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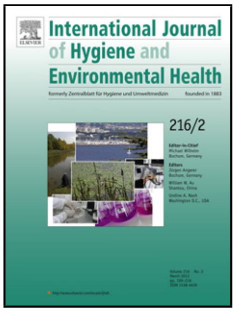

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The effectiveness of respiratory protection worn by communities to protect from volcanic ash inhalation. Part I: Filtration efficiency tests

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ABSTRACT

During volcanic eruptions and their aftermath, communities may be concerned about the impacts of inhaling volcanic ash. Access to effective respiratory protection (RP) is therefore important for many people in volcanic areas all over the world. However, evidence to support the use of effective RP during such crises is currently lacking. The aim of this study was to build the first evidence base on the effectiveness of common materials used to protect communities from ash inhalation in volcanic crises.

Key Words: respirator, facemask, $PM_{2.5}$, ash, volcano, filtration efficiency

We obtained 17 forms of RP, covering various types of cloth through to disposable masks (typically used in occupational settings), which communities are known to wear during volcanic crises. The RP materials were characterised and subjected to filtration efficiency (FE) tests, which were performed with three challenge dusts: ashes from Sakurajima (Japan) and Soufrière Hills (Montserrat) volcanoes and aluminium oxide (Aloxite), chosen as a low-toxicity surrogate dust of similar particle size distribution. FE tests were conducted at two concentrations (1.5 mg/m^3

and 2.5 mg/m^3) and two flow rates (equivalent to 40 and 80 l/min through 15.9 cm^2 sections of each RP type). Each material was held in a sample holder and $PM_{2.5}$ dust concentrations were measured both outside the mask material and inside the sample holder to determine FE. A limited number of tests were undertaken to assess the effect on FE of wetting a bandana and a surgical mask, as well as folding a bandana to provide multiple filter layers.

Overall, four RP materials performed very well against volcanic ash, with median FEs in excess of 98% (N95-equiv., N99-equiv., $PM_{2.5}$ surgical (Japan), and Basic flat-fold (Indonesia)). The two standard surgical masks tested had median FEs of 89-91%. All other materials had median FEs ranging from 23-76% with no cloth materials achieving >44%. Folding a bandana resulted in better FE (40%; 3x folded) than single-layered material (29%). Wetting the bandana and surgical mask material did not improve FE overall.

This first evidence base on the FE of common materials used to protect communities in volcanic crises from ash inhalation has been extended in a companion study (Steinle et al. submitted) on the total inward leakage of the best-performing masks when worn by human volunteers. This will provide a complete assessment of the effectiveness of these RP types.

INTRODUCTION

Explosive volcanic eruptions generate volcanic ash through high-energy fragmentation of magma. The ash can be distributed in the atmosphere over hundreds to thousands of kilometres, depending on the size of the eruption, and may stay in the environment for years (Blong, 1984). Ash may also be re-suspended, e.g., through wind, road traffic, or cleaning-up activities, which has long-term implications for those populations residing and working in affected areas. According to estimations by Small and Naumann (2001), 9% of the world's population live within 100 km of a historically active volcano.

Short-term respiratory health issues observed after volcanic eruptions include exacerbation of existing asthma and bronchitis, as well as symptoms such as coughing, breathlessness, chest tightness, and wheezing (Baxter et al., 1983; Horwell and Baxter, 2006). Regarding long-term respiratory effects, development of silicosis and chronic obstructive pulmonary disease (COPD) are of most concern, but have not yet been confirmed in volcanic settings (Horwell and Baxter, 2006).

Volcanic ash can vary substantially in its physicochemical characteristics and, therefore, its potential to be a respiratory health hazard (Damby et al., 2013; Damby et al., 2017; Hillman et al., 2012; Horwell et al., 2013; Le Blond et al., 2010). Every eruption generates ash of variable particle size distributions (PSD) and composition (Horwell, 2007; Horwell et al., 2007); thus, providing accurate, rapid, and timely information on the potential respiratory hazard is a challenge for governmental and humanitarian agencies. The International Volcanic Health Hazard Network (IVHHN) (www.ivhhn.org) has developed rapid protocols for assessment of health-pertinent ash characteristics (Damby et al., 2013; Horwell et al., 2013; Le Blond et al., 2010), but detailed analysis is rarely possible in the timeframe of an eruption.

With some eruptions producing ash with substantial quantities of fine-grained material (Horwell, 2007), and sometimes with concerning quantities of crystalline silica (Baxter et al., 1999; Horwell et al., 2014; Horwell et al., 2010), agencies generally take a precautionary approach and advise that individuals should protect themselves from ash inhalation (e.g., see summary at: http://www.ivhhn.org/resources/global-ash-advice.html; IVHHN, 2017). Advice for communities affected by volcanic ash includes avoiding unnecessary exposure and staying indoors during ashfall or when ash remains in the environment for prolonged periods. It may not always be possible for people to remain indoors for extended periods of time and so they may choose, or be advised by governmental or humanitarian agencies, to protect themselves by wearing a facemask or by improvising a fabric mask from cloth, to filter out ash. Despite its importance, evidence to support the efficacy of respiratory protection (RP) for use during volcanic crises is lacking (Horwell et al., 2017).

The effectiveness of RP is dependent on several factors: i) the design, to prevent penetration of a specific hazardous substance; ii) reduction of exposure to the level required to protect the wearer's health; and iii) appropriateness for the individual wearer, task, and environment (HSE, 2013; van der Sande et al., 2008). These factors form the basis for any 'fit testing' in a workplace setting, where industry certified masks with a known filtration efficiency (FE), i.e., the percentage of particles filtered by the RP material, are used, and any leakage due to gaps between face and mask into the RP (faceseal leakage) is quantified. Such assessment of suitability appears to be completely absent in the community setting for volcanic eruptions. Agencies often distribute masks (usually surgical ones) by the million, mostly from existing stockpiles for viral pandemics and usually without any information on FE and how to achieve best fit (Horwell et al., 2017). The assessment of fit is discussed in Steinle et al. (submitted). The ethical implications of agencies recommending and distributing masks in the absence of evidence of their efficacy, and without accompanying factual information, are considered separately (McDonald and Horwell, 2017).

