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Health effects following the Eyjafjallajökull volcanic eruption – a population-based study

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Abstract

Objective To determine if exposure to a volcanic eruption was associated with increased rates of physical and mental symptoms.

Design Cohort, with non-exposed control group.

Setting The Icelandic volcano Eyjafjallajökull exposed residents in southern Iceland to ash fall. This study was conducted winter 2010-2011, ca. six months after the eruption.

Participants Adult (18-80years of age) eruption-exposed South Icelanders (n=1148) and a control population of residents of Skagafjörður, North Iceland (n=510). The participation rate was 72%.

Main Outcome Measures Physical symptoms in the previous year (chronic), in the previous month (recent), General Health Questionnaire (GHQ-12) measured psychological morbidity.

Results The risk of symptoms during the last month was higher in the exposed population; tightness in the chest (odds ratio (OR) 2.5; 95% CI, 1.1-5.8), cough (OR, 2.6; 95% CI, 1.7-3.9), phlegm (OR, 2.1; 95% CI, 1.3-3.2), eye irritation (OR, 2.9; 95% CI, 2.0-4.1), and psychological morbidity symptoms (OR, 1.3; 95% CI,1.0-1.7). The risk of respiratory symptoms during the last 12 months was also higher in the exposed population; cough (OR, 2.2; 95% CI, 1.6-2.9), phlegm (OR, 1.6; 95% CI, 1.1-2.3), although the risk of underlying asthma and heart disease was similar. Twice as many in the exposed population had two or more symptoms from nose, eyes or upper-respiratory tract (24% vs 13%, $p<0.001$); this group also had increased risk of psychological morbidity (OR, 4.69; 95% CI, 3.39-6.50) compared with individuals with no symptoms. Most symptoms exhibited a dose-response pattern within the exposed population.

Conclusions Six to nine months after the Eyjafjallajökull eruption, residents living in the exposed area, particularly those closest to the volcano, had increased risk of respiratory symptoms. A portion of the exposed population presented with multiple symptoms and may be at risk for long-term physical and psychological morbidity. Studies of long–term consequences are therefore warranted.

Introduction

Throughout history, human societies have been exposed to volcanic eruptions and earthquakes which are responsible for many deaths every year worldwide.[1] Accurate information on mortality and long-term health consequences of natural disasters is instrumental to strengthen risk management and decrease their health impact.[2]

The eruption of the Eyjafjallajökull volcano in Iceland, from April 14th to May 20th 2010, made headlines worldwide, not least because of extensive effects on international flight traffic. Direct ash fall from the eruption was estimated at around 250 million tons, with rural regions in Iceland south and south-east of the volcano most severely affected.[3,4] Ash fall was continuous for about 6 weeks, and two years later ash is still re-suspended in the area. The fresh ash particles contained acids, and about 20% by mass were small enough to enter the lower airways.[5] A study of the most exposed population was conducted immediately after the eruption ended. Participants were examined by a physician, standardized spirometry was performed before and after bronchodilator usage, questionnaires about mental and physical health were applied. Ash exposure was associated with high rates of eye- and upper airway irritation (25% and 50% respectively), and exacerbation of pre-existing asthma but did not contribute to serious health problems or impair respiratory function compared to controls. 39% showed symptoms of psychological morbidity.[6] Meanwhile, the impact on long-term health of the residents remains to be explored.

Health effects of long-term exposure to a volcanic eruption are important both from a scientific and health care standpoint.[7] Iceland's population-based registries and strong infrastructure present opportunity to study such health impacts, particularly in terms of long-term follow-up.

Previous studies on volcanic ash exposure and health have shown increased respiratory morbidity and asthma attacks,[8] and increased irritation of the respiratory tract from short term exposure to volcanic gases and ash.[9] Long-term exposure to sulphuric gases (often emitted in volcanic eruptions) are associated with increased prevalence of chronic bronchitis and cardio-respiratory symptoms.[10,11] In addition to direct physical health hazards, experiencing floods, lava and gas flows and being exposed to prolonged ash suspension can be a threat to mental health. Stress levels may increase dramatically and contribute to long-term psychological morbidity such as post traumatic stress syndrom or depression.[12,13]

Utilizing the Icelandic population-based registers to identify all residents living in the vicinity of Eyjafjallajökull, the aim of this study was to investigate their self-reported physical and mental health six to nine months after the volcanic eruption. We hypothesized that residents of the Eyjafjallajökull area, particularly those most exposed, would be at increased risk of physical and psychological symptoms compared to an non-exposed population in North Iceland.

Methods

<u>Study area</u>

The exposed area in South Iceland is mostly farmland with a few villages. The area contains several volcanic systems that have been active in the past decades .[14] Almost from the onset of the eruption, the Environment Agency of Iceland monitored concentrations of inhalable particulate matter (PM_{10}) in up to three locations in the study area. The official health limit for air pollution, 50 µg/m^3 daily average, was surpassed more than half the time between May 7th and June 6th 2010, when air quality was continuously monitored in the most severely affected areas.[4]

The exposed area was divided into a low, medium and high exposure region (Supplement A). Based on satellite images of the eruption plume (coarse time resolution), information about the emission intensity[2] and observations of ash deposits on the ground.[5,15] Models calculated with FLEXPART show similar ash deposits, ranging from approximately 1000 g/m^2 in the region just south of the volcano, to about 200 g/m^2 near Vík some 50 km further east.[4]

The prevailing wind was from the north-west during the eruption, so the worst ash fall was south and east of the volcano. While ash deposits were relatively low west of the volcano, the volcano was in full view and thus residents here were more visually exposed than in other regions. The lowland regions south and west of the volcano are prone to flooding and some residents were evacuated because of glacial outburst floods in the first days of the eruption.

Study population

The study population included all residents in the municipalities closest to Eyjafjallajökull volcano (pre-defined by postal codes), identified in the population-based registry (Registers Iceland). Most live in farmlands (n=1207), the rest in small townships (N=859).[16] We identified 1615 inhabitants who were 18-80 years of age, lived in the exposed area during the eruption, could be reached and spoke Icelandic fluently. A sample of 697 demographically matched (age, gender, urban/rural habitation) residents from a non-exposed area in Northern Iceland was included as control group.

Data collection

Initially, all participants in the exposed group received an information and invitation letter. Some days after the letters were sent the recipients were contacted by telephone and asked whether they were willing to participate, and if so, whether they preferred to reply on paper or online. Subsequently, questionnaires or email invitations were sent and a week later a combined thank-you/reminder card was sent by post or e-mail. If needed, the participants were reminded again by phone. A similar protocol was used for the control group, except the introductory letter stated that a questionnaire would be sent a few days later, unless participation was declined.

Questionnaires were sent to the exposed population between November 19th and December 28th 2010 (six to seven months after the eruption ended) and the last replies were received in March 2011. The control group received questionnaires between January 26th and February 4th 2011, the last replies were received in April 2011.

The questionnaires contained no information revealing the identity of the respondent, instead, they had a running number which could be linked to the person's ID number through a list which was kept separately and securely to enable follow-up. Returned questionnaires lacking basic demographic information about gender, age and education were considered invalid and excluded.

Questionnaires

We used standard questions from the screening part of the European Community Respiratory Health questionnaire[16] and assessed underlying disease by asking "Has a medical doctor ever told you that you had the following diseases: asthma, heart disease, emphysema, chronic bronchitis and chronic obstructive pulmonary disease (COPD)" with the response alternatives "Yes" or "No" to each option. To assess recent symptoms, we asked "Have the following symptoms disrupted your daily activities during the previous month?" followed by a list of various symptoms from e.g. the respiratory system, skin or eyes or relating to pain. We also asked about smoking "Have you ever smoked","Yes" or "No", and "Have you smoked during the last month","Yes" or "No". Questions on regular use of medication were "Do you take medication regularly, that is, once per week or more often?" followed by listing asthma medication, analgesics, blood-pressure-lowering medication and sleep medication/anti-depressants/tranquillizers/medication for other mental health problems. Current psychological morbidity was evaluated from the General Health Questionnaire-12-item (GHQ-12) using a binary cut-off score of >2.[18,19]

Database & coding

The online survey was built with LimeSurvey.[20] Participants replying online accessed the survey using a unique identifier sent to them by email. Questionnaire replies on paper were entered into LimeSurvey according to uniform guidelines set by the researchers.

Statistical analysis

We first calculated descriptive statistics, contrasting background characteristics in the exposed and non-exposed population using X^2 – tests (*p* applies to all categories within demographic characteristics). Logistic regression was used to determine odds ratios (ORs) associated with residence in a) the exposed and non-exposed regions and b) the low, medium or high exposure areas within the exposed region. All models were adjusted for age, gender, smoking status (never, former and current) and education level, odds ratios and 95% confidence intervals (CI) were calculated from the outputs. A CI not including 1.0 or a *p*-value of 0.05 or less was considered statistically significant. A Venn diagram was drawn to show the interrelationship between key nasal, eye or upper respiratory symptoms (cough and/or phlegm without having a cold, eye irritation or itch, and sneeze, stuffed or runny nose). Demographic characteristics, risk factors and comorbidities of those reporting multiple symptoms were explored using X^2 – tests and logistic.

IBM SPSS 19[21] was used for data analysis. Individuals who had not replied to all relevant questions were excluded from the regression models.

Results

Valid questionnaires were obtained from 1148 of 1615 (71%) in the exposed population and 510 of 697 (73%) in the non-exposed population. More in the exposed population could not be reached or found (10.8% vs 7.2%; *P*=0.005), or refused to participate (17.8% vs 14.6%; *P*=0.069). The exposed and non-exposed participants had similar demographic characteristics; age, education levels, and occupational, marital and financial status (Table 1).

Analysis 1: Exposed vs. non-exposed

Respiratory symptoms such as waking up with a feeling of tightness in the chest, breathlessness, cough and phlegm in the last 12 months were more prevalent in the exposed population. When adjusting for sex, age, education and smoking status, symptom risks measured higher in the exposed population were; tightness in chest (OR, 2.0; 95% CI, 1.3-3.0), coughing without a cold (OR, 2.2, CI, 1.6-2.9) and having physician-diagnosed asthma (OR, 3.9, CI, 1.2-12.5) or chronic bronchitis, OR, 1.9 (95% CI, 1.1-3.1) (Table 2).

The risk of recent (during the last month), bothersome physical symptoms was increased in the exposed population; these were shortness of breath, OR, 2.1 (95% CI, 1.2-3.6), cough (OR, 2.6; 95% 1.7-3.9), phlegm (OR, 2.1; 95% CI, 1.3–3.2), and eye irritation (OR, 2.9; 95% CI, 1.8-4.5). Back pain, myalgia and insomnia were less prevalent in the exposed population. The exposed population had a marginally higher risk of recent, psychological morbidity (OR, 1.3; 95% CI, 1.0-1.7), blood pressure lowering medication use (1.3, 95% CI, 1.0-1.7), but lower risk of use of analgesics (OR, 0.7; 95% CI, 0.5-1.0) (Table 3).

Analysis 2: low, medium and high exposure

The prevalence of most respiratory symptoms during the last year increased with ash exposure. After adjusting for gender, age, education and smoking, the risk of waking up with a feeling of tightness in the chest was increased in the medium- and high exposure regions, OR, 2.1 (95% CI, 1.0-4.2) and OR, 3.1 (95% CI, 1.5-6.6) respectively. Chronic phlegm production was only increased in the high exposure region, OR, 2 .3 (95% CI, 1.2-4.4) (Table 4).

The risk of recent symptoms increased with exposure; cough (medium exposure OR, 3.6; 95% CI, 1.6-8.1; high exposure OR, 4.5; 95% CI, 2.0-10.2), phlegm (medium exposure OR, 4.2; 95% CI, 1.5-11.8, high exposure OR, 6.0; 95% CI, 2.1-17.1) insomnia (medium exposure 2.4, 95% CI, 1.2-5.0, high exposure OR, 2.8, 95% CI, 1.3-5.9), (Table 5). No significant associations were observed between level of exposure and feeling of tightness in the chest, psychological morbidity, use of analgesic- and blood-pressure lowering drugs, or physician-diagnosed disease, though a non-significant trend was observed with some outcomes.

Analysis 3: Multiple symptoms

A subgroup within both populations reported multiple symptoms from nose, eyes or upper respiratory organs. The proportion reporting two or more symptoms was proportionally larger in the exposed population than the non-exposed (23.8% vs 12.9%) (Supplement B). Within the exposed population the proportion was 13.3% in the low-exposure area, 24.7% in the medium exposure area, and 26.7% in the high-exposure area. In the exposed area, those who reported multiple key symptoms were more likely to be female (58.1% female *vs* 41.9% male, p<0.015), and have asthma, compared to those with no symptoms (26.9% asthma *vs* 3.4% asthma, p<0.001).

Analyzing the association between exposure and psychological morbidity and adjusting for multiple symptoms, we found that having multiple symptoms was associated with psychological morbidity, OR, 4.69 (95% CI, 3.39-6.50), irrespective of exposure level.

Discussion

Our study found that six to nine months after the Eyjafjallajökull eruption ended the participants from exposed areas reported increased wheezing, cough and phlegm, recent eye and skin irritation. Participants from medium and high exposure regions experienced significantly higher rates of upper respiratory, skin and eye irritation symptoms than those from the low exposure region. This suggests a dose-dependent relationship of the Eyjafjallajökull ash exposure on respiratory health, however, respiratory function was not investigated in this study. Many of the recent physical and mental symptoms were only marginally more prevalent in the high than the medium exposure area, indicating that there is a threshold beyond which additional exposure does not result in increased morbidity. Reporting two or more key respiratory symptoms was more common in the exposed population. Compared to the non-exposed, the exposed population reported only marginally higher prevalence of psychological morbidity. However, psychological morbidity was reported to be much higher in the subgroup reporting two or more symptoms, indicating that those with many symptoms represent a more sensitive subgroup within the population which should be especially targeted in preventive actions.

The main strengths of this study, our ability to identify the whole population experiencing a volcanic eruption as well as the high participation rate, both minimize the risk of selection bias. In addition, the internal response rate (answers to specific items) was high. The exposed and non-exposed populations were demographically similar and adjustment for age, gender and education further reduces the risk of confounding.

Regarding the limitations of the study, we have no information on the health status of the two populations before the eruption nor the health status of non-respondents, and cannot exclude the possibility that the groups may have differed before the eruption. Although the study benefits overall from high response rate, we have limited information on non-responders and therefore it remains uncertain to what extent, if at all, attrition affects our comparison across exposure areas.

