being limited and highly variable in quality due to thunderstorm asthma being a rare event,

this article reviews this evidence in relation to the role of aeroallergens, meteorological features and the impact of thunderstorm asthma on health services. This review has found that several thunderstorm asthma events have had significant impacts on individuals' health and health services with a range of different aeroallergens identified. This review also makes recommendations for future public health advice relating to thunderstorm asthma on the basis of this identified evidence.

Introduction

Thunderstorm asthma is a term used to describe any observed increase in acute bronchospasm cases following the occurrence of thunderstorms in the local vicinity; it does not assume that a formal asthma diagnosis has been made in the cases discussed here. Several previous episodes have been studied by scientists from a range of disciplines;

there is no standard definition of a thunderstorm asthma episode.

Thunderstorm asthma is important as sudden surges in acute respiratory illness have the potential to increase pressures on acute health services, and deplete available resources. The interest in studying this phenomenon in detail is to identify its impact, verifying the relationship between asthma and thunderstorms and identifying

contributing factors, which might aid early detection and warning.

Aim of the review

This review summarizes current knowledge of thunderstorm asthma and relates patient characteristics, impacts on health services and evidence for associations with excess acute asthma, aeroallergens and other meteorological features to inform public health advice. It does not seek to address molecular or cellular mechanisms for thunderstorm asthma.

Search strategy (shown in Figure 1)

The bibliographic databases MEDLINE, EMBASE and CINAHL were searched for publications with the key terms 'thunderstorms AND asthma'. Filtering for English-language only publications



Figure 1. Flow of publications identified through literature search.

and those relevant to the topic (on the basis of abstract), left 35 publications. Of these, 28 were accessible. Inspection of reference lists for these articles yielded a further seven publications. This resulted in a total of 35 publications for consideration for this review. Of note, all these publications studied episodes occurring in high-income countries. These publications are listed in Table 1.

These publications were reviewed and graded on the basis of methodological quality, using the SIGN methodology (which is widely accepted as an approach to assessing the quality of evidence at different levels of the research hierarchy).

Results

As thunderstorm asthma is a rarely recognized event, the literature search only identified 35 publications. The rare nature of this phenomenon may also help to explain why all the identified publications were retrospective in nature, and why they were highly variable in terms of study design and quality. They ranged from simple qualitative observations to mixed-method studies, such as meteorological, aerobiological and patient-level measures. The findings of these studies are described further, in terms of the relationship between thunderstorms and asthma, the role of aeroallergens, patient characteristics and impact on health services.

An outline of thunderstorms and their geography in England

Thunderstorm clouds include upward air currents (updrafts) and downward air currents (downdrafts), which contribute to the development of negatively charged particles at the bottom of clouds. Lightning occurs when these negatively charged particles are attracted to positively charged objects on the ground.

Thunderstorms mainly affect the South Eastern and East Midlands regions of England during the summer, for ~20 days per year; Scotland and the Western Coast have less frequent thunderstorm patterns and do not demonstrate such a seasonal pattern.¹

Evidence for a relationship between thunderstorms and asthma

Basic observational studies have described increases in asthma cases presenting to acute services such as emergency departments (EDs) following thunderstorms, through a variety of measures. One of the earliest such observational reports was by Packe and Ayres in 1983.² Several other reports by Alderman