In many countries, for occupational settings, use of effective RP is supported by legal enforcement, with RP being required to meet national or international standards (e.g., EN 149:2001, EN 140:1998 in the EU (European Committee for Standardization, 1998, 2001) or 42 CFR 84 in the US (NIOSH, 1996)). Light-weight, disposable masks/respirators have an additional code, such as, in the UK, FFP1 (low efficiency), FFP2 (medium efficiency), or FFP3 (high efficiency) (FFP = Filtering Face Piece), with the US N95 standard being roughly equivalent to FFP2, and N99 being equivalent to FFP3. Such standards are not in place for fashion masks, nuisance-dust masks, or any type of cloth material used in non-occupational settings (Table 1). Surgical masks are designed specifically to stop airborne droplets passing from the respiratory system, including from a healthcare worker to a patient, or vice-versa (Lipp, 2003). As such, they are not designed for preventing inward penetration of particles and do not conform to the same standards.

Few published studies have assessed the effectiveness of materials used to protect people from inhalation of airborne particulates in non-occupational settings. Methods for testing the FE of RP material for non-occupational purposes vary and do not necessarily require human volunteers, as the material itself is being tested, rather than the fit of the device to the wearer. Some papers report the penetration instead of FE, i.e., the percentage of particles passing through the RP material (NB. penetration is the complementary percentage of FE).

Grinshpun et al. (2009) used a mannequin head to test the penetration of NaCl particles through the filter material of an N95 respirator and a surgical mask. The overall penetration for the N95 filter component was <1% and for the surgical mask, 5-10%. Shakya et al. (2017), using a similar methodology, but with polystyrene latex spheres and diesel particles as challenge particles, reported surgical masks to have better FE (>78%) than cloth masks (<65%), whilst Bowen (2010), also using a mannequin head and saline particles, found FEs of 6% (pre-shaped dust mask), 11% (bandana), 33% (surgical mask), and 90% for the N95 mask. Rengasamy et al. (2010) challenged different household fabrics, commonly used during pandemic respiratory infections, and compared them to N95 respirator material, following the NIOSH particulate respirator test protocol (NIOSH, 2007). The household fabrics performed poorly against the NaCl challenge (40–90% penetration) in comparison to the certified N95 material (0.12% penetration).

Jung et al. (2014) compared the FE of 44 masks and handkerchiefs commonly used by the general public to protect against particulate air pollution from yellow sand in Asia using the Korean Food and Drug Safety Administration (KFDA) and NIOSH protocols (NIOSH, 1996) against NaCl and paraffin oil. Average penetration per mask type ranged from 1% for quarantine masks to 98% for handkerchiefs. In a recent study, Cherrie et al. (Accepted) adopted another methodological approach using diesel emissions. In this study, samples of popular, commercially-available RP materials from China (cloth masks with exchangeable filters) and a selection of unrated and standard-tested non-woven masks (including the FFP2 mask used in the current study) were fitted on custom-made sample holders in a small exposure chamber (same set-up as this study). The median penetration for the FFP2 mask was ~1%.

There is a general trend that the FE of materials used in commercial facemasks is better than that measured for surgical masks, which, in turn, is better than for a range of everyday cloth items. As discussed, the challenge particles used in FE studies have previously been NaCl, diesel emissions, paraffin oil, or standard polystyrene latex spheres, each with different PSDs depending on the purpose of the masks. None of these studies considered volcanic ash particles, which tend to be coarser (with a median diameter of several micrometres; Horwell, 2007) than urban particulates or pathogens, nor the wide variety of RP typically used in volcanic crises around the world. There is evidence that the particle size of the challenge aerosol/dust, as well as the mask material and flow rate, impact substantially on the FE. Wake and Brown (1988) showed in their experiments that FE varied from 1-55%, depending on particle size of the challenge aerosol. Results of previous studies, especially those which used ultrafine, homogenous aerosols, can therefore not be directly translated and applied to volcanic ash exposures.

Horwell et al. (2017) gathered information with a rapid questionnaire survey over several days immediately after ashfall from Kelud volcano on the city of Yogyakarta, Indonesia. This questionnaire asked members of the public what type of RP they wore, where they obtained it, why they were wearing it, as well as who, if anyone, advised them to wear it and how effective they thought it was. Typical RP used by the public during volcanic crises, such as that given out by agencies, bought, and improvised (such as shawls and veils), were obtained from locations in Indonesia (I), Japan (J), and Mexico (M), where local communities have recently been affected by ashfall. Additionally, disposable, industry-certified masks, t-shirts, and handkerchiefs (the latter two observed to be used by individuals in Yogyakarta by Horwell et al. (2017)) were sourced online from the UK.

The information from this survey helped inform the selection of RP materials for which we tested the FE in this study. The aim of this study was to build the first evidence base on the effectiveness of common materials used to protect communities in volcanic crises from ash inhalation. In a companion paper (Part II; Steinle et al., Submitted), we combine these data with results from a simulation study assessing Total Inward Leakage (TIL) (a function of both leakage pathways – through the filter material and through the face seal) of the best-performing masks to provide a complete assessment of the effectiveness of these RP types. Overall, this work forms part of a larger study focussed on addressing the urgent need to provide evidence-based advice to allow humanitarian agencies to distribute or recommend RP based on known effectiveness, comfort, and behavioural and cultural considerations (HIVE - A new evidence base for respiratory Health Interventions in Volcanic Eruption Crises, http://community.dur.ac.uk/hive.consortium).

METHODOLOGY

Respiratory protection selected for testing

Seventeen RP materials were selected for testing. Some materials were tested under varying configurations, for example, a bandana material was tested as a single, double, and triple layer of the material, as information gathered by Horwell et al. (2017) showed that people modify their RP by adding additional layers (though not necessarily of the same RP material). A limited number of tests were also conducted using the bandana material and a surgical mask after they had been soaked in water for a period of 30 seconds and wrung out. This was carried out to test a common conception that wetting cloth improves protection from particle inhalation, advice given by many health/civil protection agencies around the world (see summary at: http://www.ivhhn.org/resources/global-ash-advice.html; IVHHN, 2017), implying that wetting cloth (and mask) material is more effective at filtering ash (than not wetting). It is noted, however, that an agency in Yogyakarta inform their community that wetted protection lasts less long due to the material getting more dirty (Horwell et al., 2017).

Table 1 provides information and images for each of the RP types, including their style, number of layers, and thickness of each layer (measured using a Mitutoyo digital caliper 150mm; Sakado, Takatsu-ku, Kawasaki, Kanagawa 213-8533, Japan). Each RP type was imaged by light microscopy (where materials were translucent) or scanning electron microscopy (SEM; Hitachi S2600-N at 20 kV), where opaque. Varying magnifications were used to suit the material types (between 30 and 100x).