Another limitation of the study is that all symptoms are self-reported which may confer misclassification of symptoms. However, it is unlikely that this bias differs across exposure categories. Classification of exposure areas (low, medium, high), which was based on estimated ash fall, may be imprecise and actual ash exposure may also vary within the exposure areas due to local weather conditions, terrain, or housing quality. Yet, if our classification is unclear or erroneous, this would reasonably result in compromised dose-dependent effects seen in our study and rather decrease the measured effects. It is also possible that exposures other than ash fall, e.g. noise, visibility, or living in lowlands exposed to lava and glacial outburst floods, are significant contributors to the psychological morbidity which we observed in this study.

The exposed region is varied with respect to population density and occupation; the high exposure area has a higher proportion of farmers, who spend more time outside, which may exaggerate the observed difference between the medium- and low exposure areas. On the other hand, residents of the high exposure area may have been more vigilant in avoiding exposure, which would reduce the difference between the exposure areas. Data collection for the exposed group went on in November-December, and January-February for the non-exposed group, which may induce bias with respect to respiratory symptoms which may be more common in January-February. However, this would attenuate the observed difference in respiratory symptoms.

Before the eruption of Eyjafjallajökull, dust storms frequently compromised air quality in the exposed area,[22,23,24] but during and after the eruption, air quality severely deteriorated.[4,5] Our findings of high rates of cough and eye irritation following exposure to volcanic ash are consistent with other studies, for example the Mount St. Helens eruption, where the number of emergency room visits for respiratory conditions increased three to five-fold. [25] Eye irritation was also more common in loggers exposed to Mount St. Helens ash, and the amount of eye mucus seemed to be dose-dependent on the ash density.[26]

Dose response and threshold effects of urban-type airborne particles on health have been explored in epidemiological studies,[27] but rarely in humans exposed to volcanic ash. A Japanese study of asthma treatment and volcanic ash exposure found worsening of symptoms in asthmatics in areas with more than 100 g/m^2 ash, but not in areas with less ash fall.[28] Dose response effects have been found in a study of rats exposed to high doses of volcanic ash from Mount St. Helens for up to two years developed lung lesions, but only minimal effects were found in those exposed to lower doses.[29] Other animal studies with shorter follow up or other ash types did not show the same results highlighting the need for long follow up and recognition of the variability in morbidity-inducing properties of volcanic ash.[8]

The psychological morbidity rates found in this study (20-26%) were lower than in the survey of the most exposed area at the eruptions' end (39%).[6] This may indicate some adaptation in the residents following the eruption. Although a disaster with more dramatic consequences, a similar trend was found in a Japanese study of evacuees from a volcanic area where 66.1% showed signs of psychological morbidity (GHQ-30) half a year after evacuation, while four years later the rate had fallen to 45.6%.[13] In our study, psychological morbidity was most common in the high exposure group, as was regular intake of medicines for depression, anxiety, sleep problems or other mental symptoms. Dose-response trends were found between psychological morbidity and exposure to the Mount St. Helens eruption,[12] indicating possible long-term risk of further psychological morbidity in the high exposure group.

The results from this study has implications for planners and authorities, as it indicates risk groups particularly susceptible to adverse reactions after exposure to volcanic ash. Also, the study design and registration of the participants enables that the exposed group may be followed up, both directly in a new questionnaire study, as well as in hospital, medicines and mortality registers.

Conclusions

In this population-based study we documented high prevalences of respiratory symptoms six to nine months following the Eyjafjallajökull eruption, especially among those most exposed. These findings lend important evidence for lasting health effects among those exposed to volcanic eruptions and give incentive for further studies, e.g. on predictive factors for morbidity, health of children and long-term follow-up. Important knowledge might be gained from such studies, enabling better options for decreasing morbidity among those who experiencing volcanic eruptions and increase their long-term well-being.

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Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations.

	Exposed **% (n/N)**	**Non-exposed** **% (n/N)**	***p-value***
Target population (identified in total population registers)	**1811**	**751**	
Could not be found or reached	10.8% (196/1811)	7.2% (54/751)	0.01
Study population	**1615**	**697**	
Refused to participate	17.8% (286/1615)	14.6% (102/697)	0.07
Originally agreed to participate	**1329**	**595**	
Explained non-participation *	7.0% (93/1329)	6.1% (36/595)	0.44
Un-explained non-participation **	6.6% (88/1329)	8.2% (49/595)	0.20
Response rate (participants/study population)	**71% (1148/1615)**	**73% (510/697)**	0.31
Demographic characteristics			
Male	49.0% (562)	51.4% (262)	0.36
Female	51.0 (586)	48.6% (248)	0.36
Age categories			
18-23	11.1% (128/1148)	8.2% (42/510)	0.07
24-30	8.6% (99/1148)	9.0% 46/510)	0.79

31-40	15.2% (175/1148)	14.3% (73/510)	0.55
41-50	20.3% (233/1148)	21.4% (109/510)	0.62
51-60	19.3% (222/1148)	22.2% (113/510)	0.19
61-70	15.9% (183/1148)	16.5% (84/510)	0.79
71- 80	9.4% (108/1148)	8.4% (43/510)	0.52
Education			
No formal education	5.4% (61/1134)	4.8% (24/501)	0.62
Primary education	35.9% (407/1134)	30.9% (155/501)	0.05
Secondary education	33.4% (379/1134)	37.7% (189/501)	0.09
Professional or university education	20.6% (234/1134)	23.8% (119/501)	0.16
Other education*	4.7% (53/1134)	2.8% (14/501)	0.08
Marital status			
Married or cohabitating	72.4% (831/1148)	76.6% (391/510)	0.07
Single or divorced	18.3% (210/1148)	15.5% (79/510)	0.17
Relationship – no cohabitation	6.8% (78/1148)	4.7% (24/510)	0.10
Widow or widower	2.5% (29/1148)	3.1% (16/510)	0.48

Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations (continued)

Household size			
1 adult	13.8% (151/1096)	15.4% (76/494)	0.40
2 adults	51.4% (563/1096)	56.1% (277/494)	0.40
3 adults	21.3% (233/1096)	18.0% (89/494)	0.14
≥4 adults	13.6% (149/1096)	10.5 (52/494)	0.09
Occupational status			
Full time job	60.4% (683/1130)	61.0% (310/507)	0.79
Part time job	9.1% (103/1130)	11.6% (59/507)	0.11
Unemployed	3.5% (40/1130)	1.2% (6/507)	0.01
Student	6.9% (78/1130)	5.7% (28/507)	0.29
Homemaker or maternity leave	9.4% (99/1130)	7.8% (40/507)	0.56
Retired	6.1% (69/1130)	6.3% (32/507)	0.87
On disability or sick leave	5.1% (58/1130)	6.3% (32/507)	0.33
Financial situation			
Very good	4.6% (52/1136)	4.3% (22/510)	0.81
Good	23.9% (271/1136)	26.3% (134/510)	0.92
Acceptable (“making ends meet”)	55.6% (632/1136)	56.1% (286/510)	0.87

Bad	13.5% (153/1136)	12.0% (61/510)	0.40
Very bad "(indebted or bankruptcy")	2.5% (28/1136)	1.4% (7/510)	0.16

	Exposure areas* **			**Non-exposed area**	
Smoking status	Low	Medium	High		
Never smoker	57.2% (87/152)	58.5% (377/644)	54.0% (190/352)	54.3% (277/510)	0.31
Former smoker	28.9% (44/152)	24.5% (158/644)	26.1% (92/352)	26.3% (134/510)	0.69
Current smoker	13.8% (21/152)	16.9% (109/644)	19.9% (70/352)	19.4% (99/510)	0.33

* Dropped out because of the nature of the questions, because they did not think the study applied to them, or because of illness or old age.

** Did not reply, could not be reached for reminders, did not respond to reminders or returned empty questionnaires.

*** The exposed area was divided into three areas by levels of exposure with regard to magnitude of ash fall, see Supplement A. The p-value is based on comparison between the non-exposed and the sum of the exposed area.

Table 2 Risk of respiratory symptoms (ECHRS) in a population exposed to the Eyjafjallajökull volcanic eruption compared to a non-exposed population

	Non-exposed % (n/N)	Exposed % (n/N)	OR (95%CI)*	*p*
Wheezing (last 12 months)	10.2% (51/498)	15.9% (177/1110)	1.8 (1.3-2.5	0.001
If yes, breathlessness at the same time	56.3% (27/48)	57.0% (94/165)	1.2 (0.6-2.4)	0.56
If yes, do you wheeze without a cold	66.0% (31/47)	70.7% (118/167)	1.2 (0.6-2.5)	0.59
Nocturnal chest tightness (last 12 months)	6.6 (33/500)	12.1% (135/1115)	2.0 (1.3-3.0)	0.003
Breathlessness at rest	5.4% (27/500)	7.7% (85/1103)	1.4 (0.9-2.3)	0.13
Coughing without a cold	15.9% (80/502)	28.2% (314/1114)	2.2 (1.6-2.9)	<0.001
Nocturnal cough (last 12 months)	18.8% (95/504)	23.2% (258/1110)	1.3 (1.0-1.7)	0.06
Morning winter cough	11.6% (60/504)	12.0% (133/1111)	1.0 (0.7-1.4)	0.99
Nocturnal or daytime winter cough	9.2% (46/498)	11.0% (121/1105)	1.3 (0.9-1.8)	0.23
If yes, is it chronic**	75.0% (30/40)	67.2% (78/116)	0.5 (0.2-1.4)	0.19
Morning winter phlegm	10.2% (51/500)	14.4% (159/1104)	1.5 (1.1-2.1)	0.02
Nocturnal or daytime winter phlegm	5.8% (29/497)	8.1% (89/1097)	1.5 (1.0-2.4)	0.08

If yes, is it chronic**	96.4% (27/28)	86.9% (73/84)	0.3 (0.0-2.4)	0.25
Dyspnea	7.8% (39/498)	11.8% (131/1106)	1.6 (1.1-2.3)	0.02
Nasal allergy and hay fever	19.1% (96/502)	19.1% (213/1116)	1.1 (0.8-1.4)	0.73
Allergic rhinitis	23.0% (115/501)	29.5% (327/1109)	1.4 (1.1-1.8)	0.007
Physician diagnosed conditions*				
Asthma	14.3% (71/498)	11.9% (132/1111)	0.8 (0.6-1.1)	0.17
MD confirmed asthma diagnosis	85.5% (59/69)	95.9% (117/122)	3.9 (1.2-12.5)	0.03
Heart disease	6.2% (31/503)	8.0% (89/1115)	1.4 (0.9-2.2)	0.15
Chronic bronchitis	4.2% (21/503)	7.0% (78/1107)	1.9 (1.1-3.1)	0.02
Emphysema	2.0% (10/502)	1.9% (21/1109)	1.0 (0.5-2.3)	0.96
Chronic obstructive pulmonary disease (COPD)	0.8% (4/500)	1.3% (14/1105)	1.7 (0.5-5.2)	0.36

* Odds ratios from multivariate logistic regression adjusted for age category, sex, education, and smoking status.

** Chronic: more than 3 months per year

*** Answering “Yes” to ”Has a physician ever told that you had (the disease)?“

Table 3 Risk of recent symptoms (physical and psychological), reported diseases and drug use of the exposed and un-exposed region

	Non-exposed % (n/N)	Exposed % (n/N)	OR (95% CI)*	*p*
Respiratory symptoms**				
Shortness of breath	3.5% (17/488)	6.7% (72/1074)	2.1 (1.2-3.6)	0.011
Feeling of tightness in chest	1.8% (9/491)	3.6% (38 /1070)	2.5 (1.1-5.8)	0.03
Cough and phlegm**				
Cough	6.4% (31/488)	15.3% (166/1085)	2.6 (1.7-3.9)	<0.001
Phlegm	5.5% (27 /488)	11.3% (122/1079)	2.1 (1.3-3.2)	<0.001
Irritation symptoms**				
Dry throat	3.4% (17/494)	10.1% (110/1089)	3.1 (1.8-5.3)	<0.001
Eye irritation and itch	8.6% (42/487)	20.6% (224/1085)	2.9 (2.0-4.1)	<0.001
Skin rash/eczema	5.1% (25/487)	6.2% (67/1075)	1.2 (0.8-1.9	0.39
Musculoskeletal symptoms**				
Back pain	23% (116/494)	18.2% (196/1075)	0.7 (0.5-0.9)	0.012
Myalgia	24.2% (120/496)	20.1% (216/1073)	0.7 (0.6-1.0)	0.024
Sleep and mental health**				

Insomnia	16.9% (84/497)	13.7% (148/1078)	0.8 (0.6-1.0)	0.08
Psychological morbidity***	19.0% (95/500)	24.6% (278/1129)	1.3 (1.0-1.7)	0.05
Regular drugs use (at least once per week)				
Asthma medication	4.7% (24/510)	3.4% (39/1147)	0.7 (0.4-1.1)	0.12
Analgesics	11.4 % (58/510)	8.7% (100/1147)	0.7 (0.5-1.0)	0.04
Any drug for depression, anxiety, sleeping and other mental symptoms	14.9% (76/510)	12.5% (144/1148)	0.8 (0.6-1.1)	0.12
Blood pressure-lowering medication	19.6% (100/510)	22.6 (259/1148)	1.3 (1.0-1.7)	0.10

* Odds ratios and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, gender, education and smoking status.

**Answers “Yes, to a moderate extent” or “Yes, to much extent” to the question “Have any of the following symptoms disturbed your daily activities during the last month?”.

*** Psychological morbidity was derived from GHQ-12 referring to “the previous weeks”, using a binary cut-off score of >2.

Table 4 Risk of respiratory symptoms (ECHRS) in a population exposed to Eyjafjallajökull volcanic eruption by exposure level at the residence.

