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Research Article

Adverse Health Effects Associated with Increased Activity at Kīlauea Volcano: A Repeated Population-Based Survey

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Eruptive activity at the Kīlauea volcano (Hawai'i, USA) has increased since 2008 resulting in volcanic air pollution (vog) at levels exceeding the national air quality standard for sulfur dioxide. Previous investigations during lower vog levels found adverse cardiorespiratory effects in the residents. The purpose of this 2012 survey was to reassess and compare the impact of the increased volcanic activity on population health. Prevalence of cardiorespiratory signs, symptoms, and diseases was estimated in vog exposed and unexposed communities, and descriptions of perceived health and environmental effects were collected door-to-door. Vog exposure was significantly associated with increased odds of self-reported cough, phlegm, rhinorrhea, sore/dry throat, shortness of breath, sinus congestion, continual wheezing, eye and skin irritation, and diagnosed hypertension. Field measurements identified significantly higher average systolic and diastolic blood pressures ($P = 0.045, 0.002$) and lower blood oxygen saturation ($P = 0.008$). Half of the participants perceived that Kīlauea's intensified eruption had negatively affected their health with reports of financial impacts from degradation of agriculture and livestock. Relatively stronger magnitudes of health effects were associated with the higher exposure to vog. Public concerns remain about attributed effects of the ongoing eruption. Enhanced public health efforts are recommended at Kīlauea and other degassing volcanoes worldwide.

1. Introduction

Volcanic emissions have detrimental impacts on the environment and pose numerous hazards to humans. Explosive eruptions have associated mortality and adverse effects from ash fall, whereas effusive eruptions create insidious health risks from the passive degassing of emissions into the lower troposphere [1]. An estimated 9% of the world's population live ≤100 km of a historically active volcano [2]. Therefore, it is imperative to gain an understanding of human-environmental interactions, identify health effects, and develop public health interventions for vulnerable populations exposed to volcanic air pollution.

Effusive eruption at the Kīlauea volcano on the island of Hawai'i has persisted since 1986 from various vents on the volcano's east rift zone. Emissions are predominantly water vapor mixed with carbon dioxide and sulfur dioxide (SO_2), finely-sized sulfurous particles ($PM_{2.5}$; primarily sulfuric acid aerosol), and trace gases of hydrogen sulfide, hydrogen fluoride, mercury, other halogens, and trace metals [3, 4]. As SO_2 gas oxidizes to sulfate particles through various chemical and atmospheric processes, communities downwind of Kīlauea experience exposure to volcanic smog, known as vog (Figure 1) [4]. Since 2008, regional air pollution has increased substantially due to an additional eruption vent at the volcano's summit crater (Figure 2). The World Health Organization (WHO) guideline [5] and National Ambient Air Quality Standard [6] for SO_2 are exceeded on a near-daily basis in the downwind area; a cause of concern for public health.

The impact of Kīlauea's long-standing eruption has been considerable. In 1990, lava flows destroyed over 180 homes and the entire town of Kalapana, resulting in displacement of the residents. High pollution events have occurred with the new summit activity including in April 2008 when a large subdivision located 60 km downwind spiked >2,000 ppbv SO_2, resulting in immediate agricultural destruction [7]. In July 2008, the federal government approved a disaster declaration for Hawai'i Island's farmers. Yet Hawai'i's story is not unique. Deterioration of vegetation and agriculture due

(a)

(b)

Figure 1: Exposure of volcanic smog "vog" in the geographic area downwind of Kīlauea.

Figure 2: Emissions from Kīlauea's summit showing the low-lying nature of the eruption plume.

to degassing at Masaya volcano in Nicaragua has occurred for over a century [8].

Investigations are limited on health effects associated with volcanic degassing. Consistency in these findings suggests that sulfurous volcanic emissions are associated with acute health effects and illnesses in exposed populations. The 1783 effusive eruption of Iceland's Laki volcano produced vog-like pollution over Europe, and medical records documented eye sensitivity, sore throat, cough, shortness of breath, rhinorrhea, headache, and asthma-like exacerbations in the population [9]. In 2005, workers returned to Japan's Miyakejima island after evacuation due to eruption of the island's volcano. Strong dose-response relationships were found between the SO_2 degassing and symptoms of cough, sore throat, and breathlessness [10].