Table 1 Summary of evidence identified from literature search

References	Setting	Study period	Study methods	Findings	Quality of evidence
2	Birmingham	6 July 1983	Observational study	Increase in asthma patients after 2130 on 6 July. Thunderstorm with rain on 6 July from 2000. Air pollution low. <i>Cladosporium</i> peaked late afternoon and rise in <i>Didymella exitialis</i> ascospores at 1900. High total pollen counts on 6 July and declined with rain.	3
3	ED Nottingham	20 June 1984	Observational descriptive	Descriptive. Increase from four asthma patients per day, prior to storm, to 19 in 7 h after storm. Nine of these only had a past history of hay fever and not asthma.	3
4	ED Peterborough	24–25 June 1994	Observational descriptive	39 patients attending ED and acute admissions between 11 pm 24 June and 7 am 25 June, compared with just one, during the same period the previous year. 13/38 not previously diagnosed as asthmatic; 22/38 were hay fever sufferers. Coincided with high pollen counts and high ozone levels. Largest rise in <i>Phaeosphaeria nigra</i> and <i>Diatrypaeae</i> and smaller increases in <i>Didymella exitialis</i> and <i>Sporobolomyces</i> . Close by thunderstorm activity.	3
5	Calgary, Canada	31 July 2000	Ecological study	Description of asthma cases attending following thunderstorm, and increase in cases. Description of aeroallergens occurring at time of thunderstorm asthma cases (no statistical association investigated).	3
6	ED Derby, England	1993–96	Ecological study	<i>Didymella</i> and <i>Cladosporium</i> counts increased during thunderstorm. Thunderstorms associated with increased ED visits (on same day) and asthma admission (1 day lag). However, these effects of thunderstorms were reduced outside of grass pollen season.	2+
7	UK	24/25 June 2004	Case-control study for odds of asthma on thunderstorm nights (case) compared with control nights	Pooled Mantel-Haenszel estimate for thunderstorm-affected areas was 6.36 (95% CI: 4.97–8.32) and for non-thunderstorm-affected areas was 1.01 (95% CI: 0.80–1.27), indicating only thunderstorm affected areas had a significant increase in asthma on night of thunderstorm.	2–
8	EDs, Hospital admissions and Ambulance services Melbourne Australia	1987 and 1989	(1) Ecological	Increase in adult asthma patients attending EDs (154 in 1987 and 277 in 1989) compared with expected daily average of 262 (95% CI: 18.8–33.6).	2–
			(2) Case-control	Increased asthma admissions (26 in 1987 and 47 in 1989) compared with expected daily average of 6 (95% CI: 2.9–9.5).	
				Increased ambulance calls for asthma (22 in 1987 and 44 in 1989) compared with expected daily average of 2 (95% CI: 1.6–2.4).	
				Significantly increased sensitivity using skin prick testing, to rye grass pollen among 12 cases compared with 16 controls ($P < 0.05$). However, no significant difference in sensitivity to tree pollen, animal dander, house dust mite, <i>Aspergillus</i> and <i>Cladosporium</i> .	2+
9	ED London	June–July 1994	Ecological	Epidemic asthma associated with increased rainfall, air pressure, relative humidity, an increase in grass pollen count 9 h earlier and temperature decreases 6 h earlier (1°C decrease associated with increase in presentations by a factor of 1.09).	2+
10	Hospital admissions England, UK	January 1990–February 1994	Ecological	Increased RR of asthma admission with high spheric density (≥ 1 Sf/100 km ² /day) for both 0–14 years (RR 1.13, 95% CI: 1.02–1.26) and 15+ years (RR 1.28, 95% CI: 1.15–1.43). These RRs are higher for pollen counts ≥ 50 grains/m ³ /day, with sferics, for both 0–14 years (RR 1.16, 95% CI: 1.04–1.31) and 15+ years (RR 1.47, 95% CI: 1.32–1.64).	2+

(continued)