	Low exposure*		Medium exposure*		High exposure*	
	OR	% (n/N)	OR (95%CI)**	% (n/N)	OR (95%CI)**	% (n/N)
Wheezing (last 12 months	1 (ref)	14.3% (21/147)	1.1 (0.6-1.8)	14.6% (91/623)	1.4 (0.8-2.3)	19.1% (65/340)
If yes, breathlessness at the same time	1 (ref)	47.6% (10/21)	1.2 (0.4-3.2)	54.5% (48/88)	1.8 (0.6-5.4)	64.3% (36/56)
If yes, do you wheeze without having a cold	1 (ref)	71.4% (15/21)	0.8 (0.2- 2.5)	67.4% (5/607)	1.1 (0.3-3.9)	75.4% (64/335)
Nocturnal chest tightness (last 12 mo)	1 (ref)	6.0% (9/149)	2.1 (1.0-4.2)	11.4% (71/624)	3.1 (1.5-6.6)	16.1% (55/342)
Breathlessness at rest	1 (ref)	2.7% (4/146)	3.3 (1.2-9.3)	8.2% (51/619)	3.3 (1.1-9.7)	8.9% (30/338)
Coughing without having	1 (ref)	19.5% (29/149)	2.0 (1.3-3.1)	31.1% (194/623)	1.6 (1.0.-2.6)	26.6% (91/342)
Nocturnal cough (last 12 months	1 (ref)	13.6% (20/147)	2.1 (1.3-3.5)	25.0% (155/619)	2.0 (1.2-3.2)	24.1% (83/344)
Cough in the morning in winter	1 (ref)	6.7 % (10/149)	2.2 (1.1-4.3)	13.7% (85/620)	1.6 (0.8-3.3)	11.1% (38/342)
Cough during the day or night in winter	1 (ref)	7.5% (11/147)	1.7 (0.9-3.4)	12.1% (75/619)	1.3 (0.6-2.7)	10.2% (35/342)
If yes, it is chronic***	1 (ref)	70.0% (7/10)	0.6 (0.1-3.6)	63.9% (46/72)	1.1 (0.2-6.9)	70.6% (24/34)
Morning winter phlegm	1 (ref)	8.3% (12/145)	1.7 (0.9-3.2))	13.7% (85/620)	2.3 (1.2-4.4)	18.3% (62/339)
Nocturnal or daytime winter phlegm	1 (ref)	4.9% (7/144)	1.5 (0.6-3.3)	6.9% (42/613)	2.4 (1.0-5.5)	11.8% (40/340)
If yes, is it chronic***	1 (ref)	85.7% (6/7)	0.7 (0.0-20.8)	92.5 (37/40)	0.5 (0.2-15.7)	81.1 (30/37)
Dyspnea	1 (ref)	6.7% (10/144)	1.9 (1.0-3.7)	6.9% (42/613)	2.4 (1.2-4.9)	11.8% (40/340)
Nasal allergy and hay fever	1 (ref)	17.2% (25/145)	1.2 (0.7-1.9)	19.4% (122/628)	1.1 (0.7-1.9)	19.2% (66/345)
Allergic rhinitis	1 (ref)	22.8% (33/145)	1.5 (0.9-2.2)	29.5% (184/624)	1.7 (1.1-2.7)	32.4% (110/340)
Physician diagnosed conditions****						
Asthma	1 (ref)	17.2% (25/145)	0.6 (0.4-0.1)	10.5% (65/622)	0.7 (0.4-1.2)	12.3% (42/342)
MD confirmed asthma diagnosis	1 (ref)	95.5% (21/22)	0.3 (0.0-3.2)	93.7% (59/63)	Na*****	100% (37/37)
Heart disease	1 (ref)	10.1% (15/149)	0.8 (0.4-1.4)	7.2% (45/628)	0.8 (0.4-1.7)	8.6% (29/338)
Chronic bronchitis	1 (ref)	6.1% (9/147)	1.3 (0.6-2.7)	6.8% (42/620)	1.3 (0.6-3.0)	7.9% (27/340)
Emphysema	1 (ref)	1.4% (2/146)	1.6 (0.3-7.5)	1.8% (11/623)	1.4 (0.3-7.1)	2.4% (8/340)

Chronic obstructive pulmonary disease (COPD)	1 (ref)	0.7% (1/146)	2.5 (0.3-20.2)	1.5% (9/619)	1.7 (0.2-14.2)	1.2% (4/340)

* Regions are seen in figure 1.

** Odds ratios from multivariate logistic regression adjusted for age category, gender, education, and smoking status.

*** Chronic: more than 3 months per year

**** Answering "Yes" to "Has a physician ever told that you had (the disease)?"

***** Cannot divide with 0.

Table 5 Risk of recent symptoms (physical and psychological), reported diseases and drug use within regions of the exposed area

	Low exposure*		Medium exposure*		High exposure*	
	OR (95%CI)**	%	OR (95%CI)**	%	OR (95%CI)**	%
Respiratory symptoms* **						
Shortness of breath	1 (ref)	2.8% (4/144)	2.9 (1.0 - 8.5)	6.8% (41/600)	3.3 (1.1 - 9.9)	8.2% (27/330)
Feeling of tightness in chest	1 (ref)	1.4% (2/145)	3.4 (0.8 - 15.1)	3.9% (23/597)	3.1 (0.7-14.5)	4.0% (13/328)
Cough and phlegm* **						
Cough	1 (ref)	4.9% (7/143)	3.6 (1.6- 8.1)	15.7% (95/607)	4.5 (2.0- 10.2)	19.1% (64/335)
Phlegm	1 (ref)	2.8% (4/142)	4.2 (1.5-11.8)	10.8% (65/603)	6.0 (2.1-17.1)	15.9% (53/334)
Irritation symptoms* **						
Dry throat	1 (ref)	2.1% (3/145)	6.7 (2.0-21.6)	11.2% (68/608)	6.7 (2.0-22.2)	11.6% (39/336)
Eye irritation and itch	1 (ref)	8.3% (12/144)	3.4 (1.8-6.5)	21.5% (130/606)	3.6 (1.9-7.0)	24.5% (82/335)
Skin rash or eczema	1 (ref)	2.1% (3/146)	3.0 (0.9-10.1)	6.0% (36/600)	4.3 (1.3-14.3)	8.5% (28/329)
Musculoskeletal symptoms* **						
Back pain	1 (ref)	15.4% (22/143)	1.3 (0.8-2.1)	18.0% (108/599)	1.2 (0.7-2.1)	19.8% (66/333)
Myalgia	1 (ref)	16.6% (24/145)	1.3 (0.8-2.1)	20.0% (120/600)	1.3 (0.8-2.3)	22.0% (72.328)
Sleep and mental health						

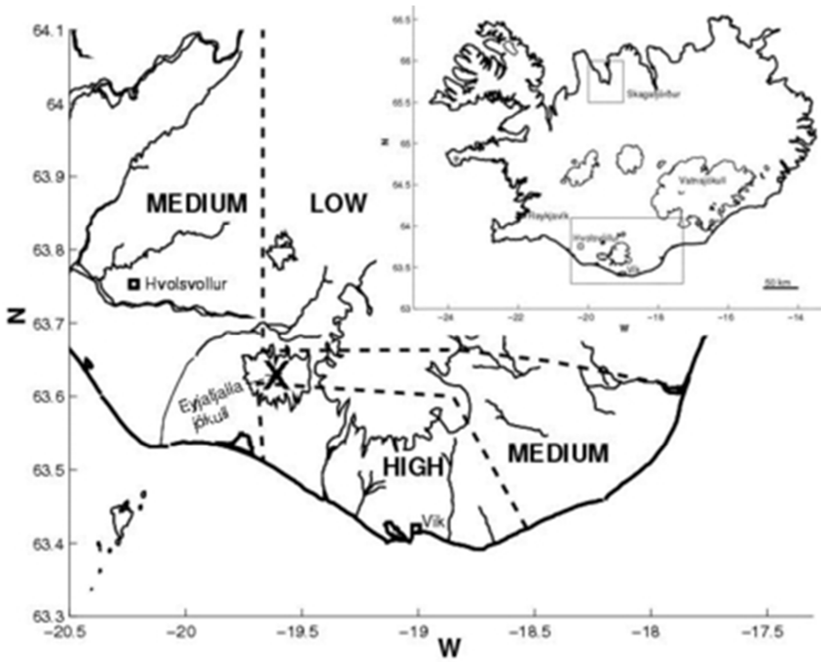
Insomnia***	1 (ref)	6.3% (9/143)	2.4 (1.2-5.0)	13.8% (83/601)	2.8 (1.3-5.9)	16.8 (56/334)
Psychological morbidity*****	1 (ref)	20.0% (30/150)	1.2 (0.8-1.9)	24.8% (157/634)	1.3 (0.8-2.1)	26.4% (91/345)
Regular drugs use (at least once per week)						
Asthma medication	1 (ref)	3.9% (6/152)	0.7 (0.3-1.9)	2.5% (16/644)	1.2 (0.4-3.2)	4.8% (17/352)
Analgesics	1 (ref)	7.2% (11/152)	1.5 (0.7-2.9)	9.0% (58/644)	1.2 (0.6-2.6)	8.8% (31/352)
Any drug for depression, anxiety, sleeping and other mental symptoms	1 (ref)	5.3% (8/152)	3.6 (1.7-7.8)	13.7% (88/644)	2.8 (1.3-6.3)	13.6% (48/352)
Blood pressure-lowering medication	1 (ref)	19.7% (30/152)	1.7 (1.1-2.8)	22.8% (147/644)	1.4 (0.8-2.4)	23.3% (82/352)

* Regions are seen in figure 1.

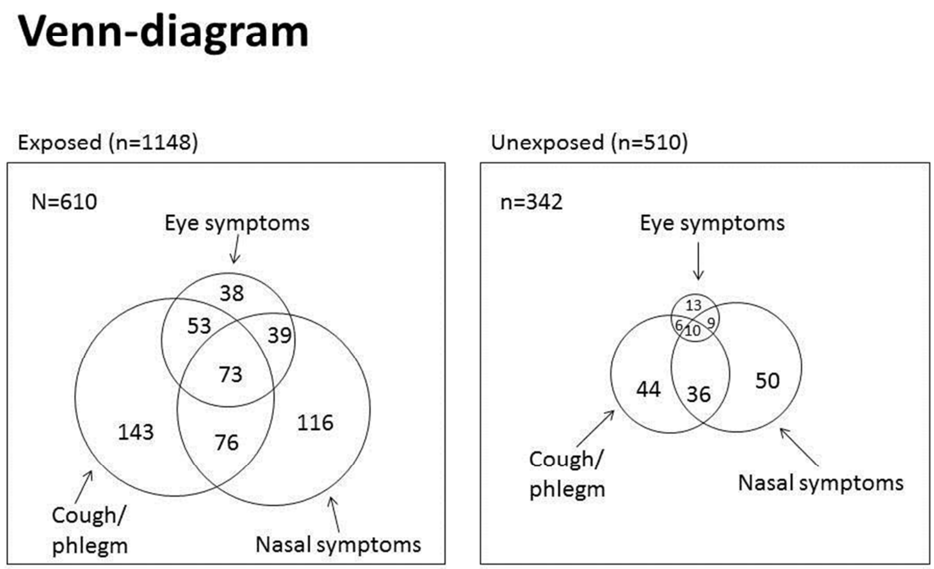
** Odds ratios and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, gender, education and smoking status.

*** Answering "Yes, to a moderate extent" or "Yes, to much extent" to the question "Have any of the following symptoms disturbed your daily activities during the last month?".

**** Psychological morbidity was derived from GHQ-12 referring to "the previous weeks", using a binary cut-off score of >2.



nserted map of Iceland shows the location of Skagafjörður (non-exposed, control area) in the north and of the exposed area in South Iceland. The larger map of the exposed area shows Eyjafjallajökull (marked with X) and the low, medium and high ash exposure areas.
17x13mm (600 x 600 DPI)



Venn diagram of exposed and non-exposed participants reporting one or more key symptom six to nine months after the Eyjafjallajökull eruption.
254x190mm (96 x 96 DPI)

STROBE Statement—for Volcano-Health study….page numbers pertain to the submitted manuscript file.

	Item No	Recommendation	
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	Page 1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	Abstract page3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	P 5
Objectives	3	State specific objectives, including any prespecified hypotheses	P 7
Methods			
Study design	4	Present key elements of study design early in the paper	Page 6(intro)
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Page 8, data collection
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	Page 9, data collection.
		(*b*) For matched studies, give matching criteria and number of exposed and unexposed	Page 8, study population
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	Page 9, questionnaire, coding.
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Page 9 (same)
Bias	9	Describe any efforts to address potential sources of bias	Page 8 study population
Study size	10	Explain how the study size was arrived at	P9 datacolletio
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	n/p10 results
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	-
		(*b*) Describe any methods used to examine subgroups and interactions	P10 statistical analysis
		(*c*) Explain how missing data were addressed	Page 10, Stat. analys.
		(*d*) If applicable, explain how loss to follow-up was addressed	-
		(*e*) Describe any sensitivity analyses	-
Results			

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	P1 Results/table 1
		(b) Give reasons for non-participation at each stage	Table 1
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 1 and others
		(b) Indicate number of participants with missing data for each variable of interest	Ok
		(c) Summarise follow-up time (eg, average and total amount)	-
Outcome data	15*	Report numbers of outcome events or summary measures over time	Tables.
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	Tables. P10 stat.methods
		(*b*) Report category boundaries when continuous variables were categorized	-
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	P 10 Stat methods/p 12
Discussion			
Key results	18	Summarise key results with reference to study objectives	P13
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	P13-14
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	P14-15.
Generalisability	21	Discuss the generalisability (external validity) of the study results	P15
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Page 2. -

*Give information separately for exposed and unexposed groups. **Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at http://www.strobe-statement.org.	

Health effects following the Eyjafjallajökull volcanic eruption – a population-based study

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Health effects following the Eyjafjallajökull volcanic eruption– a population-based study

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Statements

All the authors conceived and designed the study and had full access to the data. AH, UAV, ÞBK, and GP gathered the data and HKC, AH, UAV, and GP did the statistical analyses. ÞÞ provided estimates of ash fall density. HKC and AH drafted the article, which was critically revised by all the authors, who also approved the final report. GP (guarantor) supervised the study, had full access to all the data in the study and carries the final responsibility for deciding to submit it for publication, and takes responsibility for the integrity of the data and the accuracy of the data analysis.

The participants of this study gave informed consent before participating in the study. The consent includes future follow-up, by questionnaire or in registers.

None of the authors have conflicts of interests or competing interests to declare.

The study was approved by The Icelandic Data Protection Authority (nr. S4878/2010) and The Science Bioethics Committee (nr. VSNb2010080002/03.7).

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We do not wish to share the data used in this study.

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Data Sharing

Professor Pétursdóttir holds all the data used in this study. The data set holds additional information about health of children and mental health, which the authors seek to publish later. The data is anonymised, but could hold identifable details, thus we do not wish to share the data.