Challenge particles

We used two volcanic ash samples collected, pristine, from ash deposited on the ground from Soufrière Hills volcano, Montserrat, and Sakurajima volcano, Japan (supplied through CJH). The first is quite a fine-grained ash, the second being a coarser ash, as was confirmed by laser-diffraction particle size analysis (Malvern Mastersizer 3000; Supplementary Material Figure). These differences allowed us to test for changes in FE with particle size, as observed by Wake and Brown (1988). In addition, we sourced and assessed the FE of a low-toxicity surrogate: aluminium oxide dust (Aloxite, supplied by Washington Mills). Aloxite was selected as the challenge particle in the subsequent human volunteer simulation studies for ethical purposes; therefore, it was useful to quantify and interpret any FE differences between the ash and Aloxite

(Steinle et al., Submitted). It was chosen as a dust with a similar modal particle size distribution to volcanic ash, as opposed to most previously-tested challenge particles, such as NaCl (Grinshpun et al., 2009; Jung et al., 2014; Rengasamy et al., 2010) and diesel particulate (Cherrie et al., Accepted; Shakya et al., 2017), which generally have a mode of < 1 µm diameter.

Experimental set-up

Each RP type, and its variation where appropriate, was tested to determine the FE of the material by drawing air, loaded with particles, through a known area of the material. A circular section was cut out from each RP material and fitted into a sample holder (radius 2.25 cm; area = 15.9 cm^2). Tests were conducted at two constant flowrates equivalent to 40 l/min and 80 l/min through the RP material, scaled proportionately from the area of the mask/material to the area of the cut-out section (i.e., 15.9 cm^2), to represent breathing during a range of physical activity from moderate to high levels (Panis et al 2010). FE is assumed to decrease with increasing flowrate (Wake and Brown, 1988).

Figure 1 illustrates the sampling setup. Sample holders were placed inside a purpose-built exposure chamber (0.5 m [L] x 0.25 m [W] x 0.12 m [H]). The particle-air suspension was generated using a Venturi nozzle, and a rotating table was loaded with the dust. Each material was tested in triplicate per flowrate and at two $PM_{2.5}$ concentrations (1.5 and 2.5 mg/m^3). These concentrations were selected, as they could be generated using the available particle-suspension generation equipment in a consistent, repeatable manner. They would both be representative of exposures to high concentrations of volcanic ash, generated during the actual ashfall, resuspension from human activity (e.g., vehicles, occupational hazards, or clean-up activities), and/or wind (Moore et al., 2002; Searl et al., 2002). The particle concentration within the exposure chamber (challenge concentration, C_{Chal}) was monitored using a factory-calibrated (using Arizona Road Dust, which is similar to volcanic ash in its composition and, therefore, light scattering properties) TSI SidePak (SP) AM510 aerosol monitor (TSI, Minnesota, USA) fitted with a $PM_{2.5}$ impactor. This was set to run at 1.7 l/min, according to the manufacturer's guidance, logging the average concentration every 10 seconds. SPs with the same setup were attached to the sample holders measuring the concentration downstream of the RP material to sample and log the penetration concentration (C_{Pen}). Although volcanic ash does not usually contain a high fraction of $PM_{2.5}$ (Horwell, 2007), we chose this fraction because this is the size range of most health concern (World Health Organization, 2013) and therefore the fraction that RP should preferentially filter. We assumed that any coarser particles will also not penetrate the material if $PM_{2.5}$ is effectively filtered (Fisk et al., 2002). A pump was attached to the sample holders in order to reach the desired overall flow rate (MCS 10 Air sampling pump, SKC, Dorset, UK). The chamber was set up to allow simultaneous testing of two RP samples. Each test lasted approximately 12 minutes.

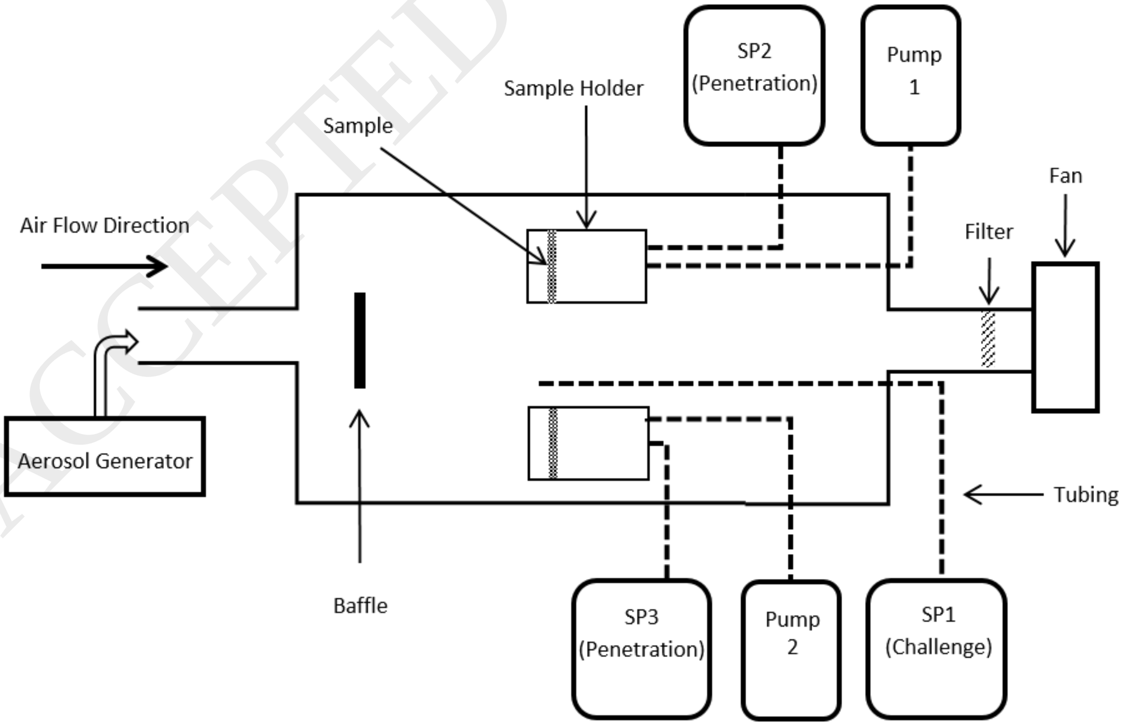

Figure 1: Experimental set-up for filtration efficiency tests. Two identical sample holders were in the test chamber connected to SP2 and SP3 measuring C_{Pen}. SP1 measures C_{Chal} inside the chamber. The fan draws the air through the chamber. The baffle helps to distribute the aerosol as it enters the chamber.

