

**ACUTE IMPACT OF VOLCANIC ASH ON ASTHMA SYMPTOMS AND TREATMENT**

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**Information about the impacts of disasters on health is useful for establishing hazard prediction maps and action plans of disaster management. This study aims at learning effective asthma management from the volcano disaster of Mount Asama eruption in Japan on September 1, 2004. We conducted a cross-sectional study to assess the acute impact of volcanic ash on asthma symptoms and their treatment changes by using a questionnaire completed by 236 adult asthmatic patients and their physicians. In the ashfall over 100g/m<sup>2</sup> area, 42.9% of asthma patients suffered exacerbations, PEF decreased, asthma treatments increased, and inhalation of  $\beta_2$  stimulants was used most for exacerbated asthma. Compared to severe asthma patients, mild and moderate asthma patients were most at risk. Severe asthma patients were not affected since most of them knew their asthma status was severe, and did not go outside and kept windows closed. Deteriorated asthma symptoms of wheezing, chest tightness and cough appeared in the ashfall over 100g/m<sup>2</sup> area. Ash contained inhalable 10 $\mu$ m diameter particles, and included high concentrations of airway toxic substrates of silica. These data suggest that ashfall over 100 g/m<sup>2</sup> is harmful, access to these areas by asthma patients needs to be restricted, and these areas need to improve asthma treatment. In addition, the increase in the proportion of asthma patients with wheeze and cough are diagnostic clues for ash-induced asthma in affected areas, and can be used by doctors to tell whether patients are receiving sufficient asthma treatment.**

Mount Asama, an active volcano located 200 km northwest of Tokyo in Gunma, Japan, last erupted on September 1, 2004. The total amount of volcanic ash resulting from the eruption amounted to 200 000 tons, and heavy ashfall was observed in the area northeast of Mt. Asama in Gunma prefecture. The ash particles from the crater reached Souma city in Fukushima prefecture 250 km to the northeast (Japan Meteorological Society). In a case-control study on acute exposure to ash after the Mount St. Helens eruption in 1980, ninety percent of asthma patients had exacerbated symptoms (1). The potential danger of the ash from the Mt. Asama volcanic eruption concerned asthma patients.

Although volcanic eruptions are naturally occurring events, the ability to make quick decisions and to take immediate action are necessary prerequisites for medical doctors working in disaster situations. While volcanic eruptions do not occur frequently, when they occur they are usually associated with catastrophe and casualties (2). To carry out disaster management effectively, it is therefore important to collect data about past disasters and

analyze the impact on health encountered at the time of the disaster.

In this study, we conducted a cross-sectional study on asthma symptoms and treatments in response to the Mt. Asama eruption on September 1, 2004. The Center for Disease Control (CDC) in the U.S.A. published a detailed report on the immediate public health concerns and necessary responses at the time of the Mount St. Helens eruption (3). The CDC proposed the following actions in the event of an eruption: 1) Assessment of the potential health impact and recommendations regarding prevention and control. 2) Restricted areas-designation and enforcement near the volcano for the general public. 3) Air monitoring for the type and concentration of respirable and/or total suspended particles in ashfall areas (determination of sampling methods and locations and interpretation of data). To determine the health impact of volcano ash and the restrict area, we evaluated the impact of volcanic ash on the ratio of affected asthma patients, the grades of asthma severity and which grades were most at risk, the peak expiratory flow rate changes (PEF),

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the apparent exacerbation in respiratory symptoms in asthma patients, and the medicines that were administered by doctors and self-administered by patients with exacerbated asthma. The relationship between the particle size and the nature of ash particles and its exposure on asthma were also discussed. From this study, we aimed to learn effective asthma management in volcano disasters.

#### MATERIALS AND METHODS

##### *Scale of the volcanic eruption and nature of ashfall.*

Volcanic ash fell to the northeast of the crater in the September 1 eruption. Analysis of the distribution of ashfall, the size and constituents of the ash were conducted by the Dept. of Medicine and Molecular Science, and Faculty of Health Science at Gunma University (4). The distribution of the ashfall is shown in Figure 1. Ashfall was expressed in g/m<sup>2</sup> per 24 hr, and was measured at 14 locations. The eruption of Mt. Asama was associated with earthquakes, rumbling, streams of molten rock and volcanic ash, and tephra was ejected over an area of 2 to 3 km from the crater.

