Introduction to IVHHN Standardized Protocols to Assess the Health Impacts from Volcanic Eruptions

A key challenge to identifying the health impacts from volcanic eruptions is to devise and apply epidemiological methods which can be rapidly deployed at eruption onset. Opportunities for study have been missed in the past, leaving large gaps in our knowledge for dealing with human risk in future eruptions. Despite these evidence gaps, health impacts ought to be at the forefront of volcanic risk assessments and decision-making on timely evacuations of populations, and on provision of evidence-based public health messaging to vulnerable groups exposed to volcanic emissions.

To assist with the generation of health evidence from volcanic contexts, IVHHN has developed standardized protocols to facilitate epidemiological studies of populations that have been, or may be in the future, exposed to volcanic ash and gases. The intent is for these protocols to be applicable in all volcanic contexts and settings, regardless of resource availability, health records systems, or timeframe. The overarching purpose is to answer the question: Has there been a short-term increase, at either the individual or population level, in adverse health outcomes following a volcanic eruption?

The protocols provide guidelines to undertake two types of studies: (i) a basic study tallying hospital and clinic visits of respiratory (and potentially other health) outcomes, to be conducted during or immediately following a volcanic eruption, and (ii) a more detailed, cross-sectional survey of individuals exposed to volcanic emissions, which may be undertaken if the basic study indicates adverse health effects. The 'basic' study offers a simple design allowing a quick survey at a population level to identify if there is any increase in ill-health in areas exposed, compared to the period before the volcanic event (or to a similar but unexposed area). The 'cross-sectional' study examines ill-health and estimated exposure to volcanic ash/gases at an individual level, with the aim of determining whether health effects occur more commonly in those areas with higher exposures. A cross-sectional approach takes advantage of individual-level data, allowing a finer resolution to link exposure and health, thus enabling stronger inferences to be made about any impacts from the volcanic eruption.

Advising relatively simple and inexpensive methods, these protocols mark the necessary first steps in tracking early health signals from inhalation of volcanic emissions. If these protocols are implemented across different geographic settings, results could be pooled to reach even stronger conclusions about the potential health effects. However, if varied methods are employed across eruptions and environments, results may not be readily combined and thus important opportunities to build our knowledge and protect affected communities may continue to be missed. While other study designs are indeed possible, including case-control and longitudinal, these typically involve more complex methods and higher costs. Case-control studies, typically employed when the disease under investigation is rare, would not be needed for the assessment of relatively common exacerbations and symptoms of respiratory illness, though follow-up studies may be important to update the findings from the standardized protocols over time. Longitudinal studies, by their nature, take a long time to complete and are resource intensive and expensive to conduct. As such, they would not be suitable for the shorter-term identification of increases in adverse health effects following a volcanic eruption, which is the primary aim of the standardized protocols provided by IVHHN.

Compared to other natural disasters, there is a wide range of causes of death and injury and other health impacts corresponding to the multiple phenomena of eruptions and volcanic behavior, which vary both from eruption to eruption and among volcanoes. The studies, therefore, have to be done in close collaboration with the volcanologists who are advising the authorities on the hazards that may arise in a particular crisis, both before and after eruptive events.

There are several cardinal aspects to disaster epidemiology that require a different approach and expertise in planning and executing studies than in standard epidemiology. These include a rapid response to capture fleeting exposures, taking account of other important issues including a potential breakdown in normal public health functioning, the disruption of a community in the event of evacuations, a diversion of health sector resources to coping with urgent disaster needs such as food and shelter, and health professionals concerned about their own (and their family's) safety and livelihoods.

Operating under such circumstances is clearly a daunting task, but it is widely accepted that the information that epidemiological investigations provide is essential for sound decision-making and building trust between those managing a disaster and the population involved. To emphasize the point above, a key advantage of standardized methods is the ability to compare and pool results from different populations, settings, and exposure levels; dose-response data, which are currently absent from the existing evidence, would be invaluable to help prepare guidance to protect populations from undue risks. In addition to standardization, the accompanying protocols can help reduce the time and costs associated with study design, as well as to provide approximate expectations of resources needed to complete the two proposed study types.

In the sections below, we outline some of the significant, historic volcanic events in a narrative review, and provide a more detailed table of past epidemiological studies undertaken.

Lessons learned from past, significant volcanic eruptions

The following chronology describes some of the significant past eruptions in recent history and draws together the main lessons, underscoring the need for standardized approaches to study health impacts. This discussion is intended to be illustrative and not exhaustive. In addition to this narrative review, we provide a more comprehensive list of past health studies in the summary tables below.