At Kīlauea, studies identified adverse health effects associated with low levels of vog prior to the 2008 summit eruption. In the first decade of eruption, workers at Hawai'i Volcanoes National Park reported cough, phlegm, headache, eye irritation, nasal irritation, wheezing, shortness of breath, and throat irritation [11]. In 2004, an initial health survey was conducted when daily SO_2 exposure averaged 25 parts per billion (ppbv). Vog-exposed residents experienced increased prevalence of cough, phlegm, rhinorrhea, sore/dry throat, sinus congestion, wheezing, eye irritation, and bronchitis compared to unexposed island residents [12]. Significant elevations in systolic blood pressure and pulse rate were also observed. In a qualitative study, vog-exposed informants noted difficulty in controlling preexisting respiratory conditions at the low exposure levels [13]. In early 2008, when Kīlauea's activity increased and SO_2 exposure increased threefold (averaged 75 ppbv/day) from the previous months, significant associations were found between higher vog and increased outpatient clinic visits for cough, headache, pharyngitis, and acute airway problems [14]. In mid-2008, a 6-month hospital surveillance study found a significant increase in emergency department visits for broadly-defined respiratory problems within vog-exposed areas of the island [15]. Still, investigations have not assessed if the increased volcanic activity is concordant with health effects. Therefore, the purpose of this study was to reassess the health impact relative to Kīlauea's increased activity and higher exposure of vog. Study objectives were to (1) determine prevalence of current cardiorespiratory symptoms and diseases from groups of vog-exposed and unexposed island residents; (2) examine differences in cardiorespiratory signs; (3) estimate the associated effect of increased exposure; and (4) compare epidemiological estimates to the initial findings from 2004.

2. Materials and Methods

A cross-sectional environmental-epidemiological design assessed exposure and selected the geographic study areas. Volcanic emission data for point source estimation was obtained from the Hawaiian Volcano Observatory of the US Geological Survey (USGS), and air quality data for the exposure assessment was obtained from air monitors in the study area operated by the State of Hawai'i Clean Air Branch. Study groups were selected based on geographic exposure relative to the island's wind patterns. A cross-sectional design was then used to collect health data obtained by clinical assessment from a door-to-door survey using geographic stratified sampling. The study protocol was approved by the Biomedical Institutional Review Board of the University of Nevada, Reno. The study design, sampling framework, procedures, and analyses were replicated from the initial 2004 population health survey at Kīlauea [12]. The exposure level,

geographic study locations, and participants were different, yet allowed comparison to earlier findings.

2.1. Setting and Exposure. The exposed and unexposed geographic areas were rural, with accessible health care facilities that served clients regardless of health insurance coverage. The areas were comparable in meteorology, topography, vegetation, grazing lands, and historical agriculture. No site had substantial anthropogenic air pollution. The residents shared similar histories and lived in areas of former sugar plantations where companies had constructed small towns of plantation-style houses called *camps* that remained populated today. The study areas also included modern towns and residential subdivisions.

The southern region of the island was continually exposed to Kīlauea's emissions due to the flow of the Pacific trade winds through the marine boundary layer and a temperature inversion at ~1800 m above sea level. The exposed study area was selected to assess geospatial effects and ranged from the boundary of Hawaii Volcanoes National Park to ~70 km distance from source (DFS; i.e., distance from Kīlauea's summit vent) on the southern Kona coast. The most proximal area (~30 km DFS) experienced a diurnal pattern of vog exposure with the highest concentrations of SO_2 and $PM_{2.5}$ from 7 pm to 10 am daily; SO_2 was the predominant pollutant. Downwind distal areas (≥50 km DFS) received an inconsistent temporal pattern yet were continually exposed to relatively more sulfate $PM_{2.5}$ than SO_2. The unexposed area was similar in size and ranged from 40 km to 90 km DFS along the northeastern section of the island.

Environmental conditions during the 6-week study during spring of 2012 included usual northeastern Pacific trade winds without disturbances, continuous volcanic activity on the east rift zone and summit, and no lava-sea entries. Kīlauea's emissions averaged 1,340 tpd SO_2, as estimated by the USGS using a FLYSPEC spectrometer [21]. Ambient air quality was assessed from state-operated fixed monitors and the researcher's portable instrument. SO_2, measured continuously by a TECO pulsed-fluorescence fixed monitor, averaged 49 ppbv/day (hourly range: 0–1,700 ppbv) in the exposed area and was negligible in the unexposed area. The National Ambient Air Quality Standard for SO_2 was exceeded on 72% of the study days (1-hr average ≥75 ppbv) [6, 22]. WHO's 24-hr SO_2 guideline [5] was exceeded on 100% of the study days. Real-time SO_2 measurements were obtained at each exposed participant's residence with an Interscan 4000 Series SO_2 monitor and ranged from 0 ppbv to 600 ppbv. The average 24-hr concentration of $PM_{2.5}$, measured by a Met-One beta-attenuation mass fixed monitor, was 6.4 $\mu g/m^3$ (hourly range: 0.0–52.0 $\mu g/m^3$) in the exposed area and 2.0 $\mu g/m^3$ (hourly range: 0.0–4.0 $\mu g/m^3$) in the unexposed area. In addition, remote sensing data were reviewed daily from the Ozone Monitoring Instrument (Figure 3) and the Moderate Resolution Imaging Spectroradiometer to confirm vog exposure and nonexposure in the reference area.