Table 1 Continued

References	Setting	Study period	Study methods	Findings	Quality of evidence
11	EDs Atlanta, Georgia, USA	1993–2004	Ecological	Positive association between daily counts of asthma ED visits and thunderstorm occurrence ($P<0.001$). When stratified by rainfall: significant for thunderstorms ($P<0.05$) and rainfall but non-significant for thunderstorms without rainfall ($P=0.777$). Stratification by wind speed: significant for thunderstorms and wind speed between 9.4 and 14.3 m/s ($P<0.001$). Significantly increased odds of thunderstorms within 80 km (OR 5.0, 95% CI: 2.4–10.5) and thunderstorm outflows (OR 15.0, 95% CI: 6.0–37.6).	2+
12	NSW, Australia	January 1995–December 1998	Case-control study investigating odds of thunderstorms on epidemic asthma days Environmental sampling	4-fold increase in closed pollen grains and 7-fold increase in ruptured pollen grains, compared with the previous hour, when the thunderstorm outflow was detected, for one epidemic day. Significant association between 25 June (day after thunderstorm) and increased asthma consultation rate for adults ($P<0.0001$), children ($P=0.0002$), elderly ($P=0.0013$) and all ages ($P<0.0001$). Significant association between grass pollen and asthma consultation rate for adults ($P<0.0001$), children ($P=0.0257$) and all ages ($P=0.0013$). However, inclusion of grass pollen and the 25 June in the multivariate model, showed that the association between grass pollen and asthma consultation rate, was no longer significant. Significantly increased RR of asthma epidemic days both separately, and combined for days with high lightning and high pollen counts, within the same regional health authorities. Alerting based on high density of sterics (lightning) and high pollen levels, only 15% alerts would be followed by thunderstorm epidemics, while 88% of all epidemic days were not detected by these alerts. Significant increase in asthma attendances (640) over those expected according to control period ($P=0.003$). 58% attended within 8 h of thunderstorm. Mean age was 32 years; 365 aged between 21 and 40 years and 86 aged less than 16 years; 57.5% were female. For 44.2% patients, this was their first recorded asthma attack. For 635 patients with available data, 78.7% were discharged home, 16.4% admitted. Of 11 EDs providing information, 5 ran out of nebuliser face masks, 1 ran out of peak flow meter mouthpieces, 4 of β_2 agonist nebulisers, 6 of β_2 agonist inhalers and 8 ran out of prednisolone tablets. The daily average pollen count and air levels of damp air spores (e.g. <i>Phaeosphaeria nigrans</i> , <i>Diatrypaceae</i>) were high prior to and during the thunderstorm, respectively. Increased odds of sensitization to rye grass (OR 23.0, 95% CI: 6.62–84.33, $P=0.0001$) and <i>Cladosporium</i> (OR 2.8, 95% CI: 1.21–6.29, $P=0.02$) among cases (asthma patients attending within 24 h of thunderstorm), compared with controls (attending during the rest of study period). Increased odds of onset of asthma symptoms with being exposed to outdoors, compared with being indoors with windows closed (OR 2.11, 95% CI: 1.12–3.97, $P=0.02$) Pollen increased to a 6 year high. Fungal spore levels varied with location. There was a transient increase in <i>Cladosporium</i> in Cambridge and Leicester. There were also increases in <i>Phaeosphaeria nigrans</i> and <i>Diatrypaceae</i> in Cambridge and Norwich, with <i>Sporobolomyces</i> increasing early the next day.	2+
13	General Practice London, UK	January 1992–December 1994	Ecological		2++
14	Hospital admissions England	1987–94	Ecological study		2+
15	EDs London	24 June 1994	Descriptive study		3
16	Wagga Wagga, New South Wales, Australia	July–October 1997	Case-control study		2+
17	England, UK	June 1994	Environmental sampling		3

(continued)