<u>Mount St Helens, USA, 1980</u>

The first time a modern society had to contend with a massive ashfall event is considered to be in the USA following the Mount St Helens eruption in 1980. A major air pollution episode caused by suspended fine ash particles lasted six days that was shown by health surveillance (daily hospital attendances) to have minimal impact on healthy people, with only limited reassurance for those with pre-existing cardio-respiratory conditions. However, persons with pre-existing illnesses limited their exposure to ash by staying indoors in well-constructed US houses. A study of loggers provided with respiratory protection showed no lasting respiratory impact of exposure to ash, but we now recognize that other heavily-exposed outdoor groups, such as emergency workers, require follow up too. There was conflicting evidence from the results of prevalence studies of respiratory impacts in children, and there was no comprehensive mortality study conducted at the time (Bernstein et al., 1986).

Mt Pinatubo, Philippines, 1991

Pinatubo erupted in a one-off massive eruption after 2 months of premonitory activity. Apart from a prevalence survey in evacuation camps, which showed minimal respiratory impacts in areas of heavy ashfall (Surimeda et al., 1992), there were no long-term studies of large populations exposed for several years to the re-suspended ash. A "snapshot" survey was done on the main cause of death in the eruption – the collapse of roofs under the weight of ash and the vulnerability of certain building types (Spence et al., 2005). Unfortunately, it was not extended to link types of injuries and deaths to the building failure. The rebuilding happened very quickly so any study needed would have had to be completed in the days immediately after the eruption. Ash deposits persisted for years. Because it was one of the largest eruptions of the 20th century, this was an extremely important disaster that warranted investigation for disaster mitigation: no comparable opportunities for study have presented in the world since.

Cerro Negro, Nicaragua, 1992

This small eruption deposited fine ash in the city of Leon and its surroundings. A persistent, strong trade wind created a constant plume of ash that could be seen travelling many kilometers and out to sea. Clinicians reported that the city suffered an obvious outbreak of respiratory illness for weeks while the plume persisted, with an influx of patients, but the medical facilities were poorly equipped (Malilay et al., 1996). One theory is that the coarse component of the ash broke up plant matter as it battered the vegetation in the strong wind, increasing the amount of fine, allergenic material in the air that could trigger sensitization in susceptible individuals. No investigations to look into this hypothesis were feasible at the time.

Soufrière Hills volcano, Montserrat 1995 – 2011

Montserrat is a small volcanic island in the Caribbean – a British Overseas Territory. The volcano unexpectedly started erupting on a small scale and then gradually escalated to have a devastating eruption in June 1997 when 19 people died in a pyroclastic flow. The population was exposed to frequent ashfalls during the eruption, from small explosions and lava dome collapses, which presented a respiratory hazard of silicosis due to crystalline silica in a proportion of the respirable ash particles. Two risk assessments (1997 and 2003) involved repeated exposure surveys in outdoor workers and the community. The exposed population reduced in number as islanders left for other countries, which made cohort studies unfeasible, but the risk assessments suggested that the silicosis risk was small. A survey of asthma in island schoolchildren showed an effect in those living in ashfall areas, whereas visits to the single hospital on island and numbers of anti-asthma drugs dispensed at the island pharmacy showed no change during the eruption. Asthma (prevalence 18% in the children's study) was being poorly recognized and treated on the island, especially with a small and dysfunctional health system as a result of the crisis (Baxter et al., 2014).

Rabaul, Papua New Guinea, 2007 – 8.

In a small eruption at Rabaul volcano in 2007 – 2008, a persistent plume of ash and gas fumigated a wide area where 70,000 people lived, presenting a severe air pollution crisis. For several months, in 2008, there was a drought which allowed the ash to accumulate everywhere, adding to the health hazard from inhaling the persistent plume of respirable ash mixed with sulphur dioxide gas. Respiratory problems were widely reported and schools had to deal with children who suffered from asthma attacks. Untreated tuberculosis was already rampant in the area before the eruption. The absence of an adequate infrastructure prevented the undertaking of rapid respiratory surveys on which to base urgent medical advice to the most vulnerable in the population.