*Selection of surveillance area.* A cross-sectional study was designed to assess the health impact of the eruption. Given that volcanic ash fell on the northeastern side of the crater on September 1 (Fig. 1), we designated the northeastern area as the ashfall area. The area to the southeast of the crater was designated as the control area because ash was not observed in the area. We then divided these areas into four study areas based on the amount of ashfall; the >100 g/m<sup>2</sup> ashfall area, the 100 g/m<sup>2</sup>> ashfall> 10 g/m<sup>2</sup> ashfall area and their respective control areas. The heavy ashfall area was located 35 km from the crater and included Agatsuma town. The amount of ash inside this area was >100 g/m<sup>2</sup> and is delimited by the 100 isoline, which also includes the area delineated by the 1000 g/m<sup>2</sup> isoline in figure 1 (100 g/m<sup>2</sup> ashfall area). The next ashfall area was located 35 to 50 km from the crater around Takayama town and Numata city. The amount of ash in this area was 100 g/m<sup>2</sup>> ashfall> 10 g/m<sup>2</sup> and is delimited by isolines 10 and 100 in figure 1 (10 g/m<sup>2</sup> ashfall area). The control areas were located on the southeastern slopes of the volcano and had no ashfall after the September 1 eruption. These two areas were the 100 g/m<sup>2</sup> area controls which lay within 35 km from crater near the towns of Matsuida and Shimonita (100 g/m<sup>2</sup> ashfall control area; not shown in Fig. 1). The control for the 10 g/m<sup>2</sup> ashfall area was 35 to 50 km southeast of the crater area near Tomioka city (10 g/m<sup>2</sup> ashfall control area; not shown in Fig. 1).

##### *Hospital-based surveillance network for asthma patients.*

All of the main hospitals located in the selected areas were identified and questionnaires were sent to a total of thirteen on September 3. A total of ten hospitals were identified in the ashfall area and three hospitals were picked in the control area. Nine hospitals in the ashfall area and three hospitals in the control area returned questionnaires. Given that the capacity of the individual hospitals in the ashfall area were smaller than those of the control area, a larger number of hospitals were sampled. Asthma patients in the ashfall and control areas who visited an emergency room, who were admitted to hospital, or who visited hospitals for regular medical examinations, were asked about their condition before and after the September 1 eruption. The questionnaire survey was limited to the first

eruption on September 1. There were 42 patients in the 100 g/m<sup>2</sup> ashfall area (men=20, women=22) with a mean age of 60 ± 20 (mean±SD). In the 10 g/m<sup>2</sup> ashfall area, there were 76 patients (men=51, women=35) with a mean age of 58±20 (mean ± SD). The 36 patients in the 100 g/m<sup>2</sup> ashfall control area (men=19, women=17) had a mean age of 69±12 (mean ± SD), and in the 10 g/m<sup>2</sup> ashfall control area the 74 patients (men=40, females=34) had a mean age of approximately 55 ± 28 (mean ± SD). Since the 100 g/m<sup>2</sup> ashfall area is located on a mountain side and nearer to the crater than the 10 g/m<sup>2</sup> ashfall area, fewer patients lived in the 100 g/m<sup>2</sup> ashfall area than in the 10 g/m<sup>2</sup> ashfall area. All patients gave written informed consent before submitting the questionnaire. The surveillance was conducted by the Department of Molecular Science of Respiratory and Allergy, and the Department of Health Science at Gunma University of Medicine

*Questionnaire.* A questionnaire was used to survey asthma patients (supplemental data 1). The questionnaire was composed of two parts and the questions only related to the September 1 eruption. Briefly, the first half of the questions (Q2-Q9) were for patients and related specifically to exacerbated asthma symptoms (Q2: wheeze, Q3: chest tightness, Q4: volume of sputum, Q5: expectation of sputum, Q6: cough, Q7: early morning attack, Q8: night time attack Q9: asthma attack frequency). The second half of the questionnaire was for the medical doctor, requiring information on the medication prescribed/administered in response to volcanic ash exposure and the patients' medications before the eruption. Administered medicines were as follows; A: short-acting  $\beta_2$  stimulants, B: steroid inhalation, C: long-acting  $\beta_2$  stimulants, D: intal inhalation, E: oral  $\beta_2$  stimulants, F:antibiotics, G:leukotriene antagonists, H: anti-cholinergics, I: theophylline injections, J:steroid injections, K: oral anti-allergics.