2.2. Sampling. Cross sections of each study area, proximal to distal from the volcano, were employed to obtain a geographically representative and probability-based sample. Sampling included all towns and camps as well as residences in outlying locations. Participants were systematically selected from every 4th household on every street in towns and rural subdivisions. Sampling was restricted to no more than two participants per household to avoid over-representation of any one household. Sampling occurred during daylight hours 6 days a week. Eligible participants were adults aged ≥20 years with a minimum residence of 7 years (i.e., chronic exposure). The residents of the study areas were primarily Filipinos, native Hawaiians, Japanese, Pacific islanders, and non-Hispanic Whites [23]. The participation rate among eligible residents was 94%.

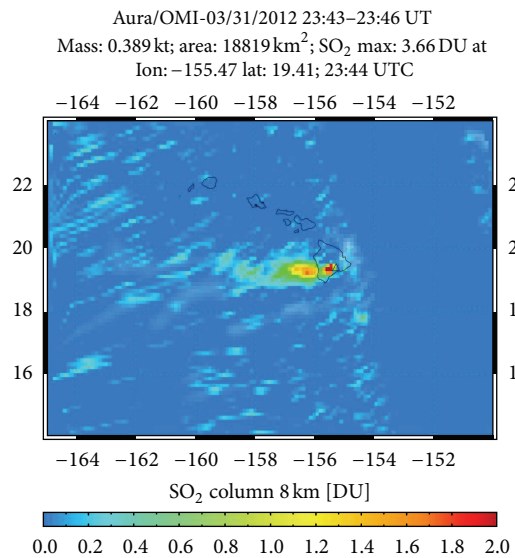

Figure 3: An example of daily remote sensing data used for assessing SO_2 exposure in the Hawaiian Islands during the study's time frame. Credit: National Aeronautics and Space Administration, Goddard Space Flight Center, Volcanic Hazards Project.

2.3. Procedures. Verbal informed consent was obtained from all participants at the outset of their participation. Health data were collected by interview and physical assessment at participants' homes by the researcher (an advanced public health nurse) in English (94%) or Tagalog (6%); none were needed in Japanese translation. The health interview was comprised of standardized, yes/no questions (current cardiorespiratory and dermal symptoms; lifestyle factors and demographic data) taken from the validated National Health and Nutrition Examination Survey [24], and American Thoracic Society's Respiratory Symptom Questionnaire [25]. A health history was obtained for medically diagnosed diseases (since 2008) and current medications. Participants provided qualitative descriptions of how Kīlauea's increased activity had affected their health, daily lives, and the environment.

The health assessment included blood pressure (BP), radial pulse rate, respiratory rate, and oximetry taken on all participants after 15 minutes of rest in a sitting position. BP was measured with a calibrated aneroid sphygmomanometer placed at heart level, with a proper cuff for arm size, using the slow-deflation auscultatory method [26]. For systolic

pressures ≥160 mm Hg, two measurements were taken 5 minutes apart. Radial pulse rates were taken for 30 seconds with regular rhythm and 1 minute for irregular rhythms. Respiratory rate and blood oxygen saturation measured by an oximeter were assessed over a 1-minute time period. The same researcher and equipment were used with all study participants to prevent interviewer bias, minimize misclassification bias, and ensure reliability of these data. Time commitment for participants averaged 20 minutes.