Table 1 Continued

References	Setting	Study period	Study methods	Findings	Quality of evidence
			Observational	High hourly concentrations of O ₃ , NO ₂ , SO ₂ . Weather: strong low level outflow and wind speeds in London, North of England and East Anglia. Increase in general practice deputising service calls. Four of eight English Regional Health Authorities observed a 6-fold increase in asthma attendances at ED. 11 District health authorities identified difficulty in service provision in ED.	
18	England UK	1994	Case series	Of 16 subjects who attended A&E with thunderstorm asthma, 12 had very high IgE levels for pollen and only 2 were negative for IgE pollen.	3
19	Cambridge and Derby, UK	29 July 2002	Environmental sampling Case-control study of odds of aeroallergen sensitization. Environmental monitoring of pollen and spore counts.	Increases in <i>U. segetum</i> at three sites; multiple sites with increased cladosporidium and increased ascospores after rain including <i>Phaeosphaeria nigrans</i> and diatrypaceous. Significantly increased odds of <i>Cladosporium</i> or <i>Alternaria</i> species sensitivity in thunderstorm asthma cases compared with seasonal asthma cases (OR 63.966, 95% CI: 3.58–1143.9, $P<0.0001$). Above threshold levels of <i>Cladosporium</i> and <i>Alternaria</i> species on 28 and 29 July 2002 and increased concentrations of <i>Didymella</i> on 30 July 2002 and ascospores on 30 and 31 July 2002.	2+
20	ED Ottawa, Canada	1993–97	Also multivariate analysis of asthma admission rates Ecological study	Significant association between asthma admission rates and broken <i>Alternaria</i> species (OR 2.21, 95% CI: 1.51–3.27, $P<0.0001$), <i>Didymella</i> species (OR 1.65, 95% CI: 1.42–1.90, $P<0.0001$) and <i>Cladosporium</i> (OR 1.47, 95% CI: 1.20–1.79, $P=0.0002$). An increase in total spores by the seasonal mean increased the ED visits for asthma by 2.15%. This was observed individually for Deuteromycetes (1.81% increase in visits), Basidiomycetes (3.41%) and Ascomycetes (2.96%). There was no significant increase in visits associated with increases in pollen grains from trees, grass and ragweed.	2–
22	ED Naples	4 June 2004	Case series	Sensitivity with allergic respiratory symptoms, to <i>Parietaria</i> species pollen in all seven subjects. Not sensitive to other grasses and other aeroallergens such as pollen grains and moulds. This coincided with peak airborne concentrations of <i>Parietaria</i> (144 grains/m ³) on 3 June but low concentrations of grasses and <i>Alternaria</i> species.	3
24	EDs Birmingham	July 1983	Case-control.	50% thunderstorm asthma patients responded. Of 18 patients, all had history of hayfever, 17 had asthma history. Only 10 on treatment for asthma compared with 18 controls from asthma clinics, no significant difference in sensitivity between thunderstorm cases and controls.	2–
25	Review	2004	Review	Review of thunderstorm asthma studies and proposes a hypothesis for pollen rupture during thunderstorms	2++/4
30	GP deputising service, Luton	24 June 1994	Case report	First call for home visit with asthma was 20 min after start of thunderstorm. That evening 23 of 56 (41.7%) home visit calls were for asthma, and 24 of 89 (26.95) ED visits were for asthma. On morning of 25 June, 5 of 10 general practice patients presented for asthma which started during thunderstorm. No comparator group described.	3
31	ED Athens Greece	January 1985 to December 1992	Ecological study	No significant difference in asthma visits to chest ED between thunderstorm and control days, matched on basis of day of week, temperature ± 3 C, humidity within 5% and daily levels of SO ₂ , NO ₂ and O ₃ ($P=0.39$).	2+
32	EDs	1992–2000	Case-crossover design		2+

(continued)