Cordon Caulle volcano, Chile, with widespread ash dispersion in Patagonia, Argentina 2011

In 2011, the Cordon Caulle eruption in Chile produced a heavy ashfall in the semi-arid Patagonian Steppe with dramatic consequences (Folch et al., 2014). Ash storms were created by the regular strong winds in the area in the absence of rainfall, leading to very high exposures to respirable ash on those occasions, with ash readily infilling flimsy, open rural buildings in which farming families lived. Normal life did not return for 3 months after the eruption. A health risk assessment, particularly in children, was badly needed with a view to temporarily removing them from the affected areas; adults with pre-existing chronic illness also needed advice for protecting themselves. No disaster epidemiological studies or exposure surveys were undertaken.

Fuego, Guatemala, 2018

During the eruption of Fuego, about 1500 rescuers were sent to the scene of a town buried by a pyroclastic flow, but they were untrained for such an eventuality in which they were exposed to clouds of hot, fine ash with inadequate facemasks (or training in their use). Afterwards, complaints of respiratory symptoms were widespread in the group and needed investigation.

Conclusion

Despite the magnitude of these volcanic eruptions, little information exists on the impacts of such large events in low income countries, especially those in warm countries with open housing construction and widespread indoor cooking with solid fuels. In addition, there is no information on such ashfall in communities with a high incidence of childhood pneumonia, one of the most common causes of death in infants in developing countries (Liu et al., 2015). Key questions, such as determining exposure-response relationships and how exposure to ash triggers airway sensitivity in previously well individuals, in particular children and the elderly, have remained largely unanswered.

An ongoing challenge is that eruptions often occur in countries with poor or non-existent gathering of routine health statistics from hospitals and clinics, and death registrations. This surveillance, as well as registers of emergency workers and others engaged in outdoor duties which result in extreme ash exposures, should be established after every major eruption if not already in existence, to undertake health screening and longitudinal follow-up. Health surveillance therefore requires disaster epidemiology techniques for such countries, in the context of the disaster likely further reducing any existing capacity for investigation.

There are numerous obstacles to undertaking epidemiological studies in volcanic eruptions, but there is no shortage of questions to answer. A major constraint is the lack of protocols that can be applied in a crisis to rapidly investigate the health impacts for risk assessment purposes as well as to answer questions on the long term effects of high exposures to ash and gases in volcanic emissions.

Summary table of epidemiological study methods and results from volcanic settings.

The following table summarizes epidemiological studies undertaken in populations exposed to volcanic emissions, though this list is not exhaustive. The studies are grouped by, and intend to reflect, the main epidemiology study designs employed to date (Bonita et al., 2006; Rothman et al., 2008). More comprehensive lists of existing studies are available on the IVHHN website[1] and in published reviews (e.g., Horwell & Baxter, 2006; Gudmundsson, 2011, Hillman et al. 2012).

- Ecological/time-series: Data at the group level are used to compare outcomes either between different populations during the same period or in the same population across time.
    - *Example*: Comparing hospital admissions in two cities.
    - *Strengths*: Low-cost, convenient, fast.
    - *Limitations*: No individual level data, so cannot directly link exposure to health outcome.

- Cross-sectional: Individual data to compare prevalence of an outcome by exposure status.
    - *Example:* Comparing asthma prevalence in a sample of individuals in two cities.
    - *Strengths*: Low-cost, relatively quick.
    - *Limitations*: Occurs at a given point in time, so difficult to determine cause and effect.

- Case-control: Individuals with (cases) and without (controls) a given illness from a source population to compare likelihood of exposures.
    - *Example:* Comparing tobacco use in patients with lung cancer and healthy controls.
    - *Strengths*: Effective for the study of rare diseases.
    - *Limitations*: Difficult to ensure cases and controls are equivalent except for disease status. Issue of reverse causation arises, whereby disease may have contributed to exposure.

- Cohort/longitudinal: Follow-up of individuals over multiple time-points to track exposures and development of disease.
    - *Example:* Tracking onset of cancer in an occupational cohort.
    - *Strengths*: Yields high-quality data on risk factors for disease, particularly for rare exposures.
    - *Limitations*: Expensive, time-consuming.