2.4. Statistical Analyses. To estimate the effects of vog exposure, crude odds ratios (ORs) were calculated from prevalence estimates for each exposure group. The 95% confidence interval (CI) of the point estimate was used for significance testing. Stratified analyses were conducted initially to evaluate for confounding and test for effect modification (EM). The Mantel-Haenszel estimator was used to control confounding for a uniform OR, and the chi-square test for heterogeneity was used to test for EM. The Mantel-Haenszel extension test was used for analysis of trends. Finally, logistic regression analyses adjusted the OR for *a priori*-selected potential confounders. Adjusted ORs and 95% CIs were calculated after controlling for categorical variables and prespecified confounders of gender, smoking (never, former, or current), occupational dust exposure, race (Hawaiian, Filipino, Japanese, White, and other), age (years), and body-mass index (BMI). Symptoms of cough or dry cough are known side effects from certain antihypertensive medications; hence, analyses for these symptoms were restricted to participants not taking these medications. Measures of central tendency were calculated on vital sign variables and Student's t-test of nondirectional hypotheses was performed for comparison of the unexposed and exposed groups. Demographic data of the groups were compared using chi-square or t-test analyses. All analyses employed a 5% probability of a Type I error ($\alpha = 0.05$). Power analysis *a priori* determined the study's sample size to allow detection of ≥2.0 epidemiological magnitude of effect. Data were analyzed with SPSS version 20.0 (SPSS, Chicago, IL).

3. Results

Study groups were comparable for nearly all demographic and health characteristics (Table 1). Significant differences between groups were identified in the percentage of native Hawaiians participants and average residency time.

Vog exposure was associated with substantially increased odds of self-reported cardiorespiratory and dermal symptoms (Table 2). Prevalence for daily cough, nocturnal dry cough, and cough with phlegm was significantly higher in the exposed group even when restricted to nonsmokers. The OR for SOB without exertion was three times higher in the vog-exposed group with even higher magnitude for nonsmoking participants. Although prevalence of wheezing in the last year did not differ between groups, the symptom of wheezing most days and nights was significant with effect modification in exposed participants <65 years of age (OR = 6.05, CI: 1.67–21.94; $P = 0.015$). Upper airway, skin, and eye symptoms were over four times more likely to be reported by vog-exposed participants. All symptoms experienced while outdoors were associated with high exposure ORs. Significantly higher effect measures for sore or dry throat, wheezing day and night, and sinus congestion were associated with an increased distance from source ($P = 0.03$, 0.02, and 0.04, resp.).

Medically-diagnosed hypertension was the only cardiorespiratory disease associated with vog exposure (OR = 1.92, CI: 1.01–3.67). Significant differences between groups were identified in vital sign measurements (Table 3). Elevated BP was associated with vog exposure in both OR and t-test analyses. The likelihood of having high BP (≥90 diastolic or ≥140 systolic) was doubled in exposed participants (adjusted OR = 2.32, CI: 1.30–4.14), with effect modification in elderly participants (OR = 4.65, CI: 1.82–11.91; $P = 0.005$). BP did not vary in relation to distance from source. A significantly higher mean systolic BP (+5.18 mm Hg) and mean diastolic BP (+4.70 mm Hg) were identified in vog-exposed participants. Significant exposure effects on BP were identified in nonsmokers, males, Filipinos, Whites, the elderly, and participants of normal weight. Nonsmokers exposed to ≥30 ppbv SO_2 had significantly higher diastolic BP (+9.08 mm Hg; $P = 0.01$). Exposure effects were also detected for blood oxygen saturation. Average pulse measurements did not significantly differ between study groups; however, when analyses were restricted to nonsmokers and nonmedicated participants, exposed individuals averaged nearly 10 beats per minute (bpm) faster than their unexposed counterparts.

Half of all study participants perceived that the eruption since 2008 had affected their health. Not surprisingly, more participants from the exposed group (61%) than from the unexposed group (37%) expressed this belief. Exposed participants shared about daily experiences with the ongoing eruption and elevated vog, whereas unexposed residents described their experiences when vog came into their area or they visited an exposed area on the island. Health effects attributed to vog varied from minor nuisances to deterioration of health status. Participants without respiratory disease reported upper respiratory symptoms, irritability, low energy levels, body aches, sleep disturbances, and headaches. Chronic symptoms were throat irritation and a persistent cough that lasted for weeks. Participants with cardiorespiratory disease reported breathing difficulties ranging from exacerbations of chest tightness and breathlessness during everyday vog levels to distress only during high pollution events. These participants noted the importance of being compliant with self-care maintenance activities such as carrying emergency medications, using at-home nebulizer treatments and air conditioning in the car, and staying indoors.

Participants also noted aesthetic concerns, agricultural and animal husbandry effects, and financial impacts on their lives attributed to the increased eruption. They described occasionally experiencing the noxious sulfurous odor of vog, a metallic or acid-like taste, and declared the sky was no longer blue. Agricultural effects included kills of flower and vegetable crops (i.e., proteas, orchids) during high vog events, as well as overall reduced production in crops (i.e., coffee, avocados). Many participants reported nearly continuous visible leaf damage and showed the researcher examples in their garden or patios. In addition to a direct loss of income

Table 1: Demographic and health characteristics of the study groups.