Table 1 Continued

References	Setting	Study period	Study methods	Findings	Quality of evidence
	Ontario Canada			No significant increase in odds of asthma visits to ED for children for thunderstorms compared with non-thunderstorm periods ($P=0.15$). (However, periods of study too short at 6 h, as some other studies showed some longer course of action.)	
33	Review	2009	Review	Overview of sensitivity to allergens, etc.	2++
34	Editorial	2007	Editorial	Identifies four specific conditions for a thunderstorm-asthma epidemic to occur on basis of literature.	4
35	Review	2007	Review	Review of other published thunderstorm asthma data.	2++
36	Hospital admissions South Wales	January 1990–December 1996	Ecological	Number of asthma admissions higher on thunderstorm days compared to thunderstorm days ($P=0.04$). When compared between winter and summer seasons, the summer season had a significant association between thunderstorms and asthma admissions ($P<0.001$) but not for the winter season.	2+
				No significant association between counts of individual pollen species/fungal spore counts and asthma admissions. No significant correlation between asthma admissions and pollen/fungal spore counts. Also, no significant relationship between rainfall and asthma admissions. Ozone concentrations significantly associated with asthma admissions, after controlling for thunderstorms and season ($P=0.02$).	
37			Editorial	No new data.	4
38			Letter	No new data. Suggests testing for sensitivity to moulds.	n/a
39	EDs London	24–25 June 1994	Observational	Observed excess of asthma attendances in London hospitals. Suggestion of pollen and fungal spores.	3
40		1996	Editorial	Summarizes findings of previously listed articles	n/a

*et al.*³ and Campbell-Hewson *et al.*⁴ have also observed increases in asthma cases following thunderstorms.

A report from Canada identified that acute asthma accounted for 5 and 17% of ED visits on thunderstorm asthma days, compared with just 2% on a non-thunderstorm asthma day.⁵ Significant associations were identified between thunderstorms and increases in asthma presentations to ED [relative risk (RR) 1.3, 95% confidence interval (CI): 1.0–1.7] and asthma admissions (RR 1.7, 95% CI: 1.1–2.5) in a study of one English city.⁶

In England, a study considered the relationship between asthma calls to general practice deputising services and lightning strikes within 20 km in England.⁷ Pooled Mantel-Haenszel odds ratios for the odds of asthma calls in thunderstorm-affected areas were significant (6.36, 95% CI: 4.97–8.32) but non-significant in non-thunderstorm affected areas (1.01, 95% CI: 0.80–1.27).

From Australia, Bellomo *et al.* also identified a significant increase in patients attending EDs for bronchospasm related symptoms, in relation to two thunderstorms in two different years in Melbourne⁸ (154 and 277 for thunderstorms compared with a daily average of 26.2, 95% CI: 18.8–33.6). There were also increased ambulance calls for asthma compared with the expected daily averages on both occasions (22 and 44 compared with daily average of 2, 95% CI: 1.6–2.4).

A challenge to studying this phenomenon is that localized storms can lead to small or unnoticed excesses of asthma cases, and it is therefore easier to identify larger scale events. In addition, a limitation of the previously described studies is that they did not account for other relevant confounding factors, such as age, cigarette smoking and atopy. Further studies have considered thunderstorm asthma in the context of a range of environmental and meteorological factors, such as temperature and changes in aeroallergens.

The relationship between recorded acute asthma attendances to a London ED, meteorological features and aeroallergens, was investigated by Celenza *et al.* They identified significant associations between increased asthma presentations ($P < 0.05$) and preceding decreased air temperatures, falls in grass pollen counts, rises in sulphur dioxide concentrations, 1–9 lightning strikes and reduced rainfall in the same day.⁹

Hospital admissions for regions of England were assessed in relation to regional density of sferics (atmospheric signals accompanying lightning, related to the strength of thunderstorm updrafts and charges on hydrometeors). This identified an increased RR of asthma admissions for high sferic

density, for patients aged less than 15 years (RR 1.13, 95% CI: 1.02–1.26) and those aged 15 years or more (RR 1.28, 95% CI: 1.15–1.43). These increased RRs remained significant at minimum pollen counts of 50 grains/m³/day.¹⁰ This study examined large areas covered by these 14 regions in England. This highlights the challenge of studying thunderstorm asthma, where smaller units of populations may lack adequate numbers of asthma cases for statistical analysis.