*Grading of asthma severity.* Asthma severity was graded based on the Global Initiative For Asthma® (GINA 2002) (5).

*Airway monitoring and asthma treatment score.* To objectively evaluate airflow limitations, peak expiratory flow (PEF) was measured using a Mini Wright PEF meter (Health Scan Products Inc, Cedar Grove, New Jersey) and the American Thoracic Society (ATS) scale. PEF was compared between pre and post the day of eruption on September 1. The Japan Asthma Treatment Score (JATS) was used to evaluate the changes in medication pre-and post-eruption (6) (supplemental data 2)

*Statistical analysis.* Differences between patient numbers in areas and severity in response to ashfall were calculated by the m x n Chi square test, with Yates' test applied to adjust data with samples <10. Changes in PEF and asthma treatment score before and after ashfall were determined using the Paired-t test and statistical significance was taken as \* $P < 0.05$ .

#### RESULTS

Patients with deteriorated asthma symptoms numbered 32/136 (23.5%) of the total in the entire ashfall area, 11/110 (10%) in the total control area, 18/42 (42.9%) in the 100 g/m<sup>2</sup> ashfall area, 3/36 (8.3%) in the 100 g/m<sup>2</sup> control area, 14/94 (14.9%) in the 10 g/m<sup>2</sup> ashfall area, and 8/74 (10.8%) in the 10 g/m<sup>2</sup> ashfall control area. Patients that lived in either the 10 g/m<sup>2</sup> or 100 g/m<sup>2</sup> ashfall areas exhibited significantly deteriorated asthma compared to

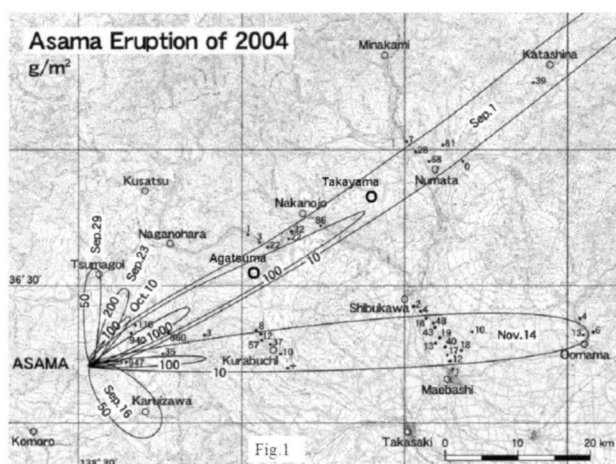


**Fig. 1.** The distribution and magnitude of ashfall from the Mt. Asama eruption in Japan on September 1, 2004. The amount of ash in this area was  $100 \text{ g/m}^2 > \text{ashfall} > 10 \text{ g/m}^2$  and is delimited by isolines 10 and 100 in figure 1 ( $10 \text{ g/m}^2$  ashfall area). Modification of Hayakawa et al (10).; reproduced with permission.

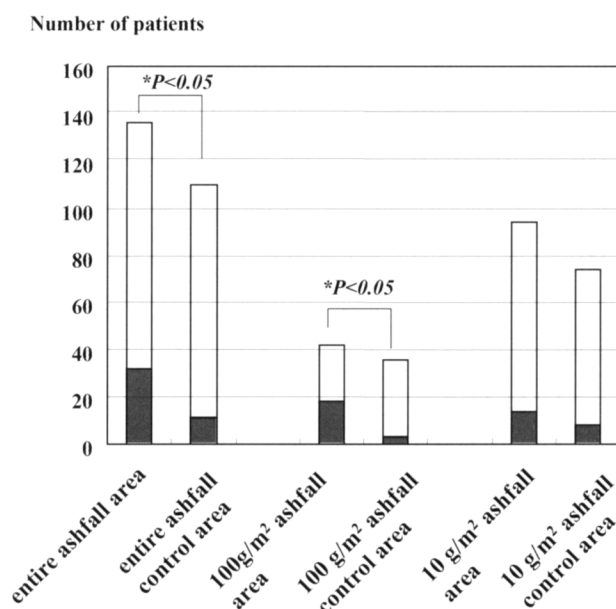


**Fig. 2.** Number of patients presenting with asthma symptoms in the ashfall and control areas. Shaded bars indicate the number of patients that showed deterioration of asthma and blank bars indicate the number of patients with no deterioration of asthma. \* $P < 0.05$ .

