Health Effects from Chronic Low-Level Exposure to Hydrogen Sulfide

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ABSTRACT. The acute toxic effects of hydrogen sulfide have been known for decades. However, studies investigating the adverse health effects from chronic, low-level exposure to this chemical are limited. In this study, the authors compared symptoms of adverse health effects, reported by residents of two communities exposed mainly to chronic, low-levels of industrial sources of hydrogen sulfide, to health effects reported by residents in three reference communities in which there were no known industrial sources of hydrogen sulfide. Trained interviewers used a specially created, menu-driven computer questionnaire to conduct a multi-symptom health survey. The data-collection process and questions were essentially the same in the reference and exposed communities. The two exposed communities responded very similarly to questions about the major categories. When the authors compared responses of the exposed communities with those of the reference communities, 9 of the 12 symptom categories had iterated odds ratios greater than 3.0. The symptoms related to the central nervous system had the highest iterated odds ratio (i.e., 12.7; 95% confidence interval = 7.59, 22.09), followed by the respiratory category (odds ratio = 11.92; 95% confidence interval = 6.03, 23.72), and the blood category (odds ratio = 8.07; 95% confidence interval = 3.64, 21.18). Within the broader health categories, individual symptoms were also elevated significantly. This study, like all community-based studies, had several inherent limitations. Limitations, and the procedures the authors used to minimize their effects on the study outcomes, are discussed. The results of this study emphasize the need for further studies on the adverse health effects related to long-term, chronic exposure to hydrogen sulfide.
<Key words chronic exposure, hydrogen sulfide, industrial sources, low level>

HYDROGEN SULFIDE (H_2S) is a highly toxic gas that occurs naturally in the environment (e.g., in volcanic gases, marshes, swamps, sulfur springs, decaying matter) and is a byproduct of many industrial processes, such as paper manufacturing. Ambient levels of H_2S are not measured routinely,[1] but available information indicates levels in the low parts per billion (ppb) range.[1,2] Levels of H_2S in industrial settings can be in the range of 0.5–10 parts per million (ppm).[3] Spills, leaks, malfunctions, or the accumulation of H_2S in enclosed workplaces or low-lying areas can result in much higher levels that can be highly toxic and quickly lethal. Exposure to H_2S is one of the leading causes of sudden death in the workplace.[1] In the United States, investigators attributed at least 5,563 exposures and 29 deaths to this chemical between 1983 and 1992.[4] In 1977, the National Institute for Occupational Safety and Health (NIOSH) estimated that approximately 125,000 employees in 73 industries were potentially exposed to H_2S in the United States.[5] Atmospheric release of H_2S represents the most significant public health concern of the growing geothermal energy industry.[6]

Many occupational and community studies, as well as studies of laboratory animals, have documented the adverse health effects of acute exposure to relatively high levels of H_2S.[2,7–9] The mechanism of action of H_2S involves interaction with a number of enzymes and other macromolecules, including hemoglobin and myoglobin. A critical target enzyme of H_2S is cytochrome oxidase.[10] Most organ systems are susceptible to the effects of H_2S; therefore, this toxic gas has often been regarded as a broad-spectrum toxicant. Organs and tissues most susceptible to H_2S toxicity, however, are those with exposed mucus membranes and those with high oxygen demands.[9] Neurotoxicity of the central nervous system (CNS) and pulmonary edema are well-documented consequences of acute H_2S poisoning.[7,9] Cardiovascular toxicity and gastrointestinal disturbances are also associated with exposure to this chemical.[7,9]

Although many individuals are exposed regularly to relatively low levels of H_2S through their jobs, or because they live in communities near industrial emissions of H_2S, studies investigating the adverse health effects of chronic, low-level exposures to this compound are limited. In one study, former workers and citizens who lived downwind from the processing of crude oil had neurophysiological abnormalities. Residents who lived near the plant were exposed to H_2S at 10 ppb—with periodic peaks to 100 ppb.[11] In a study of sewer workers, evidence indicated that low-level exposure to H_2S may be associated with reduced lung function.[3] Residents in an area of Finland located near paper mills reported an excess of adverse health symptoms (e.g., respiratory, eye, nasal symptoms) in comparison with a reference community,[12,13] although results in children did not reach statistical significance.[14] H_2S accounted for two-thirds of the total released sulfur compounds monitored in the reported studies.[15] Recent evaluations of hospital discharge records in Rotorua, New Zealand, which is situated near a geothermal field, showed an elevated prevalence of diseases of the nervous system and eye.[16] The results of several additional community and occupational studies indicate a considerable variety of adverse health effects from low-level, chronic exposure to H_2S.[17]