Abstract

Objectives The study aimed to determine whether exposure to a volcanic eruption was associated with increased prevalence of physical and/or mental symptoms.

Design Cohort, with non-exposed control group.

Setting Natural disasters like volcanic eruptions constitute a major public health threat. The Icelandic volcano Eyjafjallajökull exposed residents in southern Iceland to continuous ash fall for more than 5 weeks in spring 2010. This study was conducted November 2010-March 2011, six to nine months after the Eyjafjallajökull eruption.

Participants Adult (18-80 years of age) eruption-exposed South Icelanders (n=1,148) and a control population of residents of Skagafjörður, North Iceland (n=510). The participation rate was 72%.

Main Outcome Measures Physical symptoms in the previous year (chronic), in the previous month (recent), General Health Questionnaire (GHQ-12) measured psychological morbidity.

Results The likelihood of having symptoms during the last month was higher in the exposed population, such as; tightness in the chest (odds ratio (OR) 2.5; 95% CI, 1.1-5.8), cough (OR, 2.6; 95% CI, 1.7-3.9), phlegm (OR, 2.1; 95% CI, 1.3-3.2), eye irritation (OR, 2.9; 95% CI, 2.0-4.1), and psychological morbidity symptoms (OR, 1.3; 95% CI,1.0-1.7). Respiratory symptoms during the last 12 months were also more common in the exposed population; cough (OR, 2.2; 95% CI, 1.6-2.9), dyspnea (OR, 1.6; 95% CI, 1.1-2.3), although the prevalence of underlying asthma and heart disease was similar. Twice as many in the exposed population had two or more symptoms from nose, eyes, or upper-respiratory tract (24% vs. 13%, $p<0.001$); these individuals were also more likely to experience psychological morbidity (OR, 4.69; 95% CI, 3.39-6.50) compared to individuals with no symptoms. Most symptoms exhibited a dose-response pattern within the exposed population, corresponding to low, medium, and high exposure to the eruption.

Conclusions Six to nine months after the Eyjafjallajökull eruption, residents living in the exposed area, particularly those closest to the volcano, had markedly increased prevalence of various physical symptoms. A portion of the exposed population reported multiple symptoms and may be at

risk for long-term physical and psychological morbidity. Studies of long–term consequences are therefore warranted.

What this paper adds:

What is already known:
Natural disasters like volcanic eruptions constitute a major public health threat. Exposure to volcanic ash may affect respiratory health.

What this paper adds:
A larger population-based cohort with a control group was assessed with questionnaires and increased rates of respiratory and mental health symptoms were found some six months after exposure to a volcanic eruption, indicating that health effects may be long-lasting.

Introduction

Throughout history, human societies have been exposed to natural disasters like volcanic eruptions and earthquakes. In 2010, 300 000 individuals were killed worldwide in natural disasters.[1] Accurate information on mortality and long-term health consequences of natural disasters is instrumental to strengthen risk management and decrease their negative health impact.[2]

The eruption of the Eyjafjallajökull volcano in Iceland, which lasted from April 14th to May 20th 2010, made headlines worldwide, not least because of extensive effects on international flight traffic. Direct ash fall from the eruption was estimated at around 250 million tons, the rural regions in Iceland south and south-east of the volcano were most severely affected.[3,4] Ash fall was continuous for about 6 weeks, and following the eruption the ash was frequently resuspended in the area.[4,5] The surface of the fresh ash particles contained reactive salts and as much as 20% of the particles (by mass) were less than 10 µm in aerodynamic diameter and could enter the lower respiratory tract.[6] A study of local residents (N=207) was conducted immediately after the eruption ended. Participants were examined by a physician and to ascertain respiratory health, standardized spirometry was performed before and after bronchodilator usage. Adult participants also answered questionnaires about mental and physical health. Ash exposure was associated with high prevalence of eye- and upper airway irritation (25% and 50% respectively), and exacerbation of pre-existing asthma but did not contribute to serious health problems or impair respiratory function compared to controls. 39% showed symptoms of psychological morbidity as measured by the General Health Questionnaire (GHQ).[7] Residents from the region east of Eyjafjallajökull have expressed a need for more detailed information concerning ash fall during the eruption as the health effects were not known.[8] Meanwhile, the impact on long-term health of the residents remains to be explored.

Previous studies on volcanic ash exposure and health have shown increased respiratory morbidity and asthma attacks,[9,10] and increased hospital visits for respiratory illness in association with some eruptions[11] but not in others.[12] Also, increased irritation of the respiratory tract from short-term exposure to volcanic gases and ash.[13] Long-term exposure to sulphuric gases (often emitted in volcanic eruptions) were found to be associated with increased prevalence of chronic bronchitis and cardio-respiratory symptoms in some studies.[14,15] In addition to direct physical health hazards, experiencing floods, lahars, as well as being exposed to prolonged ash suspension can be a threat to mental health. Stress levels may increase dramatically and have been shown to contribute to psychological morbidity such as post traumatic stress syndrome or depression.[16, 17]

Health effects of long-term exposure to a volcanic eruption are important both from a scientific and health care standpoint.[18] Iceland's population-based registries and strong infrastructure present an important opportunity to study such health impacts, particularly in terms of long-term follow-up. Utilizing the Icelandic population-based registers to identify all residents living in the vicinity of Eyjafjallajökull, the aim of this study was to investigate their self-reported physical and mental health six to nine months after the volcanic eruption. We hypothesized that residents of the Eyjafjallajökull area, particularly those most exposed, would be at increased risk of physical and psychological symptoms compared to a non-exposed population in North Iceland.

Methods

<u>Study area</u>

The exposed area in South Iceland is mostly farmland with a few villages. It has several active volcanoes[19] which along with sand plains and river beds are a source of dust storms.[20, 21] Apart from traffic on the national highway and agricultural activities, there are no major sources of anthropogenic particles in the area.

Almost from the onset of the eruption, the Environment Agency of Iceland monitored concentrations of inhalable particulate matter (PM_{10}) in up to three locations in the study area. The official health limit for PM_{10}, 50 μg/m^3 daily averages, was surpassed more than half of the days between May 7th and June 6th 2010, when air quality was continuously monitored in the most severely affected areas.[4] Monitoring continued after the eruption ended and until the end of out study period (Ultimo March 2011), ash was repeatedly resuspended and the mean 24-hour concentration of PM_{10} particles was 41 μg/m^3. The official health limit of 50 μg/m^3 daily average was exceeded 25 times, mostly during summer and fall of 2010. From November 2010 onwards the number of exceedences declined rapidly.[5]

In addition to a non-exposed control area in North Iceland, the study area was divided into a low, medium and high exposure regions in South Iceland (Figure 1) based on satellite images of the eruption plume (coarse time resolution), information about the emission intensity[3] and observations of ash deposits on the ground.[4,22] Models calculated with FLEXPART show similar ash deposits, ranging from approximately 1000 g/m^2 in the region just south of the volcano, down to about 200 g/m^2 near Vík some 50 km further east.[4]

During the eruption, the prevailing wind was from the north-west, causing the heaviest ash fall south and east of the volcano. While ash deposition was relatively low in the western part of the medium exposure region, the volcano was in full view there and thus these residents were more visually exposed to the volcano than in other regions. The lowland regions south and west of the glacier are prone to flooding and many residents were evacuated because of glacial outburst floods in the first days of the eruption.

Study population

The study population consisted of all residents in the municipalities closest to Eyjafjallajökull volcano (pre-defined by postal codes), identified in the population-based registry (Registers Iceland). Most live in farmlands (n=1207) and the rest in small townships (N=859).[23] By these means we identified 1,615 inhabitants who were 18-80 years of age, resided in the exposed area during the eruption, could be reached and spoke Icelandic fluently. In addition, a sample of 697 demographically matched (age, gender, urban/rural habitation) residents from a non-exposed area in Northern Iceland was included as control group. Sheep and dairy farming are predominant in both areas.

Data collection

Initially, all participants in the exposed group received a letter including information about the study and an invitation to participate. Some days after the letters were sent the recipients were contacted by telephone and asked whether they were willing to take part, and if so, whether they preferred to reply on paper or online. Subsequently, questionnaires or email invitations were sent and a week later a combined thank-you/reminder card was sent by post or e-mail. If needed, the participants were reminded again by phone. A similar protocol was used for the control group, with the exception that the introductory letter stated that a questionnaire would be sent a few days later, unless participation was declined.

Questionnaires were sent to the exposed population between November 19th and December 28th 2010 (six to seven months after the eruption ended) and the last replies were received in March 2011. The control group received questionnaires between January 26th and February 4th 2011, the last replies were received in April 2011.

The questionnaires contained no information that revealed the identity of the respondent, instead, they had a running number which could be linked to the person's ID number through a list which was kept separately and securely to enable later follow-up. A few of the returned questionnaires lacked most of the required information and were excluded from the analysis (n=13).

Questionnaires

The questionnaires contained questions concerning demographic background and current well-being, including various physical and psychological symptoms. We used standard questions from the screening part of the European Community Respiratory Health questionnaire[24] and assessed underlying disease by asking "Has a medical doctor ever told you that you had the following diseases: asthma, heart disease, emphysema, chronic bronchitis or chronic obstructive pulmonary disease (COPD)" with the response alternatives "Yes" or "No" by each option. To assess recent symptoms, we asked "Have the following symptoms disrupted your daily activities during the previous month?" followed by a list of various symptomsfrom e.g. the respiratory system, skin or eyes, or relating to pain. We also asked about smoking "Have you ever smoked", "Yes" or "No", and "Have you smoked during the last month", "Yes" or "No". Questions on regular use of medication were "Do you take medication regularly, that is, once per week or more often?" followed by listing asthma medication, analgesics, blood-pressure-lowering medication and sleep medication/anti-depressants/tranquillizers/medication for other mental health problems. Current psychological morbidity was evaluated from the General Health Questionnaire-12-item version (GHQ-12),[25,26] a non-specific screening tool for psychological morbidity which measures anxiety, loss of self-confidence and social dysfunction.[27] We used a binary cut-off score of >2.

Database & coding

The online survey was built with LimeSurvey.[28] Participants replying online accessed the survey using a unique identifier sent to them by email. Questionnaire replies on paper were entered into LimeSurvey according to uniform guidelines set by the researchers.

Statistical analysis

We first calculated descriptive statistics, contrasting background characteristics in the exposed and non-exposed population using X^2 – tests (*p* applies to all categories within demographic characteristics). Logistic regression was used to determine odds ratios (ORs) associated with residence in a) the exposed and non-exposed regions and b) the low, medium, or high exposure areas within the exposed region. All models were adjusted for a priori selected variables: age, gender, smoking status (never, former and current), and education level, odds ratios and 95% confidence intervals (CI) were calculated from the outputs. A CI not including 1.0 or a *p*-value of 0.05 or less was considered statistically significant. A Venn diagram was drawn to show the interrelationship between key nasal, eye, or upper respiratory symptoms (cough and/or phlegm without having a cold, eye irritation or itch, and sneeze, stuffed, or runny nose). Demographic characteristics, risk factors and comorbidities of those reporting multiple symptoms were explored using X^2 – tests and logistic regression.

IBM SPSS 19[29] was used for data analysis. Individuals who had not replied to all relevant questions were excluded from the regression models.

The study was approved by The Icelandic Data Protection Authority (nr. S4878/2010) and The Science Bioethics Committee (nr. VSNb2010080002/03.7), all participants gave informed consent.

Results

Valid questionnaires were obtained from 1,148 of 1,615 from the exposed population (71%) and 510 of 697 (73%) from the non-exposed population. A higher proportion of the exposed population could not be reached or found (10.8% vs. 7.2%; *P*=0.005), and more refused to participate (17.8% vs. 14.6%; *P*=0.069). The exposed and non-exposed participants were similar with respect to demographic characteristics; age, education levels, and occupational, marital, and financial status (Table 1).

Analysis 1: Exposed vs. non-exposed

Respiratory symptoms such as waking up with a feeling of tightness in the chest, breathlessness, cough, and phlegm in the last 12 months were more prevalent in the exposed population. After adjusting for sex, age, education, and smoking status, the exposed population was more likely to report symptoms like tightness in chest (OR, 2.0;95% CI, 1.3-3.0), coughing without a cold (OR, 2.2, CI, 1.6-2.9), and having chronic bronchitis, OR, 1.9 (95% CI, 1.1-3.1)(Table 2). In addition, bothersome physical symptoms during the last month were more common in the exposed population; these were shortness of breath, OR, 2.1 (95% CI, 1.2-3.6), cough (OR, 2.6; 95% 1.7-3.9), phlegm (OR, 2.1;95% CI, 1.3–3.2), and eye irritation (OR, 2.9; 95% CI, 2.0-4.1). Back pain, myalgia, and insomnia were less prevalent in the exposed population. Psychological morbidity was marginally more common in the exposed population (OR, 1.3; 95% CI, 1.0-1.7), as was the use of blood pressure lowering medication (1.3, 95% CI, 1.0-1.7), while use of analgesics was less common (OR, 0.7; 95% CI, 0.5-1.0) (Table 3).

Analysis 2: Low, medium, and high exposure

The prevalence of most respiratory symptoms during the last year increased with ash exposure. Adjusting for gender, age, education, and smoking, the likelihood of waking up with a feeling of tightness in the chest was higher in the medium- and high exposure regions, OR, 2.1 (95% CI, 1.0-

4.2) and OR, 3.1 (95% CI, 1.5-6.6), respectively. Chronic morning phlegm was only increased in the high exposure region, OR, 2.3 (95% CI, 1.2-4.4) (Table 4).

The experience of recent symptoms increased with exposure; cough (medium exposure OR, 3.6; 95% CI, 1.6-8.1; high exposure OR, 4.5; 95% CI, 2.0-10.2), phlegm (medium exposure OR, 4.2; 95% CI, 1.5-11.8, high exposure OR, 6.0; 95% CI, 2.1-17.1), and insomnia (medium exposure 2.4, 95% CI, 1.2-5.0, high exposure OR, 2.8, 95% CI, 1.3-5.9), (Table 5). No significant associations were observed between level of exposure and feeling of tightness in the chest, psychological morbidity, use of analgesic- and blood-pressure lowering drugs, or physician-diagnosed disease, though a non-significant trend was observed with some outcomes. ORs not adjusted for age, gender, education or smoking were similar to the adjusted ones.