[1] https://www.ivhhn.org/ivhhn-library

Ecological/time-series studies

Author, Year	Volcano	Population	Outcome	Exposure	Result
Kraemar & McCarthy, 1985	Mt St Helens, US	Spokane County, Washington	Childhood asthma hospital admissions	Ashfall?	2x rates in year of volcano vs following year
Wakisaka et al., 1988	Mt Sakurajima, Japan	25 cities surrounding Mt Sakurajima	Respiratory mortality	10, 20, 30 km from Mt Sakurajima	Deaths from bronchitis were elevated within 20 km, but not other respiratory causes.
Wakisaka et al., 1989	Mt Sakurajima, Japan	4 districts located within 15 km of Mt Sakurajima	Clinical consultations for respiratory diseases	<10 km, 10-15 km from Mt Sakurajima	Higher rates of consultations in areas <10 km
Malilay et al., 1996	Cerro Negro, Nicaragua	Proximal residents	National Surveillance for hospital visits	Ashfall	Acute respiratory visits in 2 communities: 3.6x & 6x increased vs before volcano
Gordian et al., 1996	Mt Spurr, Alaska	Population of Anchorage	Hosp. visits asthma, Upper Resp Infections	PM_{10} monitor, 40 -> 70 ug/m^3	Per 10 ug/m^3: 3-6% ↑ asthma, 1-3% ↑ upper respiratory infection, but not after volcano
Choudhury et al., 1997	Mt Spurr, Alaska	Population of Anchorage	Medical visits for respiratory reasons	PM_{10} (mean=41.5 μg/m^3)	Same day association in PM_{10} and respiratory visits.
Hickling et al., 1999	Mt Ruapehu, New Zealand	General population	Hospital visits	Areas w/ >0.25 mm ashfall	Similar rates in 3 months vs 7 years prior, borderline ↑ bronchitis
Naumova et al., 2007	Guagua Pichincha, Ecuador	General population - children	Paediatric ER visits – resp.	Eruption period & afterward	2.2x & 1.7x increases for lower & upper resp. infections 3 weeks after eruption. 345 extra ER visits in 28 days following.
Longo et al., 2008	Kilauea, Hawai'i	General population	Clinic visits	$PM_{2.5}$, SO_2 (averaged 74.9 ± 51.9 ppbv/day)	6x ↑ airway issues after vs before, esp. younger indiv.
Higuchi et al., 2012	Mt Sakurajima, Japan	Populations in Sakurajima and Taramizu	Respiratory Mortality	Exposed vs less exposed	Elevated risk of lung cancer found in more exposed city (Sakurajima).

Oudin et al., 2013	Grimsvötn, Iceland	21 regions in Sweden exposed to ashfall.	All-cause mortality	Average $PM_{2.5}$ increase of 10 μg/m^3	No significant differences.
Balsa et al., 2016	Puyehue, Chile	23 hospitals in Montevideo	Pregnancy & perinatal outcomes	PM_{10} exposure during pregnancy	Preterm birth per 10 μg/m^3 in 3rd trimester OR=1.10

Cross-sectional studies

Author, Year	Volcano	Population	Outcome	Exposure	Result
Research committee on Volcanic emissions, 1982	Mt Sakurajima, Japan	Residents of 2 towns	Pneumoconiosis, lung function	Distance of volcano to towns	0 cases of pneumoconiosis, Slight ↓ lung function in exposed women, but Total Suspended Particulates (TSP) too low to cause effect.
Yano et al., 1986	Mt Sakurajima, Japan	Women in 3 towns	Respiratory diseases	Distance of volcano to towns	No difference in symptoms, overall respiratory disease prevalence low, but higher in town with highest TSP
Yano et al., 1990	Mt Sakurajima, Japan	Women in 2 towns	Respiratory diseases	Distance of volcano to towns	Respiratory disease slightly higher in town with higher TSP
Uda et al., 1999	Mt Sakurajima, Japan	School children	Asthma	Proximity of school	No significant difference in asthma proportion between exposed and control groups
Cowie et al., 2001	Soufriere Hills, Montserrat	Emigrants to UK, n=465	Questionnaire for resp. symptoms	Compared to the UK population.	Slightly ↑ respiratory symptoms vs UK population
Cowie et al., 2002	Soufriere Hills, Montserrat	Workers (various) n=421	Lung function, respiratory symptoms, X-rays	Residence in Low/ Medium /High ashfall	Low prevalence of symptoms, ↓ lung function in gardeners & road workers
Sasayama et al., 2002	Mt Unzen Fugen, Japan	School children, aged 6-11 years	Asthma questionnaire	Location of school	Some indication of deteriorated asthma.