Participant characteristics	Unexposed (n = 110)	Vog exposed (n = 110)	P value
Age, years x (SD)	59.0 (19.5)	56.4 (17.3)	0.31
Body-mass index, x (SD)	26.0 (6.0)	27.4 (5.4)	0.48
≥25 n (%)	66 (60)	72 (65)	
Gender n (%)			0.34
Female	66 (60)	59 (54)	
Male	44 (40)	51 (46)	
Ethnicity n (%)			0.03
Filipino	38 (35)	35 (32)	
White	30 (27)	37 (34)	
Hawaiian	11 (10)	23 (21)	
Japanese	20 (18)	7 (6)	
Others	11 (10)	8 (7)	
Residency, years x (SD)	39.4 (24.1)	32.0 (21.1)	0.02
Lifetime residency n (%)	(45)	(35)	0.11
Employment n (%)			0.35
Working	40 (36)	45 (42)	
Unemployed	11 (10)	20 (15)	
Retired	53 (48)	37 (36)	
Disabled	6 (5)	8 (7)	
Education, years x (SD)	12.62 (2.7)	12.65 (2.4)	0.93
Occupational exposures n (%)			
Sugarcane	28 (26)	20 (19)	0.22
Macadamia Nuts	16 (15)	28 (26)	0.05
Dust	53 (49)	60 (56)	0.27
Age of home, years x (SD)	41.8 (20.2)	40.7 (24.8)	0.72
Plantation-style house n (%)	32 (29)	34 (31)	0.77
Health insurance n (%)	103 (94)	95 (90)	0.06
Smoking status n (%)			0.64
Never	53 (49)	48 (44)	
Former	40 (36)	40 (36)	
Current	17 (16)	22 (20)	
Medication usage n (%)			
Respiratory	15 (14)	10 (9)	0.30
Antihypertensive	48 (44)	49 (45)	0.84
Subjective view of health n (%)			0.35
"Excellent"	10 (9)	12 (11)	
"Very good"	37 (34)	32 (29)	
"Average"	56 (51)	50 (46)	
"Worse than average"	5 (4)	11 (10)	
"Very poor"	2 (2)	5 (4)	
Interviews English/Tagalog n	103/7	103/7	1.0

Note. All participants were ≥20 years with a minimum of 7 years residency in the study areas.

from cash crops, farmers and ranchers reported additional expenses such as replacement of fencing (sometimes hundreds of square miles), vitamin supplements for livestock, fertilizers for the soil, and replacement of new plants. Despite these adverse effects, some participants perceived a benefit from increased tourism on the island due to the attraction of Kīlauea's increased activity.

4. Discussion

This study at Kīlauea volcano identified higher prevalence estimates and stronger magnitudes of cardiorespiratory effects associated with the increased volcanic activity and higher levels of pollution. Although SO_2 emissions in this study were similar in total amount as during the 2004 study

Table 2: Prevalence and exposure odds ratio of cardiorespiratory symptoms in adult residents of Hawai'i Island, USA.