Side-by-side measurements using the SPs were conducted after each experiment to determine any variations in the SP instrument readings and allow correction factors to be applied to the collected data for each test run, as necessary, before calculation of the FEs. Briefly, this involved calibrating SP2/3 (measuring penetration) to SP1 (measuring the challenge concentration) by multiplying SP2/3 by the ratio of mean SP1 to mean SP2/3 concentrations from the side-by-side measurements (Equation 1).

$$Equation\ 1: \qquad Correction\ Factor\ (CF) = \frac{Mean\ C_{SP1\ (Reference)}}{Mean\ C_{SP2/3}}$$

Statistical Methods

The FE of each RP type was based on the C_{Chal} within the experimental chamber and C_{Pen} using the following formula (Bowen, 2010) (Equation 2):

$$Equation\ 2: \qquad Filtration\ Efficiency\ (FE) = (1 - [\ C_{Pen} \div C_{Chal}]) \times 100\%$$

Forty-two measurements (0.001% overall) across eight RP materials had large negative[1] (10-second average) FEs, which were substituted with a value of -100% for analysis purposes. Normal data assumptions were not satisfied for the distribution of FEs for each RP type, nor after the log-transformation of values, as determined through Shapiro-Wilk tests ($p < 0.001$). Non-parametric (i.e., Kruskal-Wallis) tests were performed to test filtration differences across RP materials exposed to different dust types at two concentrations and flow rates, and also to assess the effectiveness of using a wetted versus dry RP material. The wetted materials were

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[1] A negative FE occurs when $C_{Pen} > C_{Chal}$, e.g., from natural fluctuations.

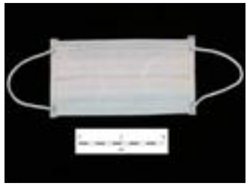
tested only at the 40 l/min flowrate because of extensive evaporation (and the material drying out) over the duration of the test at the higher rate.

Data analysis was performed using MS Excel and Stata 13.1 (StataCorp, College Station, TX, USA).

RESULTS

The composition and thickness of each mask is described in Table 1.

Table 1: Details of RP types used in filtration study – number of layers, type of material layer and thickness of layer[2].

RP type	**Description of RP**	**Image of RP**	**Description and thickness (mm) of layer N**			
			Layer 1	**Layer 2**	**Layer 3**	**Layer 4**
N95-equiv.	A certified disposable dust respirator with valve, conforming to EN 149: 2001 standard. Model: 3M Aura 9322		Fibres fused together, (0.19)	Cotton non-woven, metal strip at nose area, (0.72)	Non-woven transparent, sponge at nose area, (0.11)	
N99-equiv.	A certified disposable dust respirator with valve, conforming to EN 149: 2001 standard. Model: 3M Aura 9332		Fibres fused together, (0.20)	Cotton non-woven, metal strip at nose area, (0.76)	Non-woven transparent, sponge at nose area, (0.16)	
$PM_{2.5}$ surgical (J)	A surgical-style mask, purporting to block $PM_{2.5}$ particles, with adaptations to improve fit (cheek/chin flaps); sold in pharmacies and supermarkets		Fibres fused together, transparent, (0.15)	Fibres fused together, transparent, (0.09)	Cotton & metal strip across nose area, (0.22)	Fibres fused together, transparent, (0.16)
Surgical (J)	A standard, pleated surgical mask (but with shaped edge) available from pharmacies and supermarkets in Japan, commonly worn by the public for daily use as well as when ash is present		Fibres fused together, transparent, (0.17)	Cotton non-woven & metal strip across nose area, (0.20)	Fibres fused together, transparent, (0.18)	

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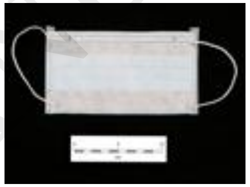
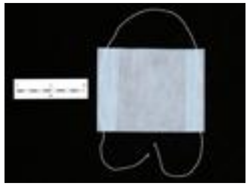
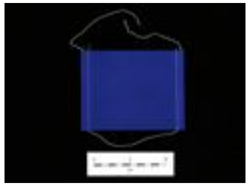
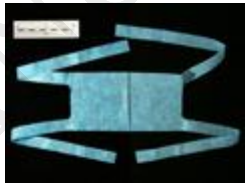
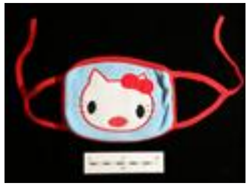
[2] Information on use of RP in Indonesia is taken from Horwell et al. (2017). Information on use of RP in Mexico is taken from information gathered during interviews for the HIVE project. J = Japan; M = Mexico; I = Indonesia. The scale bar on the images of the masks is 10 cm long.

RP type	Description of RP	Image of RP	Description and thickness (mm) of layer N			
			Layer 1	Layer 2	Layer 3	Layer 4
Surgical (M)	A standard, pleated surgical mask available from pharmacies in Mexico		Fibres fused together (folded), (0.29)	Cotton non-woven & metal bar across nose area (folded), (0.20)	Fibres fused together (folded), (0.24)	
Basic flat-fold (I)	A basic mask with ear loops contiguous with the mask material, distributed widely by the Red Cross (PMI) in Yogyakarta, Indonesia, during volcanic eruptions. Donated to PMI by the Japanese Red Cross		Fibres fused together, transparent, (0.24)	Cotton non-woven, (0.13)	Fibres fused together, transparent, (0.20)	
Basic non-pleated #1 (M)	A basic, liquid-repellent mask made of a single, rectangular piece of non-woven material, with adjustable ear loops, commonly distributed by agencies in Mexico but designed for medical use (according to packaging)		Fibres fused together, transparent, (0.23)	Fibres fused together, transparent, (0.21)		
Basic non-pleated #2 (M)	A basic, liquid-repellent mask made of a single, rectangular piece of non-woven material, with adjustable ear loops, commonly distributed by agencies in Mexico but probably designed for medical use. Slightly thicker than (#1), above		Fibres fused together, (0.52)			