Forbes et al., 2003	Soufriere Hills, Montserrat	Schoolchildren	Respiratory symptoms	Residence in low/med/high ashfall	4x as likely to report wheeze in most heavily exposed
Tobin & Whiteford, 2004	Mount Tungurahua, Ecuador	Residents of 3 towns, n=314	Self-reported symptoms	High ash/no evacuation, low ash/evacuation, no ash/no evacuation	No differences in reported respiratory or gastrointestinal illness, but differences in eye, skin and throat
Shimizu et al., 2007	Mt Asama, Japan	Adult asthma patients, n=236	Questionnaire	Areas of >100 g/m^2, >10 g/m^2	42.9% exacerbations in 100 g/m^2 ashfall area vs 8.3% control area
Carlsen et al., 2012a	Eyjafjallajökull (Iceland)	Residents, n=1148 exposed, n=510 controls	Spirometry, questionnaires	>500 g/m^2	50% reported eye & upper Resp. irritation. ↑ lung function in exposed, but ↓ smokers

Case-control studies

Author, Year	Volcano	Population	Outcome	Exposure	Result
Baxter et al., 1983	Mt St Helens, US	Asthma (n=39) & Bronchitis (n=44) patients	Asthma, Bronchitis	Average TSP levels	Patients more likely to have resp. history, less likely to have cleaned ash
Baxter et al., 1983	Mt St Helens, US	Chronic lung disease individuals (n=97)	Symptom exacerbation	Ashfall vs none	33% worsened in exposed vs 4% in unexposed
Bradshaw et al., 1997	Mt Ruapehu, New Zealand	1392 asthmatics	Asthma symptoms & medication use	Exposed vs not exposed	No significant associations in any of the outcomes.

Longitudinal (follow-up) Studies

Author, Year	Volcano	Population	Outcome	Exposure	Result
Johnson et al., 1982	Mt St Helens, US	School children	Lung function (FEV_1, FVC)	?	No diff before and after, though decrease from exposure to urban air pollution
Buist et al., 1983	Mt St Helens, US	Children's summer camp, n=101	Lung function (FEV_1, FVC)	Respirable dust averaged 0.17 mg/m^3	No diff within or between days though after ash clean-up
Buist et al., 1986	Mt St Helens, US	Loggers at 4 camps, 2 exposed, 2 not	Lung function (FEV_1, FVC), symptoms	Ashfall vs none	Short, reversible decline in lung function
Rojas-Ramos et al., 2001	Popocatepetl, Mexico	Farmers, n=35	Lung function (FEV_1, FVC), symptoms	0.5-1 mm ash	Short, reversible decline in lung function over 7 months
Carlsen et al., 2012b	Eyjafjallajökull, Iceland	Residents, exposed, n=1148, Unexposed, n=510	Chronic, acute symptoms, GHQ-12	Exceedances of PM_{10} 50 µg/m3 during summer/ fall 2010	After 6-9 months - ↑ in exposed: OR >2.0 chest tightness, cough, phlegm
Hlodversdottir et al., 2016	Eyjafjallajökull, Iceland	Residents, exposed, n=1148, Unexposed, n=510	Chronic, acute symptoms, GHQ-12, stress	PM_{10}, Low/ Med/ High exposure areas – monitors, satellites	3 years - ↑ in 2013 vs 2010: OR >2.0 phlegm, ↑ in exposed: OR >2.0 wheezing, phlegm
Hlodversdottir et al., 2018	Eyjafjallajökull, Iceland	Children of exposed residents n=433 (n=200 unexposed)	Respiratory symptoms, headaches, anxiety, & others	PM_{10}, Low/ Med/ High exposure areas – monitor, satellites	Highly exposed children resp. symptoms, OR=1.52, worries OR= 2.77. No signif decrease in symptoms 2010-2013.

Acknowledgements

This document and the accompanying protocols were written for the International Volcanic Health Hazard Network (IVHHN) by: Will Mueller (IOM, UK), Hilary Cowie (IOM, UK), Dr Claire Horwell (Durham University, UK) and Dr Peter Baxter (University of Cambridge, UK). The protocols are an output of the Health Interventions in Volcanic Eruptions (HIVE) Consortium project and are the result of a workshop attended by respiratory epidemiologists, clinicians, disaster management specialists and volcanologists held at Durham University in January 2018. The protocols were reviewed by Prof Debbie Jarvis and Prof Paul Cullinan (Imperial College, London, UK), Prof Hiro Inoue (Kagoshima University, Japan), Prof Damien McElvenny (IOM, UK), Prof Sonia Buist (Oregon Health & Science University, USA), Dr Tamara Mancero (PAHO, Argentina), Dr Rogelio Perez Padilla (National Institute of Respiratory Diseases, Mexico) including ‘ground-truthing’ to account for local logistical, economic and cultural factors which may influence study implementation. The protocols were presented at a workshop hosted by the Pan American Health Organization, Washington DC, in December 2018, with delegates from Latin American ministries of health and other disaster response organizations. Final suggestions were incorporated following that workshop.

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Further reading.

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