Participant self-reported symptoms	Unexposed group	Vog exposed group		
	P (%)	*P* (%)	Crude OR (95% CI)	Adjusted OR[a] (95% CI)
Chest pain	20.0	29.4	1.66 (0.89–3.10)	1.61 (0.85–3.08)
Cough[b] on most days for 3 consecutive or more months/year	15.4	56.8	7.23 (3.52–14.84)	8.18 (3.81–17.58)
Restricted to nonsmokers	11.8	47.7	6.81 (3.20–14.49)	7.30 (3.32–16.03)
Dry cough at night for >14 days	13.6	30.0	2.71 (1.38–5.36)	2.93 (1.45–5.91)
Restricted to nonsmokers	14.0	27.3	2.31 (1.09–4.89)	2.56 (1.17–5.57)
Headaches often	20.0	31.8	1.87 (1.01–3.46)	1.79 (0.91–3.51)
Phlegm on most days for 3 consecutive or more months/year	14.5	39.1	3.77 (1.96–7.25)	3.61 (1.83–7.11)
Restricted to nonsmokers	10.8	33.0	4.08 (1.85–9.01)	4.02 (1.77–9.10)
Cough and Phlegm combined	10.0	34.5	4.75 (2.27–9.92)	4.78 (2.21–10.32)
Restricted to nonsmokers	6.5	28.4	5.75 (2.23–14.85)	5.86 (2.21–15.57)
Rhinorrhea frequently	12.7	35.5	3.77 (1.90–7.46)	4.66 (2.26–9.64)
Sinus/nasal congestion often	12.7	36.7	3.98 (2.01–7.87)	4.75 (2.32–9.76)
SOB without exertion	12.8	32.7	3.30 (1.66–6.57)	3.53 (1.70–7.32)
Restricted to nonsmokers	12.2	33.0	4.03 (1.82–8.91)	4.33 (1.88–10.01)
Skin irritation	7.3	26.4	4.52 (1.96–10.42)	5.12 (2.15–12.20)
Sore or dry throat frequently	10.9	40.9	5.65 (2.78–11.50)	6.31 (3.00–13.29)
Wheeze within the last 12 months	28.2	38.3	1.58 (0.90–2.80)	1.63 (0.89–2.98)
Wheeze most days or nights	7.3	19.4	3.08 (1.30–7.30)	3.06 (1.24–7.59)
Wheeze during or after exercise	9.3	17.8	2.12 (0.93–4.80)	2.07 (0.88–4.87)
Symptoms while outdoors:				
Cough	1.8	35.8	30.09 (7.04–128.58)	32.95 (7.56–143.58)
Eye irritation	2.7	48.6	33.76 (10.09–112.89)	40.22 (11.59–139.64)
Rhinorrhea and sinus congestion	0.9	30.0	46.29 (6.20–345.72)	53.11 (7.0–401.93)
Shortness of breath	1.8	21.2	14.31 (3.28–62.39)	15.56 (3.52–68.74)
Wheezing	1.8	19.6	13.06 (2.98–57.27)	14.95 (3.30–67.70)

Note. *P*: prevalence; OR: odds ratio; CI: confidence interval; and SOB: shortness of breath. [a]Adjusted for age, gender, race, smoking status, BMI, and occupational dust exposure. [b]Nonmedicated: participants not taking medications with side effect of cough.

[12], the downwind communities experienced twofold the exposure due to the geographic location of the new summit vent relative to the island's wind flow patterns. The study further revealed an enhanced understanding of human-environmental interactions from both objective health data and subjective experiences of the eruption.

4.1. Physiological Findings. The study identified high prevalence and strong magnitudes of dermal, ocular, and cardiorespiratory effects from an average daily SO_2 exposure of 49 ppbv with hourly maximums up to 1,700 ppbv. Adverse physiological symptoms remained consistent with those identified during the initial study with lower exposure [12]. A vog-associated skin irritation was newly identified, yet previously observed in workers at Miyakejima island's volcano during periods of high SO_2 [10]. No human studies to date have been conducted on dermal effects or the dermal exposure route of SO_2 [27, 28]. Eye irritation was experienced by half of exposed participants, an increase from 33% reported previously at Kīlauea [12]. A recent case series study in Honolulu during a high vog event identified signs of conjunctival injection with clear mucous discharge, along with symptoms of eye irritation, and the authors proposed the term vog-induced conjunctivitis [29]. It is validated that SO_2 affects the mechanical functioning of the upper airways with minor ocular and nasal-pharyngeal effects [27, 30]. Most respiratory symptoms in the present study showed relatively higher prevalence and exposure odd ratios than previously identified, especially symptoms experienced while outdoors. Inhaled SO_2 is mostly absorbed in the upper respiratory tract (40%–90%) due to high water solubility [30]. Hence, the increased prevalence of respiratory symptoms relative to higher exposure is biologically plausible. Future studies in volcanic environments should include assessment of dermal exposure effects.

Further cardiorespiratory effects were revealed with the higher exposure, which included elevated BP parameters (systolic and diastolic) and SOB without exertion. The major

Table 3: Student's t-test analysis of vital sign measurements of adult residents from Hawai'i Island, USA.