RP type	Description of RP	Image of RP	Description and thickness (mm) of layer N			
			Layer 1	Layer 2	Layer 3	Layer 4
Basic non-pleated #3 (M)	A very basic mask made of a single, rectangular piece of fused material, with contiguous ear straps, commonly distributed by the Red Cross and local leaders in Mexico		Fibres fused together, (0.17)			
Hard cup (M)	A 'nuisance dust' or 'DIY' mask, commonly available from hardware stores in Mexico and around the world and recently distributed by agencies in Mexico and the Philippines		Non-woven material & metal strip across nose area, (0.60)			
Fashion (I)	'Fashion' masks are commonly available from roadside stalls in Indonesia, and are worn to prevent inhalation of urban pollution by those on scooters, as well as for prevention of ash inhalation		Thread and wool/fur, (1.72)	Sponge material, transparent, (1.97)	Woven cotton/nylon material, (0.42)	
Scooter (I)	'Scooter' masks are commonly available from roadside stalls in Indonesia, and are worn to prevent inhalation of urban pollution by those on scooters, as well as for prevention of ash inhalation		Elasticated cotton/nylon bonded to foam, (2.54)	Elasticated cotton/nylon, Foam, Elasticated cotton/nylon, (3.48)		
Bandana (I)	Bandanas can be purchased from roadside stalls in Indonesia and are commonly used to prevent ash inhalation		Woven fabric, (0.31)			

RP type	Description of RP	Image of RP	Description and thickness (mm) of layer N			
			Layer 1	Layer 2	Layer 3	Layer 4
Veil (I)	In Indonesia, Muslim women wearing veils have been observed to hold the veil over their mouth and nose in ashy conditions		Woven cotton, (0.04)			
Shawl (M)	Around Popocatepetl volcano, Mexico, indigenous women wear shawls which are pulled over the nose and mouth when ash is airborne		Woven cotton/wool, (0.85)			
Handkerchief	Around the world, people protect themselves by holding a handkerchief over their nose and mouth		Woven cotton, (0.18)			
T-shirt	In Indonesia, people have been observed pulling a T-shirt up, over the nose and mouth, to prevent ash inhalation		Woven cotton, (0.52)			

All of the masks designed for occupational use (N95-, N99-equiv. respirators, surgical masks, more basic healthcare masks, and the hard-cup mask), plus the basic flat-fold mask (obtained in Indonesia but originally from Japan), were composed of non-woven, fused fabric (often polypropylene, according to the packaging).

The cloth masks and items were all woven (mostly plaid weave except the T-shirt, which had a denser, herringbone weave) and made of common clothing fabrics, e.g., cotton, nylon, etc. The different RP types also varied in the number of layers, their thickness, and in the features which could be adapted to improve fit (e.g., nose clips, ear loops, extendable chin/cheek flaps) (Table 1).

Table 2 and Figure 2 show the results of the FE experiments for the 17 materials (with different configurations) tested. Using two flow rates and concentration levels, three dust types, and three repeats for most RP types (with exception of the wetted materials, where only a flow rate of 40 l/min was used), a total of 719 unique tests were performed with 45,521 data points collected.

Table 2: Summary statistics for the filtration efficiency (%) experiment for each respiratory protection (RP) type for both volcanic ash types combined (Sakurajima and Soufrière Hills) at both flow rates (40 l/min and 80 l/min) and particle concentrations (1.5 and 2.5 mg/m^3) (the wetted masks were only tested at 40 l/min).

RP	N	Filtration efficiency (%)							
		Arithmetic Mean	S.D.**	Min	25th Percentile	Median	75th Percentile	95th Percentile	Max
N95-equiv.	1440	99.4	2.6	16.6	99.5	99.8	99.9	100.0	100.0
N99-equiv.	1439	99.3	1.4	85.6	99.4	99.8	100.0	100.0	100.0
PM$_{2.5}$ surgical (J)*	1200	98.4	2.5	83.8	99.1	99.5	99.7	99.8	99.9
Basic flat-fold (I)*	1440	98.1	1.8	51.3	97.7	98.4	98.9	99.3	99.9
Surgical (J)	1421	88.7	11.5	28.6	88.7	91.3	93.4	95.5	99.8
Surgical (M)*	1470	87.3	9.3	19.8	85.1	89.3	92.0	98.2	99.1
Scooter (I)	1440	75.0	9.5	4.2	68.3	75.5	82.8	88.6	94.0
Fashion (I)	1531	72.4	12.5	-47.0	68.6	74.7	79.8	84.4	97.6
Surgical (M) wet	850	66.2	14.3	-44.9	59.1	68.7	75.5	84.3	99.6
Basic non-pleated #1 (M)	1440	60.2	15.1	-100.0	49.8	61.7	71.9	81.1	95.0
Hard cup (M)	1080	57.7	11.9	-40.6	51.3	57.9	65.1	76.8	82.0
Basic non-pleated #2 (M)	1320	44.2	29.7	-100.0	29.0	54.8	64.5	72.4	97.6
T-shirt	1421	42.5	21.7	-100.0	34.3	44.0	52.5	69.6	95.7
Bandana folded (x3)	1438	40.0	19.1	-71.3	27.1	40.3	54.0	65.7	99.8
Basic non-pleated #3 (M)	1470	35.3	14.4	-95.2	27.6	36.1	44.1	58.9	70.0
Bandana folded (x3) wet	660	34.4	17.0	-74.8	25.0	35.2	45.3	61.5	71.0
Shawl (M)	1440	32.6	13.6	-36.7	24.0	30.7	43.2	55.3	86.2
Bandana folded (x2) wet	720	31.4	19.0	-100.0	21.1	34.2	45.5	54.2	69.5
Bandana folded (x2)	1440	27.8	21.0	-100.0	20.5	30.9	41.1	51.1	95.0
Handkerchief	1440	22.7	13.3	-40.9	14.5	24.0	31.2	41.5	98.7
Veil (I)	1560	22.7	19.6	-31.6	10.2	23.4	33.3	54.2	83.5
Bandana (I)	1440	17.5	27.2	-100.0	-9.3	29.3	38.6	46.8	76.1