Analysis 3: Multiple symptoms

A subgroup within both populations reported multiple symptoms from nose, eyes, or upper respiratory organs. The proportion reporting two or more symptoms was larger in the exposed population than the non-exposed (23.8% vs. 12.9%, data not shown), and there was a significant overlap in reporting one or more symptoms, see Venn diagram (figure 2). Within the exposed population the proportion was 13.3% in the low-exposure area, 24.7% in the medium exposure area, and 26.7% in the high-exposure area. In the exposed area, those who reported multiple key symptoms were more likely to be female (58.1% female vs. 41.9% male, $P<0.015$), and have asthma, compared to those with no symptoms (26.9% asthma vs. 3.4% asthma, $P<0.001$).

Analyzing the association between exposure and psychological morbidity and adjusting for multiple symptoms, we found that having multiple symptoms was associated with psychological morbidity, OR, 4.69 (95% CI, 3.39-6.50), irrespective of exposure level.

Discussion

Our study found that six to nine months after the Eyjafjallajökull eruption ended the participants from exposed areas reported increased wheezing, cough and phlegm, as well as recent eye and skin irritation. Participants from medium and high exposure regions experienced significantly higher rates of upper respiratory, skin, and eye irritation symptoms than those from the low exposure region. This suggests a dose-dependent relationship of the Eyjafjallajökull ash exposure on physical symptoms.

Many of the recent physical and mental symptoms were only marginally more prevalent in the high than the medium exposure area, indicating that there is a threshold beyond which additional exposure does not result in increased morbidity. Reporting two or more key respiratory symptoms was more common in the exposed population. Compared to the non-exposed, the exposed population reported only marginally higher prevalence of psychological morbidity. However, psychological morbidity was reported to be much higher in the subgroup reporting two or more symptoms, indicating that those with many symptoms represent a more sensitive subgroup within the population which should be especially targeted in preventive actions.

The main strengths of this study, our ability to identify the whole population experiencing a volcanic eruption as well as the high participation rate, both minimize the risk of selection bias. In addition, the internal response rate (answers to specific items) was high. The exposed and non-exposed populations were demographically similar and adjustment for age, gender and education further reduces the risk of confounding. Chronic illness prevalences in this study are comparable between the two areas, suggesting that the environment and occupational exposures are not dissimilar in the two areas, who are both characterized by sheep and dairy farming.

Regarding the limitations of the study, we have no information on the health status of the two populations before the eruption or the health status of non-respondents, and cannot exclude the possibility that the groups may have differed before the eruption. Although the study benefits overall from the high response rate, we have limited information on non-responders and therefore it remains uncertain to what extent, if at all, attrition affects our comparison across exposure areas. Another limitation of the study is that all symptoms are self-reported which may confer misclassification of symptoms. However, it is unlikely that this bias differs across exposure categories.

Classification of exposure areas (low, medium, high), which was based on estimated ash fall, may be imprecise and actual ash exposure may also vary within the exposure areas due to local weather conditions, terrain, or housing quality. Yet, if our classification is unclear or erroneous, this would reasonably result in compromised dose-dependent effects seen in our study and rather decrease the measured effects. It is also possible that exposures other than ash fall, e.g. noise, visibility, or living in lowlands exposed to glacial outburst floods, are significant contributors to the psychological morbidity which we observed in this study.

The exposed region is varied with respect to population density and occupation; the high exposure area has a higher proportion of farmers, who spend more time outside, which may exaggerate the observed difference between the medium- and low exposure areas. On the other hand, residents of the high exposure area may have been more vigilant in avoiding exposure, which would reduce the difference between the exposure areas. Data collection for the exposed group went on in November-December, and January-February for the non-exposed group, which may induce bias with respect to respiratory symptoms, as the seasonal influenza peaked during February and March in 2011.[30] However, this would attenuate the observed difference seen in respiratory symptoms.

Before the eruption of Eyjafjallajökull, dust storms frequently compromised air quality in the exposed area,[20,21] however, a study from 2004 on Icelandic farmers found no difference in respiratory symptoms between controls sampled from the national population and farmers, or among farmers in different regions of Iceland.[31] Chronic disease prevalence is similar in the exposed and non-exposed areas, further suggesting that the dust storms occurring before the eruption have no lasting effect on people´s health. Also, the dose-response character of symptoms with respect to exposure to the volcano suggests that the symptoms are associated with the eruption. Our findings of high rates of cough and eye irritation after the eruption are consistent with other studies, for example the Mount St. Helens eruption, where the number of emergency room visits, especially for respiratory conditions in those with underlying illness increased three to five-fold in the weeks following the eruption. Eye irritation was also more common in loggers exposed to Mount St. Helens ash, and the amount of eye mucus seemed to be dose-dependent on the ash density.[32]

Dose response and threshold effects of urban-type airborne particles on health have been explored in epidemiological studies,[33] but rarely in humans exposed to volcanic ash. A Japanese study of asthma treatment and volcanic ash exposure found worsening of symptoms in asthmatics in areas with more than 100 g/m^2 ash, but not in areas with less ash fall.[34] The psychological morbidity found in the current study (20-26%) were lower than that found in the survey of the most exposed area right after the Eyjafjallajökull eruption ended (39%).[7] This may indicate that residents have somewhat adapted to the strain following the eruption. Although a disaster with more dramatic consequences, a similar trend was found in a Japanese study of evacuees from a volcanic area where 66.1% showed signs of psychological morbidity (GHQ-30) six months after evacuation, while four years later the rate had fallen to 45.6%.[17] In our study, psychological morbidity and insomnia was most common in the high exposure group, as was the regular intake of medicines for depression, anxiety, sleep problems, or other mental symptoms. Dose-response trends were found between psychological morbidity and exposure to the Mount St. Helens eruption,[16] indicating possible long-term risk of further psychological morbidity in the high exposure group.

At this point, we cannot speculate about the effect of financial loss because of damages to property, this will be addressed in future studies.

The results from this study has implications for planners and authorities, as it indicates risk groups particularly susceptible to adverse reactions after exposure to volcanic ash. Also, the study design and registration of the participants enables follow-up of the exposed group, both directly in a new study, as well as in hospital, medicines and mortality registers.

Conclusions

In this population-based study we documented a high prevalence of respiratory symptoms six to nine months following the volcanic eruption in Eyjafjallajökull, especially among those most exposed. Also, subgroups who reported more than one physical symptom were more prone to experience psychological difficulties. The study reveals that the adverse health effects of a volcanic eruption may last for many months beyond the eruption and the immediate disaster relief services provided. This is important for health authorities to bear in mind.

These findings give incentive for further studies, e.g. on predictive factors for morbidity, the health of children, and long-term follow-up. Important knowledge may be gained from such studies to help develop mitigation measures at future eruptions.

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Figure 1. Map of Iceland and the study areas.

Inserted map of Iceland shows the location of Skagafjörður (non-exposed, control area) in the north and of the exposed area in South Iceland. The larger map of the exposed area shows Eyjafjallajökull (marked with X) and the low, medium and high ash exposure areas.

Figure 2 Venn diagram of exposed and non-exposed participants reporting one or more key symptom six to nine months after the Eyjafjallajökull eruption.

Legend: Eye symptoms; Irritation, itch or other discomfort, Nasal symptoms; Sneeze or runny nose without having a cough, Cough and /or phlegm; Often cough without having a cold, and/or phlegm during winter. The numbers do not add up due to rounding.

Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations.

	Exposed % (n/N)	Non-exposed % (n/N)	*p-value*
Target population (identified in total population registers)	**1811**	**751**	
Could not be found or reached	10.8% (196/1811)	7.2% (54/751)	0.01
Study population	**1615**	**697**	
Refused to participate	17.8% (286/1615)	14.6% (102/697)	0.07
Originally agreed to participate	**1329**	**595**	
Explained non-participation *	7.0% (93/1329)	6.1% (36/595)	0.44
Un-explained non-participation **	6.6% (88/1329)	8.2% (49/595)	0.20
Response rate (participants/study population)	**71% (1148/1615)**	**73% (510/697)**	0.31
Demographic characteristics			
Male	49.0% (562)	51.4% (262)	0.36
Female	51.0 (586)	48.6% (248)	0.36
Age categories			
18-23	11.1% (128/1148)	8.2% (42/510)	0.07
24-30	8.6% (99/1148)	9.0% 46/510)	0.79
31-40	15.2% (175/1148)	14.3% (73/510)	0.55
41-50	20.3% (233/1148)	21.4% (109/510)	0.62
51-60	19.3% (222/1148)	22.2% (113/510)	0.19
61-70	15.9% (183/1148)	16.5% (84/510)	0.79
71- 80	9.4% (108/1148)	8.4% (43/510)	0.52
Education			
No formal education	5.4% (61/1134)	4.8% (24/501)	0.62
Primary education	35.9% (407/1134)	30.9% (155/501)	0.05
Secondary education	33.4% (379/1134)	37.7% (189/501)	0.09
Professional or university education	20.6% (234/1134)	23.8% (119/501)	0.16
Other education*	4.7% (53/1134)	2.8% (14/501)	0.08
Marital status			
Married or cohabitating	72.4% (831/1148)	76.6% (391/510)	0.07
Single or divorced	18.3% (210/1148)	15.5% (79/510)	0.17
Relationship – no cohabitation	6.8% (78/1148)	4.7% (24/510)	0.10
Widow or widower	2.5% (29/1148)	3.1% (16/510)	0.48

Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations (continued)

Household size			
1 adult	13.8% (151/1096)	15.4% (76/494)	0.40
2 adults	51.4% (563/1096)	56.1% (277/494)	0.40
3 adults	21.3% (233/1096)	18.0% (89/494)	0.14
≥4 adults	13.6% (149/1096)	10.5 (52/494)	0.09
Occupational status			
Full time job	60.4% (683/1130)	61.0% (310/507)	0.79
Part time job	9.1% (103/1130)	11.6% (59/507)	0.11
Unemployed	3.5% (40/1130)	1.2% (6/507)	0.01
Student	6.9% (78/1130)	5.7% (28/507)	0.29
Homemaker or maternity leave	9.4% (99/1130)	7.8% (40/507)	0.56
Retired	6.1% (69/1130)	6.3% (32/507)	0.87
On disability or sick leave	5.1% (58/1130)	6.3% (32/507)	0.33
Financial situation			
Very good	4.6% (52/1136)	4.3% (22/510)	0.81
Good	23.9% (271/1136)	26.3% (134/510)	0.92
Acceptable ("making ends meet")	55.6% (632/1136)	56.1% (286/510)	0.87
Bad	13.5% (153/1136)	12.0% (61/510)	0.40
Very bad "(indebted or bankruptcy")	2.5% (28/1136)	1.4% (7/510)	0.16

	Exposure areas* **			**Non-exposed area**	
Smoking status	Low	Medium	High		
Never smoker	57.2% (87/152)	58.5% (377/644)	54.0% (190/352)	54.3% (277/510)	0.31
Former smoker	28.9% (44/152)	24.5% (158/644)	26.1% (92/352)	26.3% (134/510)	0.69
Current smoker	13.8% (21/152)	16.9% (109/644)	19.9% (70/352)	19.4% (99/510)	0.33

* Dropped out because of the nature of the questions, because they did not think the study applied to them, or because of illness or old age.

** Did not reply, could not be reached for reminders, did not respond to reminders or returned empty questionnaires.

*** The exposed area was divided into three areas by levels of exposure with regard to magnitude of ash fall, see figure 1. The p-value is based on comparison between the non-exposed and the sum of the exposed area.

Remaining tables are in a separate file as they look better in Landscape format.

See Tables_Health_effects_following_the_Eyjafjallajökull_eruption.docx

Table 2 Risk of respiratory symptoms (ECHRS) in a population exposed to the Eyjafjallajökull volcanic eruption compared to a non-exposed population

	Non-exposed % (n/N)	Exposed % (n/N)	OR (95%CI)*	*p*
Wheezing (last 12 months)	10.2% (51/498)	15.9% (177/1110)	1.8 (1.3-2.5	0.001
If yes, breathlessness at the same time	56.3% (27/48)	57.0% (94/165)	1.2 (0.6-2.4)	0.56
If yes, do you wheeze without a cold	66.0% (31/47)	70.7% (118/167)	1.2 (0.6-2.5)	0.59
Nocturnal chest tightness (last 12 months)	6.6 (33/500)	12.1% (135/1115)	2.0 (1.3-3.0)	0.003
Breathlessness at rest	5.4% (27/500)	7.7% (85/1103)	1.4 (0.9-2.3)	0.13
Coughing without a cold	15.9% (80/502)	28.2% (314/1114)	2.2 (1.6-2.9)	<0.001
Nocturnal cough (last 12 months)	18.8% (95/504)	23.2% (258/1110)	1.3 (1.0-1.7)	0.06
Morning winter cough	11.6% (60/504)	12.0% (133/1111)	1.0 (0.7-1.4)	0.99
Nocturnal or daytime winter cough	9.2% (46/498)	11.0% (121/1105)	1.3 (0.9-1.8)	0.23
If yes, is it chronic**	75.0% (30/40)	67.2% (78/116)	0.5 (0.2-1.4)	0.19
Morning winter phlegm	10.2% (51/500)	14.4% (159/1104)	1.5 (1.1-2.1)	0.02
Nocturnal or daytime winter phlegm	5.8% (29/497)	8.1% (89/1097)	1.5 (1.0-2.4)	0.08
If yes, is it chronic**	96.4% (27/28)	86.9% (73/84)	0.3 (0.0-2.4)	0.25
Dyspnea	7.8% (39/498)	11.8% (131/1106)	1.6 (1.1-2.3)	0.02
Nasal allergy and hay fever	19.1% (96/502)	19.1% (213/1116)	1.1 (0.8-1.4)	0.73
Allergic rhinitis	23.0% (115/501)	29.5% (327/1109)	1.4 (1.1-1.8)	0.007
Physician diagnosed conditions* **				
Asthma	14.3% (71/498)	11.9% (132/1111)	0.8 (0.6-1.1)	0.17
Asthma diagnosis was confirmed by an MD	85.5% (59/69)	95.9% (117/122)	3.9 (1.2-12.5)	0.03

Heart disease	6.2% (31/503)	8.0% (89/1115)	1.4 (0.9-2.2)	0.15
Chronic bronchitis	4.2% (21/503)	7.0% (78/1107)	1.9 (1.1-3.1)	0.02
Emphysema	2.0% (10/502)	1.9% (21/1109)	1.0 (0.5-2.3)	0.96
Chronic obstructive pulmonary disease (COPD)	0.8% (4/500)	1.3% (14/1105)	1.7 (0.5-5.2)	0.36

* Odds ratios (OR) and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, sex, education, and smoking status.