the total control area. However, when the ashfall area was divided into the  $10 \text{ g/m}^2$  and  $100 \text{ g/m}^2$  ashfall areas, patients in the  $100 \text{ g/m}^2$  ashfall area were found to be significantly worse (42.9%). Conversely, the number of deteriorated asthma patients in the  $10 \text{ g/m}^2$  ashfall area were not significantly different from the number in the

control area (Figure 2). Affected severities of asthma are shown in Figure 3. Patients with deteriorated asthma in the  $100 \text{ g/m}^2$  ashfall area numbered 7/18 (38.9%) in the mild group, 10/15 (66.7%) in the moderate group, and 2/9 (22.2%) in the severe group. However, in the  $100 \text{ g/m}^2$  control area, the mild group numbered 0/12 (0%), the moderate group numbered 4/19 (21.1%), and the severe group contained 1/5 (20%) patients. Mild and moderate grades were significantly affected by the eruption in the  $100 \text{ g/m}^2$  ashfall area. There were no differences in the deteriorated asthma symptoms between the  $10 \text{ g/m}^2$  ashfall area and the  $10 \text{ g/m}^2$  control area in all grades of asthma patients (data not shown). Mean age (mean $\pm$ SD) and gender did not differ significantly between ashfall and control areas, and the proportion of asthma severity in mild, moderate and severe cases between areas were not significantly different (data not shown). Airflow limitations were evaluated by PEF (supplemental data 3). In the  $100 \text{ g/m}^2$  ashfall area, PEF before the eruption was  $325.7 \pm 69.5 \text{ L/min}$ , but at  $291.4 \pm 97.4 \text{ L/min}$  it was significantly less after the eruption (mean $\pm$ SD,  $n=7$ ). In the  $10 \text{ g/m}^2$  ashfall area, PEF before and after the eruption was  $347.9 \pm 157.8 \text{ L/min}$  and  $321.6 \pm 156.4 \text{ L/min}$ , respectively, which was not significantly different (mean $\pm$ SD,  $n=8$ ). The asthma treatment score in the  $100 \text{ g/m}^2$  ashfall area before the eruption was  $7.8 \pm 6.4$  (mean $\pm$ SD,  $n=42$ ), increasing significantly to  $9.65 \pm 6.9$  after the eruption (supplemental data 4). In the  $100 \text{ g/m}^2$  ashfall control area, the scores before and after the eruption remained the same at  $8.4 \pm 6.9$  and  $8.5 \pm 6.9$  (mean $\pm$ SD,  $n=35$ ), respectively. Similarly, the scores for the  $10 \text{ g/m}^2$  ashfall and control areas did not change before and after the eruption (data not shown). Variations in asthma symptoms were compared between the  $100 \text{ g/m}^2$  ashfall area, the  $100 \text{ g/m}^2$  ashfall control area, and the  $10 \text{ g/m}^2$  ashfall area (Figure 3). In the  $100 \text{ g/m}^2$  ashfall area, wheezing (Q2), chest tightness (Q3), and cough (Q6) appeared in many patients, while in the  $100 \text{ g/m}^2$  ashfall control area and the  $10 \text{ g/m}^2$  ashfall area, sputum expectoration (Q5), sputum volume (Q4), and cough (Q6) appeared many in patients. The most frequently used medicines in response to the eruption were short-acting  $\beta_2$  stimulant inhalants, steroids and long-acting  $\beta_2$  stimulants (Figure 4). The ash included particles  $10 \mu\text{m}$  in diameter. Ash particles consisted primarily of silica (60%) and also contained aluminum and other minerals (4).