In this study, we compared symptoms of adverse health effects, reported by residents of two communities exposed mainly to chronic, low levels of industrial sources of H_2S, to the health effects reported by residents in three reference communities in which there were no known industrial sources of H_2S.

Materials and Method

We used a multi-symptom health survey, with multiple descriptive variables, to compare self-reported symptoms in communities exposed to low levels of H_2S to self-reported symptoms in reference communities with no known exposure to H_2S. The same questionnaire and the same data-collection and data-evaluation techniques were used for all communities.

Communities exposed to H_2S

Odessa, Texas. Odessa is a community of approximately 96,000 persons, located in the heart of the Permian Basin in West Texas. Beginning in about 1967, certain areas of this community were exposed to H_2S produced as a result of microbial action in solar ponds of industrial wastewater containing sulfate ions. Air modeling, performed in conjunction with a lawsuit based on citizen complaints, indicated that, in 1992, the levels of H_2S 1.6 km (1 mi) from the ponds were (a) 500–750 $\mu g/m^3$ (335–503 ppb), for a maximum 8-hr measurement; (b) 150–300 $\mu g/m^3$ (101–201 ppb), for a maximum 24-hr measurement; and (c) 3–40 $\mu g/m^3$ (7–27 ppb), for an annual average (Jim Tarr, personal communication). The ponds in this community were closed and reconstructed between 1995 and 1996.

Puna, Hawaii. Puna is a district located on the island of Hawaii, which is situated on the Kilauea East Rift Zone. This area is volcanically active and is a site for geothermal energy production. Since 1976, geothermal wells in the Puna area have been drilled for the purpose of generating electrical power. The Puna Geothermal Venture (PGV) currently generates up to 25% of the electricity on the island of Hawaii.[18] There are several fixed, elevated air monitors currently operating in the Puna area. Complete data from the fixed monitors, however, are not easily accessible, thus making it difficult for investigators to establish a clear and precise documentation of the recorded levels of H_2S exposure in this community. Available monitoring data from the 1990s indicate numerous H_2S hourly averages documented in the low-ppb range in the area near the PGV plant. Measurements of monitors run by the Hawaii Department of Health in the area during this same time period also revealed levels in the low-ppb range in 1996–1997, although most hourly measurements were less than 1 ppb or were not detectable.[18] As part of an investigation of the H_2S exposures in the area surrounding PGV in 1997, the Agency for Toxic Substances Disease Registry[18] (ATSDR) was provided with 29 incident reports that spanned the time period from June 1996 to July 1997. In these reports, the peak concentration detected was 301.7 ppb.[18] Periodic releases of H_2S in the range of 200–500 ppb have also been reported during other years.

Reference communities

Hilo, Hawaii. Hilo is a community located approximately 33.8 km (20 mi) to the northwest of the PGV plant. Hilo is exposed to natural volcanic emissions that are similar to those of Puna, but there are no geothermal power plants or known sources of industrial H_2S in the Hilo area. Therefore, we would expect that exposure to H_2S in this community would be much less severe than exposures in Puna or Odessa.

Midlothian, Texas. Midlothian is a community of approximately 5,100 people, located approximately 48 km (30 mi) south of the Dallas-Fort Worth metropolitan area in Texas. The local economy is made up of both agricultural and industrial enterprises. Industries in the area include three cement companies and a secondary steel mill. There are no known industrial sources of H_2S in the area.

Waxahachie, Texas. Waxahachie, a community of about 19,000 people, is located 45 km (28 mi) south of Dallas, Texas. The local economy is mainly agricultural and small business or industrial enterprises. There are no known industrial sources of H_2S in the Waxahachie area.