** Chronic: more than 3 months per year

*** Answering "Yes" to "Has a physician ever told that you had (the disease)?"

Table 3 Risk of recent symptoms (physical and psychological), reported diseases and drug use of the exposed and un-exposed region

	Non-exposed % (n/N)	Exposed % (n/N)	OR (95% CI)*	*p*
Respiratory symptoms**				
Shortness of breath	3.5% (17/488)	6.7% (72/1074)	2.1 (1.2-3.6)	0.011
Feeling of tightness in chest	1.8% (9/491)	3.6% (38 /1070)	2.5 (1.1-5.8)	0.03
Cough and phlegm**				
Cough	6.4% (31/488)	15.3% (166/1085)	2.6 (1.7-3.9)	<0.001
Phlegm	5.5% (27 /488)	11.3% (122/1079)	2.1 (1.3-3.2)	<0.001
Irritation symptoms**				
Dry throat	3.4% (17/494)	10.1% (110/1089)	3.1 (1.8-5.3)	<0.001
Eye irritation and itch	8.6% (42/487)	20.6% (224/1085)	2.9 (2.0-4.1)	<0.001
Skin rash/eczema	5.1% (25/487)	6.2% (67/1075)	1.2 (0.8-1.9	0.39
Musculoskeletal symptoms**				
Back pain	23% (116/494)	18.2% (196/1075)	0.7 (0.5-0.9)	0.012
Myalgia	24.2% (120/496)	20.1% (216/1073)	0.7 (0.6-1.0)	0.024
Sleep and mental health**				
Insomnia	16.9% (84/497)	13.7% (148/1078)	0.8 (0.6-1.0)	0.08
Psychological morbidity***	19.0% (95/500)	24.6% (278/1129)	1.3 (1.0-1.7)	0.05
Regular drugs use (at least once per week)				
Asthma medication	4.7% (24/510)	3.4% (39/1147)	0.7 (0.4-1.1)	0.12
Analgesics	11.4 % (58/510)	8.7% (100/1147)	0.7 (0.5-1.0)	0.04

Any drug for depression, anxiety, sleeping and other mental symptoms	14.9% (76/510)	12.5% (144/1148)	0.8 (0.6-1.1)	0.12
Blood pressure-lowering medication	19.6% (100/510)	22.6 (259/1148)	1.3 (1.0-1.7)	0.10

* Odds ratios (OR) and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, gender, education and smoking status.

**Answers “Yes, to a moderate extent” or “Yes, to much extent” to the question “Have any of the following symptoms disturbed your daily activities during the last month?”.

*** Psychological morbidity was derived from GHQ-12 referring to “the previous weeks”, using a binary cut-off score of >2.

Table 4 Risk of respiratory symptoms (ECHRS) in a population exposed to Eyjafjallajökull volcanic eruption by exposure level at the residence.

	Low exposure*		Medium exposure*		High exposure*	
	OR	%	OR (95%CI)**	%	OR (95%CI)**	%
Wheezing (last 12 months	1 (ref)	14.3% (21/147)	1.1 (0.6-1.8)	14.6% (91/623)	1.4 (0.8-2.3)	19.1% (65/340)
If yes, breathlessness at the same time	1 (ref)	47.6% (10/21)	1.2 (0.4-3.2)	54.5% (48/88)	1.8 (0.6-5.4)	64.3% (36/56)
If yes, do you wheeze without having a	1 (ref)	71.4% (15/21)	0.8 (0.2- 2.5)	67.4% (60/89)	1.1 (0.3-3.9)	75.4% (43/57)
Nocturnal chest tightness in (last 12 mo)	1 (ref)	6.0% (9/149)	2.1 (1.0-4.2)	11.4% (71/624)	3.1 (1.5-6.6)	16.1% (55/342)
Breathlessness at rest	1 (ref)	2.7% (4/146)	3.3 (1.2-9.3)	8.2% (51/619)	3.3 (1.1-9.7)	8.9% (30/338)
Coughing without having a cold	1 (ref)	19.5% (29/149)	2.0 (1.3-3.1)	31.1% (194/623)	1.6 (1.0.-2.6)	26.6% (91/342)
Nocturnal cough (last 12 months	1 (ref)	13.6% (20/147)	2.1 (1.3-3.5)	25.0% (155/619)	2.0 (1.2-3.4)	24.1% (83/344)
Cough in the morning in winter	1 (ref)	6.7 % (10/149)	2.2 (1.1-4.3)	13.7% (85/620)	1.6 (0.8-3.3)	11.1% (38/342)
Cough during the day or night in winter	1 (ref)	7.5% (11/147)	1.7 (0.9-3.4)	12.1% (75/619)	1.3 (0.6-2.7)	10.2% (35/342)
If yes, it is chronic***	1 (ref)	70.0% (7/10)	0.6 (0.1-3.6)	63.9% (46/72)	1.1 (0.2-6.9)	70.6% (24/34)
Morning winter phlegm	1 (ref)	8.3% (12/145)	1.7 (0.9-3.2))	13.7% (85/620)	2.3 (1.2-4.4)	18.3% (62/339)
Nocturnal or daytime winter phlegm	1 (ref)	4.9% (7/144)	1.5 (0.6-3.3)	6.9% (42/613)	2.4 (1.0-5.5)	11.8% (40/340)
If yes, is it chronic***	1 (ref)	85.7% (6/7)	0.7 (0.0-20.8)	92.5 (37/40)	0.5 (0.2-15.7)	81.1 (30/37)
Dyspnea	1 (ref)	6.7% (10/144)	1.9 (1.0-3.7)	6.9% (42/613)	2.4 (1.2-4.9)	11.8% (40/340)
Nasal allergy and hay fever	1 (ref)	17.2% (25/145)	1.2 (0.7-1.9)	19.4% (122/628)	1.1 (0.7-1.9)	19.2% (66/345)
Allergic rhinitis	1 (ref)	22.8% (33/145)	1.5 (0.9-2.2)	29.5% (184/624)	1.7 (1.1-2.7)	32.4% (110/340)
Physician diagnosed conditions** **						
Asthma	1 (ref)	17.2% (25/145)	0.6 (0.4-1.0)	10.5% (65/622)	0.7 (0.4-1.2)	12.3% (42/342)

Asthma diagnosis was confirmed by an MD	1 (ref)	95.5% (21/22)	0.3 (0.0-3.2)	93.7% (59/63)	Na*****	100% (37/37)
Heart disease	1 (ref)	10.1% (15/149)	0.8 (0.4-1.4)	7.2% (45/628)	0.8 (0.4-1.7)	8.6% (29/338)
Chronic bronchitis	1 (ref)	6.1% (9/147)	1.3 (0.6-2.7)	6.8% (42/620)	1.3 (0.6-3.0)	7.9% (27/340)
Emphysema	1 (ref)	1.4% (2/146)	1.6 (0.3-7.5)	1.8% (11/623)	1.4 (0.3-7.1)	2.4% (8/340)
Chronic obstructive pulmonary disease	1 (ref)	0.7% (1/146)	2.5 (0.3-20.2)	1.5% (9/619)	1.7 (0.2-14.2)	1.2% (4/340)

* Regions are seen in figure 1.

** Odds ratios (OR) and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, gender, education, and smoking status.

*** Chronic: more than 3 months per year

**** Answering "Yes" to "Has a physician ever told that you had (the disease)?"

***** Cannot divide with 0.

Table 5 Risk of recent symptoms (physical and psychological), reported diseases and drug use within regions of the exposed area

	Low exposure*		Medium exposure*		High exposure*	
	OR (95%CI)**	%	OR (95%CI)**	%	OR (95%CI)**	%
Respiratory symptoms* **						
Shortness of breath	1 (ref)	2.8% (4/144)	2.9 (1.0 - 8.5)	6.8% (41/600)	3.3 (1.1 - 9.9)	8.2% (27/330)
Feeling of tightness in chest	1 (ref)	1.4% (2/145)	3.4 (0.8 - 15.1)	3.9% (23/597)	3.1 (0.7-14.5)	4.0% (13/328)
Cough and phlegm* **						
Cough	1 (ref)	4.9% (7/143)	3.6 (1.6- 8.1)	15.7% (95/607)	4.5 (2.0- 10.2)	19.1% (64/335)
Phlegm	1 (ref)	2.8% (4/142)	4.2 (1.5-11.8)	10.8% (65/603)	6.0 (2.1-17.1)	15.9% (53/334)
Irritation symptoms* **						
Dry throat	1 (ref)	2.1% (3/145)	6.7 (2.0-21.6)	11.2% (68/608)	6.7 (2.0-22.2)	11.6% (39/336)
Eye irritation and itch	1 (ref)	8.3% (12/144)	3.4 (1.8-6.5)	21.5% (130/606)	3.6 (1.9-7.0)	24.5% (82/335)
Skin rash or eczema	1 (ref)	2.1% (3/146)	3.0 (0.9-10.1)	6.0% (36/600)	4.3 (1.3-14.3)	8.5% (28/329)
Musculoskeletal symptoms* **						
Back pain	1 (ref)	15.4% (22/143)	1.3 (0.8-2.1)	18.0% (108/599)	1.2 (0.7-2.1)	19.8% (66/333)
Myalgia	1 (ref)	16.6% (24/145)	1.3 (0.8-2.1)	20.0% (120/600)	1.3 (0.8-2.3)	22.0% (72.328)
Sleep and mental health						
Insomnia***	1 (ref)	6.3% (9/143)	2.4 (1.2-5.0)	13.8% (83/601)	2.8 (1.3-5.9)	16.8 (56/334)
Psychological morbidity*****	1 (ref)	20.0% (30/150)	1.2 (0.8-1.9)	24.8% (157/634)	1.3 (0.8-2.1)	26.4% (91/345)
Regular drugs use (at least once per week)						

Asthma medication	1 (ref)	3.9% (6/152)	0.7 (0.3-1.9)	2.5% (16/644)	1.2 (0.4-3.2)	4.8% (17/352)
Analgesics	1 (ref)	7.2% (11/152)	1.5 (0.7-2.9)	9.0% (58/644)	1.2 (0.6-2.6)	8.8% (31/352)
Any drug for depression, anxiety, sleeping and other mental symptoms	1 (ref)	5.3% (8/152)	3.6 (1.7-7.8)	13.7% (88/644)	2.8 (1.3-6.3)	13.6% (48/352)
Blood pressure-lowering medication	1 (ref)	19.7% (30/152)	1.7 (1.1-2.8)	22.8% (147/644)	1.4 (0.8-2.4)	23.3% (82/352)

* Regions are seen in figure 1.

** Odds ratios (OR) and 95% Confidence interval (CI) from multivariate logistic regression adjusted for age category, gender, education and smoking status.

*** Answering “Yes, to a moderate extent” or “Yes, to much extent” to the question “Have any of the following symptoms disturbed your daily activities during the last month?”.

**** Psychological morbidity was derived from GHQ-12 referring to “the previous weeks”, using a binary cut-off score of >2.

Health effects following the Eyjafjallajökull volcanic eruption– a population-based study

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Statements

All the authors conceived and designed the study and had full access to the data. AH, UAV, ÞBK, and GP gathered the data and HKC, AH, UAV, and GP did the statistical analyses. ÞÞ provided estimates of ash fall density. HKC and AH drafted the article, which was critically revised by all the authors, who also approved the final report. GP (guarantor) supervised the study, had full access to all the data in the study and carries the final responsibility for deciding to submit it for publication, and takes responsibility for the integrity of the data and the accuracy of the data analysis.

The participants of this study gave informed consent before participating in the study. The consent includes future follow-up, by questionnaire or in registers.
None of the authors have conflicts of interests or competing interests to declare.
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Abstract

Objectives The study aimed to determine whether exposure to a volcanic eruption was associated with increased rates of physical and/or mental symptoms.

Design Cohort, with non-exposed control group.

Setting Natural disasters like volcanic eruptions constitute a major public health threat. The Icelandic volcano Eyjafjallajökull exposed residents in southern Iceland to continuous ash fall for more than 5 weeks in spring 2010. This study was conducted November 2010-March 2011, six to nine months after the Eyjafjallajökull eruption.

Participants Adult (18-80 years of age) eruption-exposed South Icelanders (n=1,148) and a control population of residents of Skagafjörður, North Iceland (n=510). The participation rate was 72%.

Main Outcome Measures Physical symptoms in the previous year (chronic), in the previous month (recent), General Health Questionnaire (GHQ-12) measured psychological morbidity.

Results The likelihood of having symptoms during the last month was higher in the exposed population, such as; tightness in the chest (odds ratio (OR) 2.5; 95% CI, 1.1-5.8), cough (OR, 2.6; 95% CI, 1.7-3.9), phlegm (OR, 2.1; 95% CI, 1.3-3.2), eye irritation (OR, 2.9; 95% CI, 2.0-4.1), and psychological morbidity symptoms (OR, 1.3; 95% CI,1.0-1.7). Respiratory symptoms during the last 12 months were also more common in the exposed population; cough (OR, 2.2; 95% CI, 1.6-2.9), dyspnea (OR, 1.6; 95% CI, 1.1-2.3), although the prevalence of underlying asthma and heart disease was similar. Twice as many in the exposed population had two or more symptoms from nose, eyes, or upper-respiratory tract (24% vs. 13%, $p<0.001$); these individuals were also more likely to experience psychological morbidity (OR, 4.69; 95% CI, 3.39-6.50) compared to individuals with no symptoms. Most symptoms exhibited a dose-response pattern within the exposed population, corresponding to low, medium, and high exposure to the eruption.

Conclusions Six to nine months after the Eyjafjallajökull eruption, residents living in the exposed area, particularly those closest to the volcano, had markedly increased prevalence of various physical symptoms. A portion of the exposed population reported multiple symptoms and may be at

risk for long-term physical and psychological morbidity. Studies of long–term consequences are therefore warranted.

What this paper adds:

What is already known:
Natural disasters like volcanic eruptions constitute a major public health threat. Exposure to volcanic ash may affect respiratory health.

What this paper adds:
A larger population-based cohort with a control group was assessed with questionnaires and increased rates of respiratory and mental health symptoms were found some six months after exposure to a volcanic eruption, indicating that health effects may be long-lasting.