## DISCUSSION

Our study revealed that the potential impact of volcano ash on asthma patients. Asthma patients exposed to ash in excess of  $100 \text{ g/m}^2$  were at high-risk for exacerbation of their asthma. At 42.9%, the ratio of this risk was very high. Mild (38.9%) and moderately (66.9%) graded asthma patients in the  $100 \text{ g/m}^2$  ashfall area were

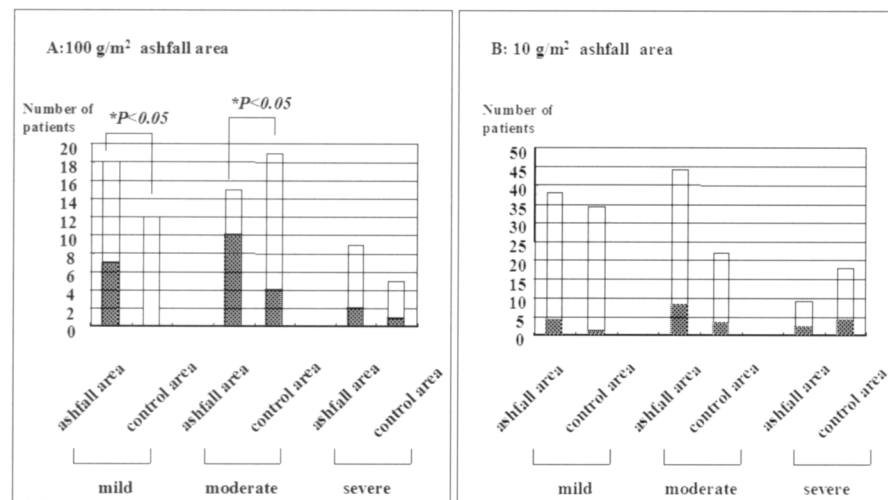


**Fig. 3.** Severity of deterioration in asthma after the eruption. Panel A shows the 100 g/m<sup>2</sup> ashfall area, and panel B shows the 10 g/m<sup>2</sup> ashfall area. Asthma severity was graded as mild, moderate and severe. Shaded bars indicate the number of patients showing a deterioration in asthma and blank bars indicate number of patients not showing deterioration in asthma. \*P<0.05.

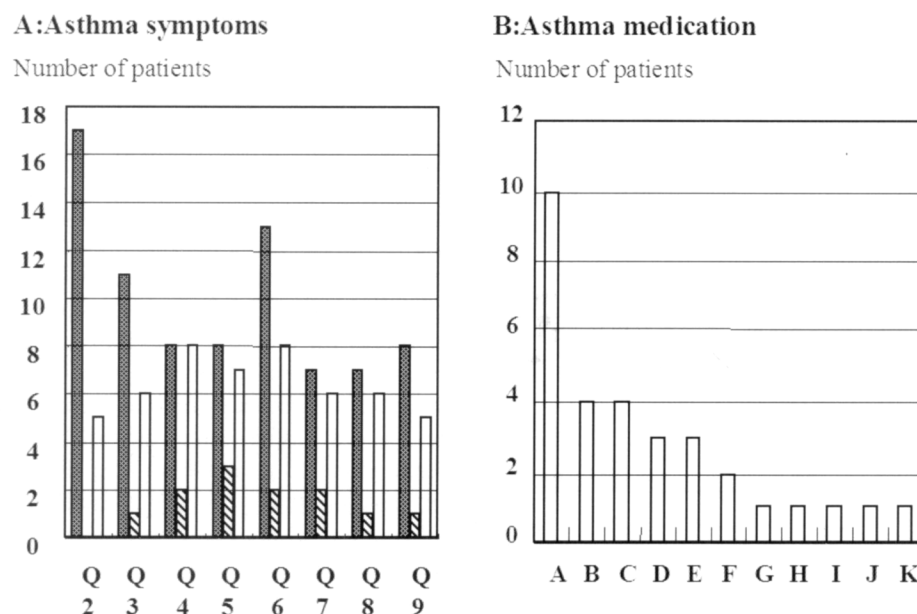


**Fig. 4.** Deteriorated asthma symptoms and treatments. Panel A shows differences in deteriorated asthma symptoms between 100 g/m<sup>2</sup> ashfall area, the 100 g/m<sup>2</sup> ashfall control area and the 10 g/m<sup>2</sup> ashfall area. The number of patients presenting with deterioration of asthma symptoms after the eruption are shown by the shaded bars for the ashfall 100 g/m<sup>2</sup> area, hatched bars for the 100 g/m<sup>2</sup> ashfall control area, and blank bars for the 10 g/m<sup>2</sup> ashfall area. Explanation of Q2 to Q6 are described in the Methods section. Panel B shows medications administered due to exacerbation of asthma associated with volcanic activity in the 100 g/m<sup>2</sup> ashfall area. Medicines of A to K are described in the Methods section.