Field-measured vital sign	Unexposed group			Vog exposed group			
	Mean	SD	n	Mean	SD	n	$p_{(2)}$
Pulse per minute (regular rhythm)	76.81	12.45	106	76.29	14.30	99	0.78
Nonsmokers and nonmedicated	75.33	12.54	12	84.90	17.54	20	0.11
Systolic blood pressure (mm Hg)	130.51	18.05	109	135.69	19.74	108	0.045
Nonsmokers	130.41	18.18	92	137.31	19.03	87	0.01
Males	129.32	16.35	44	136.72	18.78	50	0.04
Females	131.32	19.20	65	134.79	20.65	58	0.34
Hawaiians	134.18	25.15	11	135.04	22.55	23	0.92
Filipinos	127.68	18.91	37	138.34	17.78	35	0.02
Whites	128.80	14.44	30	138.40	19.24	35	0.03
Elderly ≥65 years	133.49	17.06	47	144.60	15.51	40	0.002
Nonsmokers with normal weight (BMI 18.5–24.9)	130.00	18.03	41	138.15	17.37	41	0.04
Diastolic blood pressure (mm Hg)	81.58	10.65	109	86.28	11.11	108	0.002
Nonsmokers	80.72	10.61	92	85.82	10.80	87	0.002
Respirations per minute	17.96	1.41	109	17.71	1.55	107	0.21
Blood oxygen concentration (Oximetry; % SpO_2)	96.11	1.39	109	95.55	1.70	109	0.008
Nonsmokers	96.10	1.22	92	95.45	1.72	87	0.004

Note. SD: standard deviation; BMI: body-mass index; and mm Hg: millimeters of mercury.

risk factor for an acute cardiac event in persons >50 years of age is systolic BP >140 mm Hg [26]. This parameter was exceeded by 60% of exposed participants, but by only 29% of the unexposed in this age range. Prevalence increased 12% since 2004 for this cardiovascular risk factor [12]. An elevated systolic BP in vog-exposed Filipinos was also previously identified [12] and observed in this study documenting a disparity needing further exploration. Therefore, in addition to routine screening, healthcare providers should educate on traditional cardiovascular risk factors and emphasize practical recommendations to reduce exposure [31]. Most interesting was the new finding of an exposure-associated decreased oxygen saturation, likely related to exposure of the $PM_{2.5}$ component of vog rather than SO_2. A study of 28 elders (>60 yrs of age) found a significant inverse association between urban $PM_{2.5}$ and oxygen saturation [32]. This study's findings, from an adult population in a volcanic environment, further support the hypothesis that cardiovascular functioning is affected by exposure to fine PM [31].

Most notable in this reassessment at Kīlauea were vog-associated effects among nonsmokers for symptoms of daily cough, phlegm, dry cough, SOB without exertion, and objective measures of elevated BP parameters and lower oxygen saturation. These findings suggest an enhanced cardiorespiratory risk at the higher exposure levels among the general adult population, not just sensitive members. Still, participants with preexisting conditions perceived being most affected by vog, with challenges for disease management.

Downwind geographic areas were exposed to different volcanic pollutants relative to distance from emission source. This study is the first to identify geospatial differences in prevalence of respiratory ailments. Future health studies in volcanic environments should consider distance from source in epidemiological assessments. Studies have identified built environments (e.g., structure type) that can affect vog-exposure risk and recommended interventions [16]. Hence, vulnerability is intertwined with volcanic phenomena in communities near active volcanoes.

4.2. Public Health Interventions. Over half of exposed participants perceived that their health was affected by Kīlauea's eruption, yet they were motivated in self-care practices to live with this natural source of pollution. The high study participation rate reflected shared concerns in these island communities about health and environmental effects related to the ongoing eruption. The state of Hawai'i has used research evidence in the past to develop policy and prevention initiatives related to vog [33]. The Hawai'i Rural Health Association has been an advocate for exposed populations, working to increase the community's participation in their health. In addition to volcano monitoring, the Hawaiian Volcano Observatory of the USGS has been actively engaged with educating the public, and Hawai'i island's Civil Defense has developed emergency response plans for high vog events and other volcanic hazards. However, sustained multidisciplinary efforts are still needed to educate and protect these vulnerable communities from the current and future eruptions at Kīlauea and other active volcanoes of Hawai'i.

On average, 50 volcanoes erupt each year [34]. The International Association of Volcanology and Chemistry of the Earth's Interior has a number of commissions working to reduce volcanic risk, including the multidisciplined International Volcanic Health Hazard Network [35]. Studies are now examining acute and residual effects of major eruptions and are leading to important public health interventions, disaster planning, and multidisciplinary efforts to enhance population health in volcanic areas around the world. Table 4 describes public health efforts that focus across levels of

Table 4: Public health recommendations for the Kīlauea volcano and other degassing volcanoes.