Introduction

Throughout history, human societies have been exposed to natural disasters like volcanic eruptions and earthquakes. In 2010, 300 000 individuals were killed worldwide in natural disasters.[1]Accurate information on mortality and long-term health consequences of natural disasters is instrumental to strengthen risk management and decrease their negative health impact.[2]

The eruption of the Eyjafjallajökull volcano in Iceland, which lasted from April 14th to May 20th 2010, made headlines worldwide, not least because of extensive effects on international flight traffic. Direct ash fall from the eruption was estimated at around 250 million tons, the rural regions in Iceland south and south-east of the volcano were most severely affected.[3,4] Ash fall was continuous for about 6 weeks, and following the eruption the ash was frequently resuspended in the area.[4,5] The surface of the fresh ash particles contained reactive salts and as much as 20% of the particles (by mass) were less than 10 µm in aerodynamic diameter and could enter the lower respiratory tract.[6] A study of local residents (N=207) was conducted immediately after the eruption ended. Participants were examined by a physician and to ascertain respiratory health, standardized spirometry was performed before and after bronchodilator usage. Adult participants also answered questionnaires about mental and physical health. Ash exposure was associated with high prevalence of eye- and upper airway irritation (25% and 50% respectively), and exacerbation of pre-existing asthma but did not contribute to serious health problems or impair respiratory function compared to controls. 39% showed symptoms of psychological morbidity as measured by the General Health Questionnaire (GHQ).[7] Residents from the region east of Eyjafjallajökull have expressed a need for more detailed information concerning ash fall during the eruption as the health effects were not known.[8] Meanwhile, the impact on long-term health of the residents remains to be explored. Previous studies on volcanic ash exposure and health have shown increased respiratory morbidity and asthma attacks,[9,10] and increased hospital visits for respiratory illness in association with some eruptions[11] but not in others.[12] Also, increased irritation of the respiratory tract from short-term exposure to volcanic gases and ash.[13] Long-term exposure to sulphuric gases (often emitted in volcanic eruptions) were found to be associated with increased prevalence of chronic bronchitis and cardio-respiratory symptoms in some studies.[14,15] In addition to direct physical health hazards, experiencing floods, lahars, as well as being exposed to prolonged ash suspension can be a threat to mental health. Stress levels may increase dramatically and have been shown to contribute to psychological morbidity such as post traumatic stress syndrome or depression.[16, 17]

Health effects of long-term exposure to a volcanic eruption are important both from a scientific and health care standpoint.[18] Iceland's population-based registries and strong infrastructure present an important opportunity to study such health impacts, particularly in terms of long-term follow-up. Utilizing the Icelandic population-based registers to identify all residents living in the vicinity of Eyjafjallajökull, the aim of this study was to investigate their self-reported physical and mental health six to nine months after the volcanic eruption. We hypothesized that residents of the Eyjafjallajökull area, particularly those most exposed, would be at increased risk of physical and psychological symptoms compared to a non-exposed population in North Iceland.

Methods

Study area

The exposed area in South Iceland is mostly farmland with a few villages. It has several active volcanoes[19] which along with sand plains and river beds are a source of dust storms.[20, 21] Apart from traffic on the national highway and agricultural activities, there are no major sources of anthropogenic particles in the area.

Almost from the onset of the eruption, the Environment Agency of Iceland monitored concentrations of inhalable particulate matter (PM_{10}) in up to three locations in the study area. The official health limit for PM_{10}, 50 μg/m^3 daily averages, was surpassed more than half of the days between May 7th and June 6th 2010, when air quality was continuously monitored in the most severely affected areas.[4] Monitoring continued after the eruption ended and until the end of out study period (Ultimo March 2011), ash was repeatedly resuspended and the mean 24-hour concentration of PM_{10} particles was 41 μg/m^3. The official health limit of 50 μg/m^3 daily average was exceeded 25 times, mostly during summer and fall of 2010. From November 2010 onwards the number of exceedences declined rapidly.[5]

In addition to a non-exposed control area in North Iceland, the study area was divided into a low, medium and high exposure regions in South Iceland (Figure 1) based on satellite images of the eruption plume (coarse time resolution), information about the emission intensity[3] and observations of ash deposits on the ground.[4,22] Models calculated with FLEXPART show similar ash deposits, ranging from approximately 1000 g/m^2 in the region just south of the volcano, down to about 200 g/m^2 near Vík some 50 km further east.[4]

During the eruption, the prevailing wind was from the north-west, causing the heaviest ash fall south and east of the volcano. While ash deposition was relatively low in the western part of the medium exposure region, the volcano was in full view there and thus these residents were more visually exposed to the volcano than in other regions. The lowland regions south and west of the glacier are prone to flooding and many residents were evacuated because of glacial outburst floods in the first days of the eruption.

Study population

The study population consisted of all residents in the municipalities closest to Eyjafjallajökull volcano (pre-defined by postal codes), identified in the population-based registry (Registers Iceland). Most live in farmlands (n=1207) and the rest in small townships (N=859).[23] By these means we identified 1,615 inhabitants who were 18-80 years of age, resided in the exposed area during the eruption, could be reached and spoke Icelandic fluently. In addition, a sample of 697 demographically matched (age, gender, urban/rural habitation) residents from a non-exposed area in Northern Iceland was included as control group. Sheep and dairy farming are predominant in both areas.

Data collection

Initially, all participants in the exposed group received a letter including information about the study and an invitation to participate. Some days after the letters were sent the recipients were contacted by telephone and asked whether they were willing to take part, and if so, whether they preferred to reply on paper or online. Subsequently, questionnaires or email invitations were sent and a week later a combined thank-you/reminder card was sent by post or e-mail. If needed, the participants were reminded again by phone. A similar protocol was used for the control group, with the exception that the introductory letter stated that a questionnaire would be sent a few days later, unless participation was declined.

Questionnaires were sent to the exposed population between November 19th and December 28th 2010 (six to seven months after the eruption ended) and the last replies were received in March 2011. The control group received questionnaires between January 26th and February 4th 2011, the last replies were received in April 2011.

The questionnaires contained no information that revealed the identity of the respondent, instead, they had a running number which could be linked to the person's ID number through a list which was kept separately and securely to enable later follow-up. A few of the returned questionnaires lacked most of the required information and were excluded from the analysis (n=13).

Questionnaires

The questionnaires contained questions concerning demographic background and current well-being, including various physical and psychological symptoms. We used standard questions from the screening part of the European Community Respiratory Health questionnaire[24] and assessed underlying disease by asking "Has a medical doctor ever told you that you had the following diseases: asthma, heart disease, emphysema, chronic bronchitis or chronic obstructive pulmonary disease (COPD)" with the response alternatives "Yes" or "No" by each option. To assess recent symptoms, we asked "Have the following symptoms disrupted your daily activities during the previous month?" followed by a list of various symptomsfrom e.g. the respiratory system, skin or eyes, or relating to pain. We also asked about smoking "Have you ever smoked", "Yes" or "No", and "Have you smoked during the last month", "Yes" or "No". Questions on regular use of medication were "Do you take medication regularly, that is, once per week or more often?" followed by listing asthma medication, analgesics, blood-pressure-lowering medication and sleep medication/anti-depressants/tranquillizers/medication for other mental health problems. Current psychological morbidity was evaluated from the General Health Questionnaire-12-item version (GHQ-12),[25,26] a non-specific screening tool for psychological morbidity which measures anxiety, loss of self-confidence and social dysfunction.[27] We used a binary cut-off score of >2.

Database & coding

The online survey was built with LimeSurvey.[28] Participants replying online accessed the survey using a unique identifier sent to them by email. Questionnaire replies on paper were entered into LimeSurvey according to uniform guidelines set by the researchers.

Statistical analysis

We first calculated descriptive statistics, contrasting background characteristics in the exposed and non-exposed population using X^2 – tests (*p* applies to all categories within demographic characteristics). Logistic regression was used to determine odds ratios (ORs) associated with residence in a) the exposed and non-exposed regions and b) the low, medium, or high exposure areas within the exposed region. All models were adjusted for a priori selected variables: age, gender, smoking status (never, former and current), and education level, odds ratios and 95% confidence intervals (CI) were calculated from the outputs. A CI not including 1.0 or a *p*-value of 0.05 or less was considered statistically significant. A Venn diagram was drawn to show the interrelationship between key nasal, eye, or upper respiratory symptoms (cough and/or phlegm without having a cold, eye irritation or itch, and sneeze, stuffed, or runny nose). Demographic characteristics, risk factors and comorbidities of those reporting multiple symptoms were explored using X^2 – tests and logistic regression.

IBM SPSS 19[29] was used for data analysis. Individuals who had not replied to all relevant questions were excluded from the regression models.

The study was approved by The Icelandic Data Protection Authority (nr. S4878/2010) and The Science Bioethics Committee (nr. VSNb2010080002/03.7), all participants gave informed consent.

Results

Valid questionnaires were obtained from 1,148 of 1,615 from the exposed population (71%) and 510 of 697 (73%) from the non-exposed population. A higher proportion of the exposed population could not be reached or found (10.8% vs. 7.2%; *P*=0.005), and more refused to participate (17.8% vs. 14.6%; *P*=0.069). The exposed and non-exposed participants were similar with respect to demographic characteristics; age, education levels, and occupational, marital, and financial status (Table 1).

Analysis 1: Exposed vs. non-exposed

Respiratory symptoms such as waking up with a feeling of tightness in the chest, breathlessness, cough, and phlegm in the last 12 months were more prevalent in the exposed population. After adjusting for sex, age, education, and smoking status, the exposed population was more likely to report symptoms like tightness in chest (OR, 2.0;95% CI, 1.3-3.0), coughing without a cold (OR, 2.2, CI, 1.6-2.9), and having chronic bronchitis, OR, 1.9 (95% CI, 1.1-3.1)(Table 2). In addition, bothersome physical symptoms during the last month were more common in the exposed population; these were shortness of breath, OR, 2.1 (95% CI, 1.2-3.6), cough (OR, 2.6; 95% 1.7-3.9), phlegm (OR, 2.1;95% CI, 1.3–3.2), and eye irritation (OR, 2.9; 95% CI, 2.0-4.1). Back pain, myalgia, and insomnia were less prevalent in the exposed population. Psychological morbidity was marginally more common in the exposed population (OR, 1.3; 95% CI, 1.0-1.7), as was the use of blood pressure lowering medication (1.3, 95% CI, 1.0-1.7), while use of analgesics was less common (OR, 0.7; 95% CI, 0.5-1.0) (Table 3).

Analysis 2: Low, medium, and high exposure

The prevalence of most respiratory symptoms during the last year increased with ash exposure. Adjusting for gender, age, education, and smoking, the likelihood of waking up with a feeling of tightness in the chest was higher in the medium- and high exposure regions, OR, 2.1 (95% CI, 1.0-

4.2) and OR, 3.1 (95% CI, 1.5-6.6), respectively. Chronic morning phlegm was only increased in the high exposure region, OR, 2.3 (95% CI, 1.2-4.4) (Table 4).

The experience of recent symptoms increased with exposure; cough (medium exposure OR, 3.6; 95% CI, 1.6-8.1; high exposure OR, 4.5; 95% CI, 2.0-10.2), phlegm (medium exposure OR, 4.2; 95% CI, 1.5-11.8, high exposure OR, 6.0; 95% CI, 2.1-17.1), and insomnia (medium exposure 2.4, 95% CI, 1.2-5.0, high exposure OR, 2.8, 95% CI, 1.3-5.9), (Table 5). No significant associations were observed between level of exposure and feeling of tightness in the chest, psychological morbidity, use of analgesic- and blood-pressure lowering drugs, or physician-diagnosed disease, though a non-significant trend was observed with some outcomes. ORs not adjusted for age, gender, education or smoking were similar to the adjusted ones.

Analysis 3: Multiple symptoms

A subgroup within both populations reported multiple symptoms from nose, eyes, or upper respiratory organs. The proportion reporting two or more symptoms was larger in the exposed population than the non-exposed (23.8% vs. 12.9%, data not shown), and there was a significant overlap in reporting one or more symptoms, see Venn diagram (figure 2). Within the exposed population the proportion was 13.3% in the low-exposure area, 24.7% in the medium exposure area, and 26.7% in the high-exposure area. In the exposed area, those who reported multiple key symptoms were more likely to be female (58.1% female vs. 41.9% male, $P<0.015$), and have asthma, compared to those with no symptoms (26.9% asthma vs. 3.4% asthma, $P<0.001$).

Analyzing the association between exposure and psychological morbidity and adjusting for multiple symptoms, we found that having multiple symptoms was associated with psychological morbidity, OR, 4.69 (95% CI, 3.39-6.50), irrespective of exposure level.

Discussion

Our study found that six to nine months after the Eyjafjallajökull eruption ended the participants from exposed areas reported increased wheezing, cough and phlegm, as well as recent eye and skin irritation. Participants from medium and high exposure regions experienced significantly higher rates of upper respiratory, skin, and eye irritation symptoms than those from the low exposure region. This suggests a dose-dependent relationship of the Eyjafjallajökull ash exposure on physical symptoms.

Many of the recent physical and mental symptoms were only marginally more prevalent in the high than the medium exposure area, indicating that there is a threshold beyond which additional exposure does not result in increased morbidity. Reporting two or more key respiratory symptoms was more common in the exposed population. Compared to the non-exposed, the exposed population reported only marginally higher prevalence of psychological morbidity. However, psychological morbidity was reported to be much higher in the subgroup reporting two or more symptoms, indicating that those with many symptoms represent a more sensitive subgroup within the population which should be especially targeted in preventive actions.

The main strengths of this study, our ability to identify the whole population experiencing a volcanic eruption as well as the high participation rate, both minimize the risk of selection bias. In addition, the internal response rate (answers to specific items) was high. The exposed and non-exposed populations were demographically similar and adjustment for age, gender and education further reduces the risk of confounding. Chronic illness prevalences in this study are comparable between the two areas, suggesting that the environment and occupational exposures are not dissimilar in the two areas, who are both characterized by sheep and dairy farming.

Regarding the limitations of the study, we have no information on the health status of the two populations before the eruption or the health status of non-respondents, and cannot exclude the possibility that the groups may have differed before the eruption. Although the study benefits overall from the high response rate, we have limited information on non-responders and therefore it remains uncertain to what extent, if at all, attrition affects our comparison across exposure areas. Another limitation of the study is that all symptoms are self-reported which may confer misclassification of symptoms. However, it is unlikely that this bias differs across exposure categories.