Grundstein *et al.* compared thunderstorms and other meteorological features in Atlanta, Georgia, USA with ED visit data for local hospitals, and identified a significant association between daily counts of asthma visits to the ED and thunderstorm occurrence ($P < 0.001$).¹¹ When stratified by rainfall and wind speed, associations with asthma visits were only significant for thunderstorms with rainfall ($P < 0.05$) and thunderstorms with moderate wind speed (9.5–14.3 m/s, RR = 1.049, $P < 0.001$) compared with lower and higher wind speeds.

A study of thunderstorm asthma in New South Wales, Australia used a case-control design to investigate if the odds of thunderstorms were higher on days with excess asthma (cases) compared with non-excess days (controls). Applying this approach identified significantly increased odds of thunderstorms within 80 km and thunderstorm outflows.¹²

The effect on primary care was also clearly demonstrated by an analysis of sentinel general practice attendance data which identified a significant positive association between the 25 June 1994 thunderstorm (the day after the storm, when affected persons may have attended general practices), and asthma consultation rates for adults, children and the elderly, after controlling for other relevant confounders.¹³

Who is affected by thunderstorm asthma and how are health services affected?

Newson *et al.* identified 38 excess asthma episodes in England between 1990 and 1994 using a log-linear autoregression model based on regional counts of asthma admissions.¹⁴ Of these, 12 (32%) were associated with thunderstorms.

Several descriptive studies of affected patients have identified that affected patients may not have been previously known to suffer asthma, but may suffer hayfever (such as those allergic to grass pollen or fungi) or other allergic conditions instead. In one study, 9 of 19 affected patients had a history of hayfever but not asthma³ while another reported that 22 of 38 affected patients were hayfever sufferers.⁴ The majority of patients (78.7%) in one study were able to be discharged from EDs,

following initial treatment.¹⁵ Research has identified an increased risk of symptoms in people who have been outdoors during thunderstorms rather than indoors.¹⁶

Health services have been seriously affected by thunderstorm asthma. Venables *et al.* identified that during the 24 and 25 June 1994 episode, EDs experienced exhaustion of asthma-related supplies including nebulizer face masks (5 of 11 departments), steroid tablets (8 of 11), B₂ agonist inhalers (6 of 11) and B₂ agonist nebulers (4 of 11).¹⁷ During the same event, half of all the regional health authorities in England observed a 6-fold increase in asthma attendances in EDs. Within the same study, 11 District Health Authorities reported difficulty in ED service provision.

The role of aeroallergens in thunderstorm asthma

There has been much interest in the possible role of aeroallergens such as pollen, in the development of thunderstorm asthma. Ecological level research has investigated the potential associations between aeroallergens and thunderstorm asthma episodes. For example, grass pollen counts of 50 grains/m³/day or more in combination with high sferic (lightning) density significantly increased RRs for asthma admission, over a 4-year period.¹⁰

Research in Australia also identified that there was a 4-fold increase in closed pollen grains and a 7-fold increase in ruptured pollen grains during thunderstorms compared with the previous hour, for excess asthma days.¹² These findings support the potential role of either grass pollen grains or paucimicronic starch particles in thunderstorm asthma. These latter particles are released from grass pollen grains when they rupture, and are small enough to be inhaled into the lungs. Therefore, it may be the ruptured pollen grains that are the most useful measurement.

There has also been research into the role of airborne fungi in thunderstorm asthma. A detailed environmental study during the June 1994 thunderstorm also detected *Cladosporium*, *Ustilago segetum* and ascospores in an environmental study of airborne fungal spores.¹⁸ A British study has identified increased odds of asthma admissions with elevated levels of airborne fungi such as *Didymella* (OR 1.65, $P < 0.0001$), *Cladosporium* (OR 1.47, $P = 0.0002$) and broken (not total) *Alternaria* species (OR 2.21, $P < 0.0001$).¹⁹ The levels of some spores, such as *Didymella* and *Sporobolomyces*, can increase as they are released during rainfall.