Selection of subjects. Selection of subjects in the communities potentially exposed to H_2S was conducted as follows. In Odessa, a random selection was made from a list of plaintiffs (about 600) compiled by a legal firm involved in a community investigation. Participants in Odessa had to have lived in the community for 5 or more y, and only those who lived within 1.6 km (1 mi) of the H_2S source were selected. We recruited participants in Puna by phone; we used the local phone book to identify persons who lived within 8 km (5 mi) of the PGV source. Eligible participants had to have lived in the community for at least 5 y. Flyers, which were posted in Puna at various places in the community, also informed persons about the health survey. The nature of the study, or the fact that the study involved industrial exposures, was not revealed or discussed with potential participants. The one exception to this was that several flyers, posted at only one location, encouraged persons to participate in the study "if they believed PGV was making them sick." This error was made by one of the individuals in the community who helped with the study. These flyers were discovered and were removed by the study coordinator after being posted less than 1 full day.

Volunteer participants in the reference communities had to have lived in their community for at least 5 y, and they had to live within 8 km (5 mi) of a specific zip code selected as a point of reference. Participants in Midlothian and Waxachachie were selected by random phone calls within a certain geographic area. Participants in Hilo were also recruited by this method, as well as by posted flyers that were similar to those used in Puna.

All participants signed a consent form evidencing their agreement to participate in the study. The exposed group included 126 participants from the Odessa community and 97 participants from the Puna community ($n = 223$). The reference group included 58 participants from Midlothian, 54 participants from Waxahachie, and 58 participants from Hilo ($n = 170$).

Survey instrument and data collection. The survey instrument was a specially created, menu-driven questionnaire that was extensive and very structured. The questionnaire covered a broad spectrum of symptoms within 12 different categories of physical health or function. The questionnaire also included detailed information on demographics, life style, reproductive history, cancer history, and other medical information. In all 12 categories, reported symptoms had to originate or worsen after the person moved into the community, and symptoms had to occur with sufficient frequency to constitute a significant health problem. For certain symptoms, a predetermined number of occurrences were necessary (e.g., persistent bronchitis [2 or more episodes per year], persistent cough [daily], and frequent headache [1 or more per week]). Copies of the complete questionnaire are available from the authors upon request.

Trained interviewers administered the questionnaire during face to-face interview sessions. Interviewers entered data directly into laptop computers, and the data were later downloaded to a central computer for storage and analysis. We used coded identification numbers for each subject to protect the confidentiality of the participants of the study.

The carefully constructed and refined structure of the questionnaire used for this study diminished the potential for error. Several internal checks served as indicators of data quality and, at several places in the questionnaire, respondents had to meet certain criteria before the interviewer could proceed from that point with questioning. In general, information had to be entered in the correct format for all activated data fields before the program would advance to the next field. The study coordinator also personally checked responses from each interview to be sure that they were completed, that respondents met any specific criteria required for certain areas of questioning, and that information was entered correctly in the proper format.

Interviewer selection and training. The interviewers for the 5 community surveys were previously trained graduate students and staff from the University of Texas Medical Branch, and community residents who were recruited and specially trained to assist with the study. The study coordinator personally trained each interviewer in the precise methods that had been developed for the proper use of the computer program. The coordinator also supervised mock interviews between interviewers for training purposes, and the coordinator observed each interviewer as he or she conducted the actual interviews. The study coordinator was accessible at all times during interview sessions to address any questions or potential problems.

Statistical analyses. Preliminary analysis included a 3×2 chi-square cross-comparison of the three reference communities, as well as a 2×2 chi-square cross-comparison of the two potentially exposed communities. We conducted these comparisons to determine if there were any significant differences between the two exposed communities and the three reference communities that would prevent them from being combined into the larger exposed and reference groups. Prevalence rates for total symptoms within each of the 12