*(I)=Indonesia; (J)=Japan; (M)=Mexico; ** S.D. = Standard Deviation

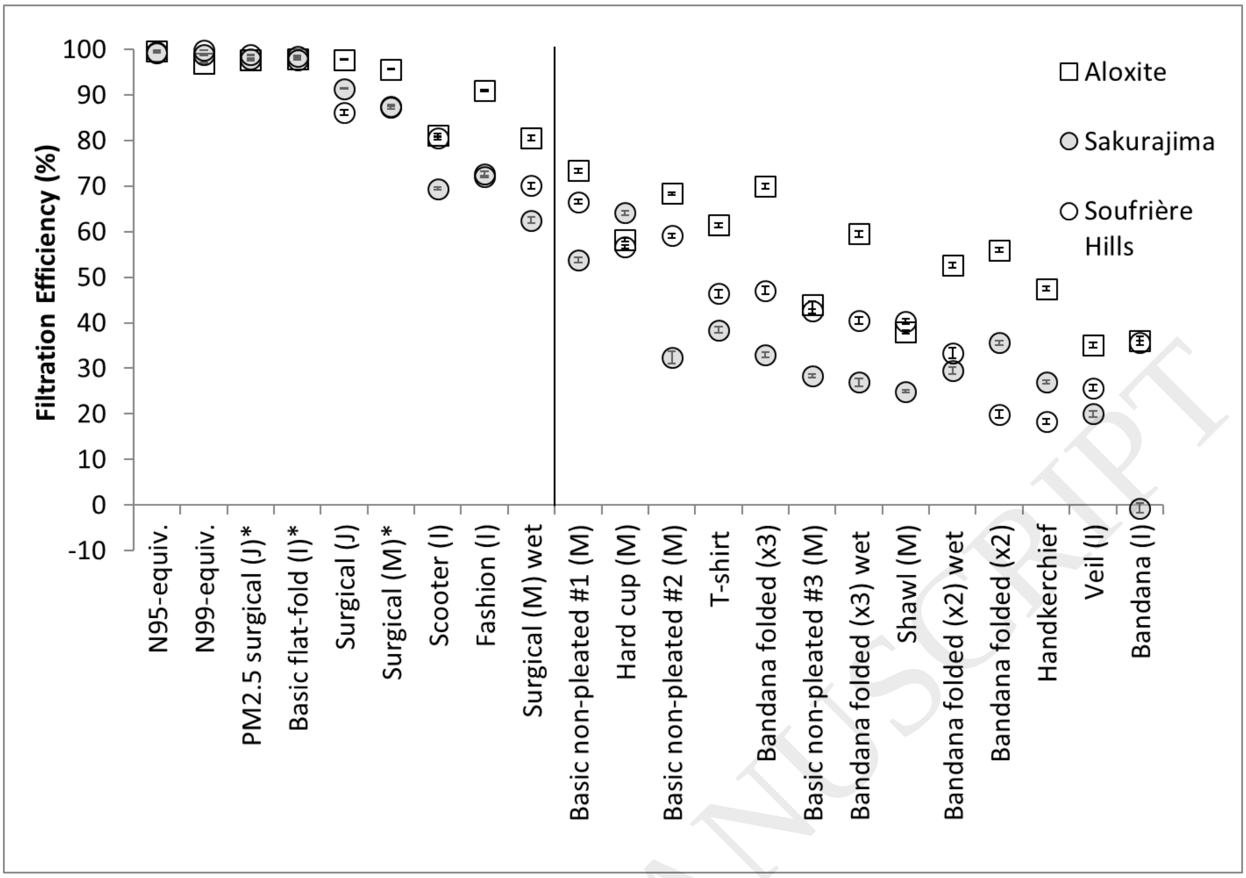


Figure 2: Mean filtration efficiency (%) of each RP for individual dusts, including both flow rates (40 l/min and 80 l/min) and particle concentrations (1.5 and 2.5 mg/m^3) (the wetted masks were only tested at 40 l/min). Vertical bars are standard errors. RP types to the left of the vertical line are multi-layered and those to the right are single-layered, unless folded. * (J) = Japan; (I) = Indonesia; (M) = Mexico.

The median FE of individual RP types, overall for volcanic ash data combined, ranged from 23.4% (Interquartile Range [IQR]: 10.2% to 33.3%) for the Veil (I) to 99.8% (IQR: 99.5% to 99.9%) for the N95-equiv. Four of the 22 RP materials and configurations tested had both mean and median FE values above 90% (Table 2 and Figure 2): the N95-equiv., N99-equiv., $PM_{2.5}$ surgical (J), and Basic flat-fold (I). These four RP types consistently achieved the highest FEs across the three different dust types (Figure 2 and Supplementary Material Tables 1-3).

A non-parametric comparison of the differences between the median FE overall for the two volcanic ashes and Aloxite (Sakurajima = 50.9%; Soufrière Hills = 61.9%; Aloxite = 72.0%) was significant ($p <$ 0.001). Significant differences between the two ashes were also found within most RPs ($p < 0.001$), except for the $PM_{2.5}$ surgical (J) ($p = 0.215$) and the surgical (M) ($p = 0.072$), with FEs typically lower for the Sakurajima ash. Further, the median FE of each RP varied between the volcanic ash and Aloxite ($p < 0.001$), demonstrating higher values with the latter, except for the hard cup (M) ($p = 0.073$). The effect over time of FE for volcanic ash was small, but significant, adding an average absolute FE of 0.06% every 10 seconds ($p < 0.001$).

Within each dust type, the 10 RP materials with the best FE were consistently commercial mask materials (rather than cloth materials). Only two commercial mask materials (Basic non-pleated #2 [M] and Basic non-pleated #3 [M]) did not achieve results within the highest 10 median FEs for any of the dusts used (see Supplementary Material Tables 1-3).

For 19 of the 22 RP types tested with volcanic ash, the two particle concentrations (1.5 and 2.5 mg/m^3) produced absolute differences of <5% in median FE values (with differences of <10% in the other three RP types). Most (19/22; 86%) of the FEs were higher at the greater concentration level, though differences in FE between the two concentrations were not significant ($p > 0.05$) for nine of the RP types[3]. A larger proportion (9/19[4]; 47%) of RP types demonstrated differences of >5% in median FE values between the two flow rates, ranging from -26% to 12% at 80 l/min compared to 40 l/min. The majority (16/19; 84%) of RPs performed better at the lower flow rate, and nearly all RPs demonstrated differential FE ($p < 0.001$), except for the PM$_{2.5}$ surgical (J) ($p = 0.420$) and the surgical (M) ($p = 0.486$).

Significant differences in the distribution of FEs were identified for each of the three RP types (both volcanic ashes combined at a flow rate of 40 l/min) where a wet and dry version were tested. The median values for the dry version were significantly higher for the Surgical (M) and Bandana folded (x3) ($p < 0.001$), but lower for the Bandana folded (x2) ($p < 0.001$) (Table 2). Pooling together the wet and dry RP data, the latter group was found to have statistically increased median FEs ($p < 0.001$)

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[3] PM2.5 surgical (J), Basic non-pleated #1 (M), Bandana folded (x3), Bandana folded (x3) wet, Bandana folded (x2) wet, Bandana folded (x2), Shawl (M), Handkerchief, Bandana (I)

[4] 19 RP types rather than 22, as the wet RP configurations were only tested at 40 l/min.