Classification of exposure areas (low, medium, high), which was based on estimated ash fall, may be imprecise and actual ash exposure may also vary within the exposure areas due to local weather conditions, terrain, or housing quality. Yet, if our classification is unclear or erroneous, this would reasonably result in compromised dose-dependent effects seen in our study and rather decrease the measured effects. It is also possible that exposures other than ash fall, e.g. noise, visibility, or living in lowlands exposed to glacial outburst floods, are significant contributors to the psychological morbidity which we observed in this study.

The exposed region is varied with respect to population density and occupation; the high exposure area has a higher proportion of farmers, who spend more time outside, which may exaggerate the observed difference between the medium- and low exposure areas. On the other hand, residents of the high exposure area may have been more vigilant in avoiding exposure, which would reduce the difference between the exposure areas. Data collection for the exposed group went on in November-December, and January-February for the non-exposed group, which may induce bias with respect to respiratory symptoms, as the seasonal influenza peaked during February and March in 2011.[30] However, this would attenuate the observed difference seen in respiratory symptoms.

Before the eruption of Eyjafjallajökull, dust storms frequently compromised air quality in the exposed area,[20,21] however, a study from 2004 on Icelandic farmers found no difference in respiratory symptoms between controls sampled from the national population and farmers, or among farmers in different regions of Iceland.[31] Chronic disease prevalence is similar in the exposed and non-exposed areas, further suggesting that the dust storms occurring before the eruption have no lasting effect on people´s health. Also, the dose-response character of symptoms with respect to exposure to the volcano suggests that the symptoms are associated with the eruption. Our findings of high rates of cough and eye irritation after the eruption are consistent with other studies, for example the Mount St. Helens eruption, where the number of emergency room visits, especially for respiratory conditions in those with underlying illness increased three to five-fold in the weeks following the eruption. Eye irritation was also more common in loggers exposed to Mount St. Helens ash, and the amount of eye mucus seemed to be dose-dependent on the ash density.[32]

Dose response and threshold effects of urban-type airborne particles on health have been explored in epidemiological studies,[33] but rarely in humans exposed to volcanic ash. A Japanese study of asthma treatment and volcanic ash exposure found worsening of symptoms in asthmatics in areas with more than 100 g/m^2 ash, but not in areas with less ash fall.[34] The psychological morbidity found in the current study (20-26%) were lower than that found in the survey of the most exposed area right after the Eyjafjallajökull eruption ended (39%).[7] This may indicate that residents have somewhat adapted to the strain following the eruption. Although a disaster with more dramatic consequences, a similar trend was found in a Japanese study of evacuees from a volcanic area where 66.1% showed signs of psychological morbidity (GHQ-30) six months after evacuation, while four years later the rate had fallen to 45.6%.[17] In our study, psychological morbidity and insomnia was most common in the high exposure group, as was the regular intake of medicines for depression, anxiety, sleep problems, or other mental symptoms. Dose-response trends were found between psychological morbidity and exposure to the Mount St. Helens eruption,[16] indicating possible long-term risk of further psychological morbidity in the high exposure group.

At this point, we cannot speculate about the effect of financial loss because of damages to property, this will be addressed in future studies.

The results from this study has implications for planners and authorities, as it indicates risk groups particularly susceptible to adverse reactions after exposure to volcanic ash. Also, the study design and registration of the participants enables follow-up of the exposed group, both directly in a new study, as well as in hospital, medicines and mortality registers.

Conclusions

In this population-based study we documented a high prevalence of respiratory symptoms six to nine months following the volcanic eruption in Eyjafjallajökull, especially among those most exposed. Also, subgroups who reported more than one physical symptom were more prone to experience psychological difficulties. The study reveals that the adverse health effects of a volcanic eruption may last for many months beyond the eruption and the immediate disaster relief services provided. This is important for health authorities to bear in mind.

These findings give incentive for further studies, e.g. on predictive factors for morbidity, the health of children, and long-term follow-up. Important knowledge may be gained from such studies to help develop mitigation measures at future eruptions.

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Figure 1. Map of Iceland and the study areas.

Inserted map of Iceland shows the location of Skagafjörður (non-exposed, control area) in the north and of the exposed area in South Iceland. The larger map of the exposed area shows Eyjafjallajökull (marked with X) and the low, medium and high ash exposure areas.

Figure 2 Venn diagram of exposed and non-exposed participants reporting one or more key symptom six to nine months after the Eyjafjallajökull eruption.

Legend: Eye symptoms; Irritation, itch or other discomfort, Nasal symptoms; Sneeze or runny nose without having a cough, Cough and /or phlegm; Often cough without having a cold, and/or phlegm during winter. The numbers do not add up due to rounding.

Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations.

	Exposed % (n/N)	Non-exposed % (n/N)	*p-value*
Target population (identified in total population registers)	**1811**	**751**	
Could not be found or reached	10.8% (196/1811)	7.2% (54/751)	0.01
Study population	**1615**	**697**	
Refused to participate	17.8% (286/1615)	14.6% (102/697)	0.07
Originally agreed to participate	**1329**	**595**	
Explained non-participation *	7.0% (93/1329)	6.1% (36/595)	0.44
Un-explained non-participation **	6.6% (88/1329)	8.2% (49/595)	0.20
Response rate (participants/study population)	**71% (1148/1615)**	**73% (510/697)**	0.31
Demographic characteristics			
Male	49.0% (562)	51.4% (262)	0.36
Female	51.0 (586)	48.6% (248)	0.36
Age categories			
18-23	11.1% (128/1148)	8.2% (42/510)	0.07
24-30	8.6% (99/1148)	9.0% 46/510)	0.79
31-40	15.2% (175/1148)	14.3% (73/510)	0.55
41-50	20.3% (233/1148)	21.4% (109/510)	0.62
51-60	19.3% (222/1148)	22.2% (113/510)	0.19
61-70	15.9% (183/1148)	16.5% (84/510)	0.79
71- 80	9.4% (108/1148)	8.4% (43/510)	0.52
Education			
No formal education	5.4% (61/1134)	4.8% (24/501)	0.62
Primary education	35.9% (407/1134)	30.9% (155/501)	0.05
Secondary education	33.4% (379/1134)	37.7% (189/501)	0.09
Professional or university education	20.6% (234/1134)	23.8% (119/501)	0.16
Other education*	4.7% (53/1134)	2.8% (14/501)	0.08
Marital status			
Married or cohabitating	72.4% (831/1148)	76.6% (391/510)	0.07
Single or divorced	18.3% (210/1148)	15.5% (79/510)	0.17
Relationship – no cohabitation	6.8% (78/1148)	4.7% (24/510)	0.10
Widow or widower	2.5% (29/1148)	3.1% (16/510)	0.48

Table 1 Participation and demographic characteristics of the exposed (South Iceland) and non-exposed (North Iceland) populations (continued)

Household size			
1 adult	13.8% (151/1096)	15.4% (76/494)	0.40
2 adults	51.4% (563/1096)	56.1% (277/494)	0.40
3 adults	21.3% (233/1096)	18.0% (89/494)	0.14
≥4 adults	13.6% (149/1096)	10.5 (52/494)	0.09
Occupational status			
Full time job	60.4% (683/1130)	61.0% (310/507)	0.79
Part time job	9.1% (103/1130)	11.6% (59/507)	0.11
Unemployed	3.5% (40/1130)	1.2% (6/507)	0.01
Student	6.9% (78/1130)	5.7% (28/507)	0.29
Homemaker or maternity leave	9.4% (99/1130)	7.8% (40/507)	0.56
Retired	6.1% (69/1130)	6.3% (32/507)	0.87
On disability or sick leave	5.1% (58/1130)	6.3% (32/507)	0.33
Financial situation			
Very good	4.6% (52/1136)	4.3% (22/510)	0.81
Good	23.9% (271/1136)	26.3% (134/510)	0.92
Acceptable (“making ends meet”)	55.6% (632/1136)	56.1% (286/510)	0.87
Bad	13.5% (153/1136)	12.0% (61/510)	0.40
Very bad “(indebted or bankruptcy”)	2.5% (28/1136)	1.4% (7/510)	0.16

	Exposure areas* **			**Non-exposed area**	
Smoking status	Low	Medium	High		
Never smoker	57.2% (87/152)	58.5% (377/644)	54.0% (190/352)	54.3% (277/510)	0.31
Former smoker	28.9% (44/152)	24.5% (158/644)	26.1% (92/352)	26.3% (134/510)	0.69
Current smoker	13.8% (21/152)	16.9% (109/644)	19.9% (70/352)	19.4% (99/510)	0.33

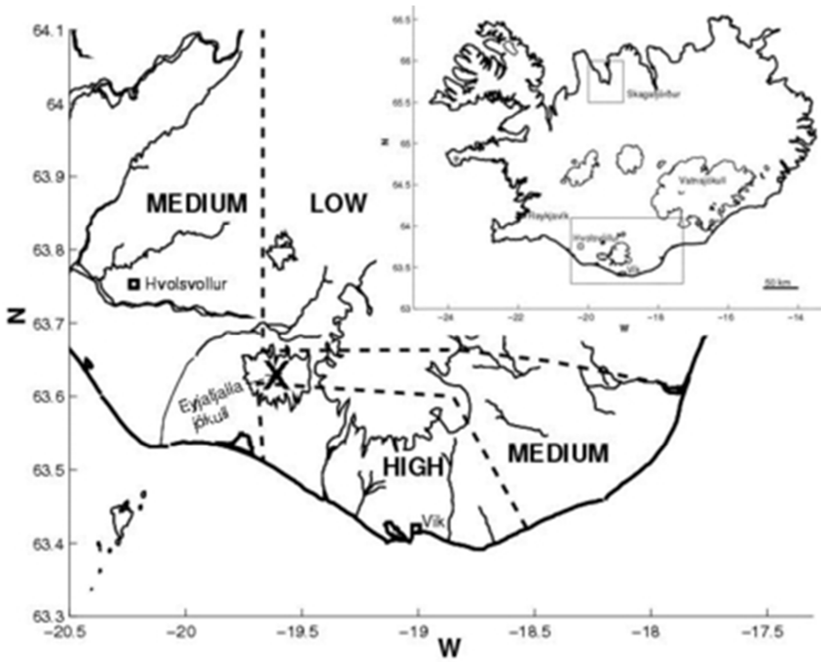
* Dropped out because of the nature of the questions, because they did not think the study applied to them, or because of illness or old age.

** Did not reply, could not be reached for reminders, did not respond to reminders or returned empty questionnaires.

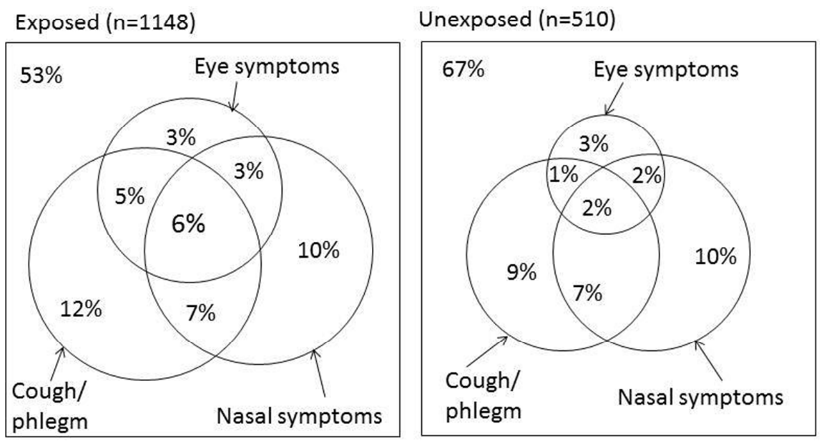
*** The exposed area was divided into three areas by levels of exposure with regard to magnitude of ash fall, see figure 1. The p-value is based on comparison between the non-exposed and the sum of the exposed area.

Remaining tables are in a separate file as they look better in Landscape format.

See Tables_Health_effects_following_the_Eyjafjallajökull_eruption.docx



Inserted map of Iceland shows the location of Skagafjörður (non-exposed, control area) in the north and of the exposed area in South Iceland. The larger map of the exposed area shows Eyjafjallajökull (marked with X) and the low, medium and high ash exposure areas.
17x13mm (600 x 600 DPI)



Venn diagram of exposed and non-exposed participants reporting one or more key symptom six to nine months after the Eyjafjallajökull eruption.

Legend: Eye symptoms; Irritation, itch or other discomfort, Nasal symptoms; Sneeze or runny nose without having a cough, Cough and /or phlegm; Often cough without having a cold, and/or phlegm during winter. The numbers do not add up due to rounding.
81x60mm (300 x 300 DPI)

STROBE Statement—for Volcano-Health study….page numbers pertain to the submitted manuscript file.

	Item No	Recommendation	
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	Page 1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	Abstract page3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	P 5
Objectives	3	State specific objectives, including any prespecified hypotheses	P 7
Methods			
Study design	4	Present key elements of study design early in the paper	Page 6(intro)
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Page 8, data collection
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	Page 9, data collection.
		(*b*) For matched studies, give matching criteria and number of exposed and unexposed	Page 8, study population
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	Page 9, questionnaire, coding.
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Page 9 (same)
Bias	9	Describe any efforts to address potential sources of bias	Page 8 study population
Study size	10	Explain how the study size was arrived at	P9 datacolletion/p10 results
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	-
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	P10 statistical analysis
		(*b*) Describe any methods used to examine subgroups and interactions	Page 10, Stat. analys.
		(*c*) Explain how missing data were addressed	
		(*d*) If applicable, explain how loss to follow-up was addressed	-
		(*e*) Describe any sensitivity analyses	-
Results			

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	P1 Results/table 1
		(b) Give reasons for non-participation at each stage	Table 1
		(c) Consider use of a flow diagram	-
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 1 and others
		(b) Indicate number of participants with missing data for each variable of interest	Ok
		(c) Summarise follow-up time (eg, average and total amount)	-
Outcome data	15*	Report numbers of outcome events or summary measures over time	Tables.
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	Tables. P10 stat.methods
		(*b*) Report category boundaries when continuous variables were categorized	-
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	-
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	P 10 Stat methods/p 12
Discussion			
Key results	18	Summarise key results with reference to study objectives	P13
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	P13-14
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	P14-15.
Generalisability	21	Discuss the generalisability (external validity) of the study results	P15
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Page 2. -

*Give information separately for exposed and unexposed groups. **Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at http://www.strobe-statement.org.	