significantly more at risk. There are currently no reports on the relationship between the severity of asthma and the amount of ashfall. The ratio of exacerbated severe asthma patients was not statistically different between any of the ashfall and control areas. The reasons why the severe asthma patients were not affected by the eruption

was because they did not go outside, kept the windows shut, or wore masks. They were aware that they were at risk and feared the ashfall, which is why they protected themselves from ash particles. Unexpectedly, patients with mild asthma were affected. We suspect that since ash particles included silica particles, which are known

airway irritants, and because mild asthma patients already exhibit airway hyper-responsiveness (5), exposure to ash particles triggered airway inflammation. Several activities can trigger an asthma attack: house cleaning, car cleaning, repeatedly opening and closing an umbrella, or collecting sand with a high ash content when doing pottery. There were no deaths and no de novo asthma was associated with the eruption. However, there were three incidents of recurrence in asthma patients who had a past history of asthma but who had not experienced symptoms for at least five years before the eruption.

In the 100 g/m<sup>2</sup> ashfall area, PEF of asthma patients decreased and asthma treatment increased. PEF was used as an objective evaluation method for asthma control (7). Doctors and patients can interpret the condition of the airway by themselves from PEF records and this information can be used for preventing asthma exacerbation. Consequently, recording PEF in ashfall areas is recommended for the prediction of asthma exacerbation.

Deterioration of asthma symptoms in the 100 g/m<sup>2</sup> ashfall area differed from those observed in the 100 g/m<sup>2</sup> control and 10 g/m<sup>2</sup> ashfall areas. More severe asthma symptoms appeared in the 100 g/m<sup>2</sup> ashfall area with wheezing, chest tightness, and cough occurring in many patients. Expectoration of sputum, increased volume of sputum, and cough were found mainly in patients from the 100 g/m<sup>2</sup> control and 10 g/m<sup>2</sup> ashfall areas. The symptoms of cough and wheeze also occurred in bronchitis and emphysema patients exposed to volcanic ash (1) and cleanup workers at the World Trade Center (WTC) (8). Cough and wheeze were probably non-specific respiratory reflux symptoms against heavy exposure to harmful irritant particles, and asthma patients have a higher risk of presenting with these symptoms. Medical doctors should ask patients about changes in wheezing, chest tightness, and coughing pre-and post eruption. By asking these questions doctors are able to estimate the risk of asthma in patients in those areas and can consider whether to administer treatment. The most commonly used medicine for asthma exacerbation at the time of the Mt. Asama eruption was a short-acting  $\beta_2$  stimulant inhalants. This was because short-acting  $\beta_2$  stimulants have a rapid effect on dilating the airway (5). It appears that the administration of short-acting  $\beta_2$  stimulants was appropriate in Mt. Asama cases. Once an asthma attack occurs, treatment requires the administration of reliever and controller medications. It would therefore be better to use both reliever and controller drugs when patients experience asthma attacks in response to an eruption. After the eruption, asthma treatment scores increased in the ashfall 100 g/m<sup>2</sup> area, indicating that a supply of asthma drugs is needed in areas where levels of ashfall are 100 g/m<sup>2</sup> at the time of volcanic eruptions.

The ash included particles 10  $\mu$ m in diameter. Particles measuring 10  $\mu$ m in diameter are respirable and are mainly deposited in the large airways (9) where they can affect asthma (10). Ash consisted of 60% (%/weight) of silica, aluminum and other minerals. Ash particles from the Mount St. Helens eruption in 1980 also included a high concentration of silica (11), which has been reported to cause increased oxidant production in human peripheral monocytes and cytotoxicity in human monocytes and alveolar macrophages (12). Furthermore, ash particles from the Mount St. Helens eruption caused asthma exacerbation (1). Mt. Asama and Mount St. Helens are both andesite volcanoes, and since the ratio of minerals in ash particles from Mt. Asama are highly similar to those of Mount St. Helens, it is likely that ash particles from Mt. Asama have the potential for asthma exacerbation.