(49.2%; IQR: 33.1% to 85.2%) compared to the filtration of the three wet RP types (46.2%; IQR: 29.8% to 64.8%) overall across the volcanic ash types.

One of the RP types (Bandana [I]) was challenged using one, two, and three-layers of material. There were statistically significant ($p < 0.001$) increases in the median FE offered by each additional layer against the volcanic ashes; the three-layer material achieved a median value of 40.3%, an additional median FE of 11.0% and 9.3% higher than that offered by one or two-layers, respectively ($p < 0.001$). The mean FE for the Bandana (I) (one-layer) was very low for the Sakurajima dust, relative to that from the other dust types, as shown in Figure 2.

DISCUSSION

This study evaluated the filtration performance of 17 materials (plus different configurations) used to provide RP during volcanic crises, sourced from communities affected by volcanic eruptions around the world. Two volcanic ash types and a surrogate dust (Aloxite) were used as the challenge particles in a small exposure chamber. Only four of the 17 materials provided mean and median FEs in excess of 90%, these being the two disposable, industry-certified masks (N95-equiv., N99-equiv.), the surgical mask from Japan designed to filter $PM_{2.5}$ particles ($PM_{2.5}$ surgical [J]), the basic mask distributed by the Red Cross (PMI Yogya) in Indonesia (Basic flat-fold [I]).

The two materials providing the greatest median FE (in excess of 99%) were the disposable, industry-certified N95-equiv. and N99-equiv. masks, designed for use in dusty, occupational settings. Such masks are rarely distributed in volcanic settings, although they have been in Iceland and Alaska, where they, rather than surgical masks, are stockpiled for pandemic outbreaks (Horwell et al., 2017; based on media images and personal communication with agencies by CJH). In most countries, however, their use is uncommon due to cost, as well as other logistical considerations (e.g., some styles take up much more space when stockpiling than surgical masks). In addition, despite these materials clearly being highly effective at filtering particles, the TIL, when worn, could be poorer than expected from the FE data, if worn incorrectly (as investigated in our accompanying study; Steinle et al., Submitted). In dusty industries, workers will be fit tested to ensure that masks fit to the shape of the individual's face and are worn correctly. Workers cannot have facial hair and will be trained to ensure that, for example, glasses do not impact the seal of the mask on the face (Bolsover, 1992). By contrast, in community settings, little-to-no training is provided, if such masks are distributed, so fit to face becomes very important.

Our study has shown that standard surgical mask materials can be effective at filtering the $PM_{2.5}$ particles found in two types of ash and Aloxite, with median FEs of around 90%, despite the masks not being designed to prevent particle penetration. These results complement those of Shakya et al. (2017), where surgical masks achieved 78-94% FE when challenged with polystyrene latex standard particles. However, our results contrast with other studies: Bowen (2010) reported a FE of 33% for a surgical mask challenged with NaCl over 30 minutes, whilst Jung et al. (2014) reported a 'medical' mask to have a penetration of 45% (i.e., FE = 55%) when challenged with NaCl (a finer challenge aerosol). These FEs, which are lower than those achieved in the current study, may be explained by the variety of filter materials used in manufacturing different surgical masks and/or the use of a finer particle and different experimental set-up/study design.

The high FE results for the surgical mask materials tested in this study do not allow us to draw conclusions on the overall protectiveness of the masks though, given that they are not designed to make a seal around the face and likely have a relatively large particle ingress around the edges. As shown in Steinle et al. (submitted), improving the fit of a surgical mask with an additional cloth layer improves overall protectiveness by decreasing face seal leakage. In Japan, surgical masks are commonly worn by the public, primarily out of politeness, to prevent the spread of communicable respiratory diseases, such as colds and flu, but also for other reasons related to a wider culture of 'risk' (Burgess and Horii, 2012) and to fashion. There are many different types of surgical-style masks available commercially, including those specifically sold to prevent inhalation of $PM_{2.5}$. In this study, the $PM_{2.5}$ surgical (J) mask performed extremely well (99.5% median FE).

A mask which performed very well was a simple 'Basic flat-fold' mask distributed by the thousand in Indonesia by the Red Cross (PMI Yogya) (Horwell et al., 2017) and originally donated to them by the Red Cross Japan, where these masks are commonly available. However, that mask does not have any adaptations or features to enhance fit (no nose clip, elasticated straps, additional flaps, etc.) which, as shown in Steinle et al. (submitted), results in a relatively high TIL, likely attributable to particle ingress around the edges.

In Mexico, a more basic, non-pleated, rectangular healthcare mask is commonly distributed by civil protection and aid agencies. We tested three of these (Basic non-pleated #1-3). The most basic type (#3) performed very poorly (36% median FE) with types #1 and #2 achieving 62% and 55% median FEs, respectively, which are both substantially less efficient than the standard surgical mask from Mexico (89% median FE).

Many agencies around the world recommend use of cloth in lieu of a light-weight, disposable mask (see Global Ash Advice database at: IVHHN, 2017). The cloth materials are often a convenient way to protect from volcanic ash as they are very accessible. Scooter and fashion masks are also already worn by people trying to protect themselves from air pollution (Horwell et al., 2017). This study has shown that all types of cloth material (bandanas, T-shirts, veils, shawls, and handkerchiefs) performed poorly in the FE tests, with none achieving >44% median FE overall. This is concerning, since they are popular and convenient. The scooter and fashion masks, commonly used in Indonesia, performed considerably better (~75% median FE). Given these findings, agencies responsible for such advice should now consider the ethical question of whether 'something is better than nothing'. Without additional information to clearly explain that such cloth materials will offer substantially reduced protection when worn (in comparison to well-fitted, industry-certified masks), agencies risk introducing a false sense of security. This may lead to individuals receiving higher exposures than had they chosen not to use any form of protection (which might have encouraged them to reduce exposure by seeking shelter indoors). If agencies decide that something is better than nothing, then modifications are worthwhile, as borne out by the data: increasing the number of layers of cloth (i.e., by folding a bandana) did significantly improve FE (but only up to 40% median FE). Therefore, future advice could suggest such adaptations, as long as the information also emphasised the need to securely fit the cloth to the face in a way which does not impede breathing.