There have also been relevant observations in other countries. A Canadian study also reported increases in air levels of different aeroallergens on the day before, and day of the thunderstorm, including algae (increased 25-fold), *Amaranthaceae* (12-fold), *Chenopodiaceae* (12-fold), *Myxomycetes* (7-fold), *Stemphylium* (6-fold), *Helicomyces* (3-fold) and a background increase of Particulate Matter of maximum diameter 10 µm (PM₁₀). Another Canadian study showed that increases equivalent to the seasonal mean total spore levels of deuteromycetes, basidiomycetes and ascomycetes were associated with increased ED visits for asthma of 2.15, 1.81, 3.41 and 2.96 respectively.²⁰

However, the previously described studies are generally ecological studies with a limited range of relevant variables included. Mixed-method designs might be more preferable as suggested by the Medical Research Council,²¹ including measurement of confounders and multiple measures of asthma frequency before and after thunderstorms.

Better study designs could also combine study of individual aeroallergen sensitivities, in addition to ecological analyses. For instance, Venables *et al.*¹⁷ identified that the 1994 episode had an increase in grass pollen to a 6 year high prior to the thunderstorm and increases in *Cladosporium*, *Phaeosphaeria nigrans* and *Diatrypaceae* occurred in thunderstorm-affected areas, with *Sporobolomyces* increasing the next day. These raised aeroallergen levels were accompanied by a decrease in temperature and increase in humidity immediately beforehand. However, pollution levels including ozone, nitrogen dioxide, sulphur dioxide and PM₁₀ during the same period were close to normal levels.

In addition, 16 patients affected by this thunderstorm underwent allergy testing, of which 12 had high IgE levels for grass pollen. However, sensitivity to other fungal spores of interest, was not assessed.

An Italian case series of seven thunderstorm asthma patients identified that all were sensitive to *Parietaria* species pollen but not other taxa. However, these two case series lack any useful comparator group such as non-thunderstorm patients.²²

Higher quality evidence for thunderstorm asthma cases also includes studies of environmental levels of aeroallergens and aeroallergen sensitivity in thunderstorm asthma patients compared with controls.

One study of patients in England demonstrated significantly increased odds of *Cladosporium* or *Alternaria* species sensitivity in thunderstorm asthma patients compared with seasonal asthma controls. A strength of this study is that selected controls had also experienced exacerbations of asthma.¹⁹ A second case-control study in Australia identified increased odds of sensitization to rye grass and

Cladosporium among cases compared with controls.¹⁶ Sensitization to *Cladosporium* and *Alternaria* is known to significantly increase the odds of suffering severe asthma, outside of thunderstorms.²³

Separately, skin-prick testing of patients affected by two thunderstorm asthma episodes in Melbourne, Australia⁸ identified increased sensitivity to rye grass pollen among 12 cases compared with 16 controls ($P < 0.05$).

In contrast, one study of aeroallergen sensitivity testing of patients affected by the July 1983 thunderstorm asthma episode in Birmingham, England failed to detect any significant difference between cases and asthma controls.²⁴ However, numbers of patients tested may have been too small to detect significant differences between the two groups.

Discussion

This review has summarized published evidence for a relationship between thunderstorms and excess asthma episodes. There have been several documented episodes with significant impacts on individuals and health services. However, further research has retrospectively identified smaller thunderstorm asthma episodes. Significant interest has focused on changes in aeroallergens and meteorological factors. The levels of aeroallergens, such as pollen grains and fungal spores (such as *Cladosporium*) have been observed to fluctuate prior to, or during thunderstorm asthma episodes. The potential mechanisms of aeroallergen involvement in thunderstorm asthma and possible approaches to predicting such episodes, are explored further below.

How might aeroallergens be involved in thunderstorm asthma?