In conclusion, we showed that ashfall in excess of 100 g/m<sup>2</sup> is harmful for asthma patients. Medical doctors and volunteers working near volcanic disaster areas should therefore have information regarding the predictable health impact of an eruption before going to the area if they are to develop effective action plans. It can take considerable time to collect information on the effects of volcanic disasters on asthma. Also, since dangerous volcanic eruptions are not easy to predict and because they occur infrequently around the world, it is difficult to collect disaster information quickly when it is most needed. It is therefore hoped that a global information center be established to facilitate access to a database containing information on disaster medicine, comprehensible disaster data, and the most effective methods of action.

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and takes responsibility for the integrity of the data and the accuracy of the data analysis.

# REFERENCES

1. **Baxter P.J., R. Ing, H. Falk and B. Plikaytis.** 1983. Mount St. Helens eruptions: the acute respiratory effects of volcanic ash in a North American community. *Arch. Environ. Health* 38:138.
2. **Bradshaw L., D. Fishwick, T. Kemp, S. Lewis, N. Rains, T. Slater, N. Pearce and J. Crane.** 1997. Under the volcano: fire, ash and asthma? *N. Z. Med. J.* 110:90.
3. **Bernstein R.S., P.J. Baxter, H. Falk, R. Ing, L. Foster and F. Frost.** 1986. Immediate public health concerns and actions in volcanic eruptions: lessons from the Mount St. Helens eruptions, May 18-October 18, 1980. *Am. J. Public Health* 76:25.
4. **Hayakawa Y., T. Miyanaga, T. Nagai, S. Yuasa and M. Arai.** 2004. Ash, lapilli, and bombs issued by asama eruption 2004. <http://www.edu.gunma-u.ac.jp/~hayakawa/news/2000/asama/index.html>
5. **National Institute of Health, National Heart, Lung and Blood institute.** 2002. Global initiative for asthma@-Global strategy for asthma management and prevention.
6. **Miyamoto T., T. Shida, H. Tomioka, S. Makino, J. Kabe and S. Nakajima.** 1994. Committee on the Definition, Severity of Bronchial Asthma. *Japanese Society of Allergology. Arerugi* 43:71.
7. **Bateman E.D., H.A. Boushey, J. Bousquet, W.W. Busse, T.J. Clark, R.A. Pauwels, S.E. Pedersen; GOAL Investigators Group.** 2004. Can guideline-defined asthma control be achieved? The Gaining Optimal Asthma Control study. *Am. J. Respir. Crit. Care Med.* 15:170:836.
8. **Landrigan P.J., P.J. Liroy, G. Thurston, G. Berkowitz, L.C. Chen, S.N. Chillrud, P.G. S.H. Gavett, P.G. Georgopoulos, A.S. Geyh, S. Levin, F. Perera, S.M. Rappaport, C. Small; NIEHS World Trade Center Working Group.** 2004. Health and environmental consequences of the world trade center disaster. *Environ. Health Perspect.* 112:731.
9. **Labiris N.R. and M.B. Dolovich.** 2003. Pulmonary drug delivery. Part I: physiological factors affecting therapeutic effectiveness of aerosolized medications. *Br. J. Clin. Pharmacol.* 56:588.
10. **Donaldson K., M.I. Gilmour and W. MacNee.** 2000. Asthma and PM10. *Respir. Res.* 1:12.
11. **Prahalad A.K., J.M. Soukup, J. Inmon, R. Willis, A.J. Ghio, S. Becker, J.E. Gallagher.** 1999. Ambient air particles: effects on cellular oxidant radical generation in relation to particulate elemental chemistry. *Toxicol. Appl. Pharmacol.* 158:81.
12. **Becker S., J.M. Soukup and J.E. Gallagher.** 2002. Differential particulate air pollution induced oxidant stress in human granulocytes, monocytes and alveolar macrophages. *Toxicol. In Vitro* 16:209.