In addition, many agencies recommend that cloth, or masks, are wetted (e.g., see summary at: http://www.ivhhn.org/resources/global-ash-advice.html; IVHHN, 2017). The assumption is that wetted materials somehow improve FE. We have found no scientific evidence in the literature to support this assertion. In this study, the wetted double-layered bandana material performed better than the dry version; however, the wetted version performed less well than the triple-layered bandana. The wetted surgical mask performed worse than dry surgical masks. Here, again, agencies might consider whether to continue advising to wet RP given the lack of consistent evidence as to the efficacy of this intervention. In addition, wet masks will tend to dry over time, so any potential advantages of the intervention will be temporary, but this may not be apparent to the user, again giving a potentially false sense of security. It should be noted that, during the tests with wetted mask materials, it is possible that FE could have been slightly underestimated in relation to the dry materials. Light-scattering particulate monitors, such as the SP, may be affected by high humidity (>50% RH) as small hygroscopic particles will grow in size from water adsorption. However, the dusts used in this study were relatively large and had low hygroscopicity, and we consider this mechanism is unlikely to have resulted in a substantial overestimation of the particle concentrations (Titos et al., 2014).

In this study, we tested the FE of the RP materials only for a short period of time, with FE increasing very modestly during the test run. Incremental increases in filtration may be assumed as particles accumulate in the RP material, eventually possibly clogging the filter. It is, to our knowledge, unknown how well the RP materials would perform if they were used over prolonged durations during volcanic crises. Similarly, it is unclear what the impact might be of any attempts to clean the RP materials, although some limited work has been conducted on extending the life of N95 masks in healthcare settings through cleaning (NIOSH, 2014; Viscusi et al., 2009); this needs to be the subject of future research.

Whilst there were small differences in FE between the two challenge concentrations, the higher flow rate resulted in lower FEs for most of the RPs. This finding suggests higher ash exposures for those who have a higher respiratory rate, including those who are physically active, e.g., ash clean-up workers.

We currently have little understanding of why the efficiency of the different types of RP can be impacted by differences in dust source and PSD or the concentrations found in different particle exposures. This type of difference was particularly prevalent for the less-effective forms of protection. As shown in the data, the two volcanic ash samples and the Aloxite achieved similar (though statistically different) FEs for the four best RP types tested, despite containing different quantities of respirable (sub-4 µm) material. Cherrie et al. (Accepted) used the same experimental setup as in this study, but tested facemasks available in Beijing against diesel exhaust particulate, which is typically < 1 µm diameter, with a substantial nanometre-sized fraction. For the N95-equiv. masks tested in that study (made by the same manufacturer with one mask being the same as that used here), FEs of around 99% were achieved, indicating that such masks are equally effective at filtering particles in a very wide range of size distributions.

However, for the other poorer performing RP types, the FE varied widely with the challenge dust, with better performances generally observed against Aloxite. In this study, we used ash samples from two different volcanoes and found FEs to vary by ash type for most RPs, with generally higher FEs achieved for the Soufrière Hills ash, which contained more sub-2.5 µm material than the Sakurajima ash sample.

The electrostatic charge on the particle or some other property of the dust may be an important determinant of the observed differences. Further research needs to be conducted to understand the cause of these findings. For volcanic eruptions, every explosion will produce different quantities of respirable and sub-2.5 µm material. For example, Horwell (2007) showed that ash samples from the Soufrière Hills volcano generated between 6 and 12 vol.% sub-4 µm particles in the bulk ash, depending on whether the ash was generated in an explosion or dome collapse event. Hillman et al. (2012) showed that modern day Sakurajima ash contains between 1 and 10 vol.% sub-4 µm material in the bulk ash (and up to 18 vol.% in ancient ash erupted when the volcano was in a more explosive phase). The fact that there is a difference in performance of RPs dependent on ash type indicates that we must assume that some types of RP, and especially those which are not certified for occupational use in dusty industries, will perform worse than the values obtained in this study, during exposures in future eruptions. This provides a strong motivation for agencies to recommend the most efficient types of masks, as these displayed the smallest differences with different dusts.

In Part II of our study (Steinle et al., Submitted), we select the best performing masks identified here (N95-equiv., $PM_{2.5}$ surgical [J], Basic flat-fold [I], and Surgical [M]) for testing for TIL on human volunteers. Aloxite was tested in the current study because it had been chosen as a low-toxicity surrogate dust for the simulation study, due to its similar PSD to volcanic ash (although it is much coarser than the usual challenge aerosols used in FE experiments). For the best performing masks in this study, there was little difference between the performance of those RP against Aloxite and volcanic ash with the exception of Surgical (M). The potential over-estimation of efficiency for Surgical (M) is considered further, within the TIL study.

CONCLUSIONS

In the first study of its kind to use volcanic ash, we have determined the FE of a wide range of products used as RP around the world during volcanic events. This evidence base indicates that materials used in industry-certified masks, and others, specifically designed to filter $PM_{2.5}$ particles, will provide better filtration efficiencies than fashion/scooter masks or *ad hoc* cloth materials (e.g., bandanas, scarves) used for protection when ash is in the air. Pleated, standard, surgical masks also had good filtration efficiencies, but other types of masks (non-pleated, single layer) for use in healthcare settings performed very poorly against volcanic ash. Cloth materials provided limited filtration, although this was slightly improved by layering the cloth. Wetting a bandana or a surgical mask did not consistently provide increased filtration, which does not lend support to such advice from agencies. Whilst it is encouraging to know that some materials will effectively filter volcanic ash from the air, this performance may be less important if the mask does not adequately seal to the face, thereby letting ingress of particles around the mask edges. The best performing masks in this study have, therefore, been tested for their TIL on human volunteers (which takes fit and facial seal into account), the results of which are described in Steinle et al. (Submitted), to give an overall assessment of protection.

DECLARATIONS OF INTEREST

None

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The use of any brand names in this report in no way endorses the use of the brand's products.

SUPPLEMENTARY MATERIAL

Supplementary Figure 1: Particle Size Distribution of Aloxite dust, and Soufrière Hills and Sakurajima ash.

Supplementary Table 1: Filtration efficiency (%) summary statistics for each respiratory protection using Aloxite at flow rate = 40 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

Supplementary Table 2: Filtration efficiency (%) summary statistics for each respiratory protection using Aloxite at flow rate = 80 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

Supplementary Table 3: Filtration efficiency (%) summary statistics for each respiratory protection using Sakurajima ash at flow rate = 40 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

Supplementary Table 4: Filtration efficiency (%) summary statistics for each respiratory protection using Sakurajima ash at flow rate = 80 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

Supplementary Table 5: Filtration efficiency (%) summary statistics for each respiratory protection using Soufrière Hills ash at flow rate = 40 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

Supplementary Table 6: Filtration efficiency (%) summary statistics for each respiratory protection using Soufrière Hills ash at flow rate = 80 l/min at both particle concentrations combined (1.5 and 2.5 mg/m^3).

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