It is unclear how pollen is exactly involved in the development of thunderstorm asthma. Taylor and Jonsson hypothesize that the updrafts which drag air into thunderstorm clouds, collect pollen grains which rupture to release pollen fragments including paucimicronic starch grains which contain allergen, and are then distributed outwards by downdrafts. The authors also speculate that pollen may be spread by pollen entering rain droplets and then being released when the rain droplets evaporate.²⁵ O'Leary *et al.* have identified on the basis of modelling, that changes in the electrical charge on aeroallergen particles, which might occur during thunderstorms, would promote deposition of particles within the alveoli.²⁶ This would increase the probability of an allergic response.

Following on the observation that being close to thunderstorm outflows increased the odds of excess asthma occurring, the role of the thunderstorm outflow itself should be investigated. These outflows, which represent the air forced out from the storm system itself, can be observed with Doppler radar,²⁷ and may help explain the interactions between thunderstorms and aeroallergens.

Would an early warning system be effective and feasible?

The scale of thunderstorm asthma and the burden it places on health services supports the need for a strategy to mitigate these effects of such phenomenon. An early warning system might be considered in this situation to warn the public and help health services prepare. Such a system would only be effective if thresholds for meteorological and aerobiological parameters are sufficiently sensitive and specific for excess acute asthma.

In 1998, Newson *et al* studied excess acute asthma episodes with and without thunderstorms to identify characteristics that could accurately predict thunderstorm asthma episodes.¹⁴ Using a model including lightning and grass pollen, they were unable to predict thunderstorm asthma episodes with sufficient specificity, leading to more episodes being predicted than actually occurred. The lack of specificity of this model may be explained by the exclusive use of grass pollen and the exclusion of the other aeroallergens identified in this review. The potential inclusion of a wider range of aeroallergens to early warning for thunderstorm asthma deserves further assessment but is limited by the range of recorded data. For instance, in England fungal spore counts occur at only a few sites (Y Clewlow, personal communication). Therefore, early warning systems for thunderstorm asthma currently have limited practical applications.

An additional limitation of an early warning system is that a proportion of affected patients will have not been previously diagnosed as asthma sufferers. Therefore, any early warning system would have only benefited a proportion of those potentially affected but might be used to warn hayfever sufferers or others vulnerable to an acute asthma attack.

Limitations of this review

Our review included only English language publications. It is possible that there may be publications in other languages relating to thunderstorm asthma which have not been identified, as this phenomenon could also occur on non-English speaking countries.

In addition, some identified English language publications could not be accessed. As thunderstorm asthma is recognized rarely, this has led to a limited number of high-quality studies being published on this subject. As a consequence, most of the public health recommendations made in the following section are based on low quality (Grade D) evidence.

Implications for public health advice

The following recommendations have been made, and graded according to the SIGN methodology²⁸ on the basis of available evidence. The SIGN methodology is a widely accepted method for assessing the quality of evidence from different levels of the research hierarchy:

- Asthma patients sensitive to known thunderstorm-related aeroallergens may be advised to shelter indoors and close windows (Grade C).
- Asthma patients should have easy access to their prescribed asthma medications such as inhalers (Grade D).
- Health professionals' advice to these patients about how to deal with acute asthma following thunderstorms, should follow national guidelines for Asthma²⁹ (Grades A–C).
- A proportion of thunderstorm asthma patients will never have suffered acute asthma before; health services must therefore be prepared for increased asthma-related presentations (Grade D).
- Acute health services should be made aware of the possibility of thunderstorm asthma and consider including excess acute asthma episodes within their business continuity plans (Grade D).

Areas for further research

Important areas of future thunderstorm-related research, for public health in the UK, are:

- The impact of thunderstorm asthma on wider health services (e.g. ambulances) should be evaluated. Small but significant increases in acute asthma may be detected but the impact of these may not be consistently documented.
- Investigation of the contribution of psychological factors in observed thunderstorm asthma cases, in relation to other factors such as aeroallergen levels.
- The potential application of syndromic surveillance systems to aid study of thunderstorm asthma episodes.

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