Level of prevention	Goals	Interventions
Primary	(1) Reduce exposure	*Advise and encourage*: self-care activities on heavy vog days: no exercise, stay indoors, and AC *Educate the residents on*: (a) The pattern of "clean air" hours for each geographic area during typical meteorological conditions to allow planning of daily activities [16] (b) The use of "real-time" air quality data accessible on the internet (c) The emergency response plan for high vog events *Establish*: (a) Disaster shelters and renovate hospitals as needed to ensure clean indoor air [16] (b) A policy of notification for new building/construction permits of the potential structural effects on indoor air quality [16] *Continue and enhance*: (a) The school system's vog response plan *(air quality equipment, training of personnel)* [16] (b) Assistance to senior centers *(air testing, air quality equipment)* (c) The emergency response plan *(revise as needed for current evidence, equipment needs, and evacuation activities for homebound or disabled residents)* (d) Communication between public health and healthcare agencies with volcanologists (e) Opportunities for community participation from residents (f) Health notices on air quality for tourists visiting vog-exposed areas
	(2) Promote general health	*Advise and encourage*: (a) "Heart healthy" lifestyles [17] (b) Prevent initiation of smoking with evidence-based interventions *Support and develop*: (a) Ongoing educational and resource needs of health care clinicians in vog-exposed areas (b) The Rural health association (c) The role of public health nursing [18] (d) Policies for nonsmoking in public areas
Secondary	(1) Identify disease in early stage(s) (2) Treat promptly	*Screen the population for disease*: (a) Conduct community health nursing fairs with screening and referral [19] (b) Clinicians should include spirometry as part of regular assessment during annual physicals *Educate*: (a) Importance of annual health screening regardless of age (b)Parents on subtle symptoms of respiratory illness in children (c) On increasing awareness and not ignoring adverse symptoms needing clinical assessment *(e.g., stroke, heart attack, SOB, chronic cough)* *Treat*: smoking using a family disease perspective and evidence-based interventions Enhance: Access to culturally-responsive healthcare and follow-up services
Tertiary	(1) Prevent disease progression (2) Maintain quality of life	*Persons with asthma*: (a) Clinicians implement guidelines from the National Heart Lung and Blood Institute [17] (b) Ensure all patients have a current "asthma action plan" and carry emergency medications as advised [17] (c) Provide innovative asthma education and support for children and their parents *(e.g., camps, web-based activities)* (d) Continue the public health nursing asthma plan for schools (e) Enhance the Hawaii Asthma Initiative to address the unique challenge of vog [20] *Persons with cardiovascular disease*: (a) Encourage self-care behaviors of monitoring BP and eating "heart healthy" (b) Educate on the importance of taking their prescribed medications and communicating with their practitioner about annoying side effects, instead of not taking the medicine

prevention and consider the vulnerable members of the population (i.e., children, elderly, and chronic disease). Knowledge gleaned from efforts at Kīlauea volcano is relevant to other communities challenged with volcanic activity and degassing.

4.3. Limitations. There are several considerations about this work that should be noted. First, the cross-sectional epidemiologic design was susceptible to selection bias, misclassification, and measured associations not causality. Vog has exposed the study area since 1983, yet migration out of the area is unknown. According to the recent 2010 US Decennial Census, both exposed and unexposed study areas experienced +9% growths in population since 2000 [21]. However, this study found residency time was lower in the exposed group. Therefore, a "healthy survivor" effect could have underestimated prevalence in the exposed area. Misclassification through subject recall bias could also have affected prevalence estimates, though both study groups would be prone to this limitation. Second, Kīlauea offers a natural laboratory to study human-environmental interactions not a controlled environment. Concentrations and chemical composition of vog vary with changes in volcanic activity and island meteorology, resulting in inconsistent exposures. Thus, the health assessments occurred with differing concentrations of vog, from relatively low to high levels. Still, at some time over a 24-hr period during the study, the exposed participants were exposed to vog. Third, the small sample size could not allow detection of small yet significant magnitudes of effect (<2.0) for other cardiorespiratory diseases that could exist in the exposed population. Finally, potential confounding of these data must be considered. Even with restriction to prevent confounding effects and analyses to control confounding, there may have been an influence of unknown confounders on these estimates.

5. Conclusions

The magnitude of associated cardiorespiratory effects has increased in vog-exposed communities at the Kīlauea volcano, Hawai'i. Many signs and symptoms of adverse biological responses have been detected in the exposed population that range from increased likelihood for experiencing upper respiratory reactions to more serious elevated cardiovascular risk factors. These findings are likely related to the higher volcanic air pollution experienced in downwind communities since the summit eruption began in 2008. Consequently, continuous epidemiologic surveillance, new screening programs, and enhanced evidence-based interventions for population health are recommended at Kīlauea and other degassing volcanoes worldwide.

Conflict of Interests

The author declares no conflict of interests.

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