Table 1.—Comparison of Symptom Categories in the Reference and Exposed Groups

	Reference population							Exposed population				
	Midlothian, Texas (n = 58)		Waxahachie, Texas (n = 54)		Hilo, Hawaii (n = 58)		Reference groups (n = 170)	Odessa, Texas (n = 126)		Puna, Hawaii (n = 97)		Exposed groups (n = 170)
Symptom/category	n	%	n	%	n	%	χ^2 (df = 2)	n	%	n	%	χ^2 (df = 1)
Central nervous system	25	43	19	35	14	24	0.1	112	89	82	85	0.45
Ear/nose/throat	31	53	26	48	24	41	0.43	110	87	84	87	0.96
Respiratory*†	19	42	5	12	8	14	< .01	58	66	54	70	0.68
Muscle/bone	17	29	25	46	16	28	0.07	79	63	58	60	0.76
Skin	15	26	10	19	13	22	0.65	58	46	56	58	0.11
Immune	15	26	11	20	11	19	0.64	79	63	55	57	0.44
Cardiovascular	23	40	27	50	20	34	0.24	78	62	53	55	0.34
Digestive	10	17	8	15	8	14	0.87	55	44	40	41	0.82
Teeth/gums	6	10	1	2	8	14	0.07	55	44	31	32	0.10
Urinary	10	17	9	17	4	7	0.19	37	29	27	28	0.92
Blood	3	5	3	6	1	2	0.53	37	29	24	25	0.54
Endocrine‡	10	17	11	20	1	2	0.01	29	23	15	15	0.22

*Reference group comparison, excluding Midlothian; χ^2 p value is .64.
†We excluded smokers from this category because confounding was possible.
‡Control comparison, excluding Hilo; χ^2 p value is .86.

health categories covered in the questionnaire, as well as prevalence rates for individual symptoms within certain categories, were tabulated for the combined reference group (n = 170) and the combined exposed group (n = 223). For certain categories, comparisons of the two exposed groups were made individually with the combined reference group. For all comparisons of the study and reference groups, we used Fisher's exact test to establish p values. Odds ratios (ORs) and their 95% confidence intervals (CIs) were also estimated.

Given the potential for a strong confounding effect of smoking on respiratory problems, smokers were removed from all analyses of respiratory symptoms. Also, as noted below, and in lieu of the findings reported in Table 1, Midlothian was removed from the reference group for analyses of respiratory symptoms, and Hilo was removed from the reference group for analysis of endocrine-system-related symptoms.

Results

Demographic characteristics of the samples drawn from the 5 exposed and reference populations are listed in Table 2. The percentages of subjects in each of the categories are similar for the exposed and reference groups, except with respect to ethnicity and age. The Odessa population was primarily African-American and Hispanic, whereas Puna and the three combined reference communities were 76% and 84% white and non-Hispanic, respectively. The mean age of the Waxahachie group (63.7 y) was higher than that of any other group, but the overall mean for the reference population was 56.2 y, which was only slightly higher than the mean of 50 y for the exposed population.

To determine if the reference groups could be combined in the analyses of individual symptoms, chi-square p values were calculated for a cross-comparison between each of the three reference communities (Table 1). Symptoms in the two exposed populations were also compared, and they were not significantly different in any category. The three reference populations were different ($p < .05$) in only two categories: respiratory and endocrine. The Midlothian population reported a high number of respiratory symptoms (Table 1). This was an expected finding because the population was near several cement kilns, thus resulting in exposure to emissions containing potential respiratory irritants.[19] When we excluded Midlothian from the control comparison for the respiratory category, the chi-square p value for respiratory symptoms between the remaining two reference communities was .64. Similarly, and as noted in Table 1, the Hilo population had only 1 subject who reported endocrine symptoms. When we removed Hilo from the reference group comparisons for endocrine symptoms, the chi-square p value between the remaining two reference groups became .86. In light of these differences, we excluded Midlothian from the respiratory category and excluded Hilo from the analysis of endocrine symptoms. For all other symptom categories, the three reference groups were not significantly different from each other and, therefore, were combined for analysis.

The numbers of symptoms reported and corresponding percentages in each of the 12 symptom categories for the two combined exposed groups and for the three combined reference groups are shown in Table 3. Fisher's exact p values, odds ratios, and 95% confidence intervals are also listed. As noted in the table, the reported numbers of symptoms in the exposed group were significantly higher than in the reference group (p < .001) for every symptom category, with the exception of the endocrine categeory. When we compared the exposed communities individually to the combined ref-

Table 2.—Demographic Characteristics of Exposed and Reference Populations

	Exposed population						Reference population							
	Odessa, Texas (*n* = 126)		Puna, Hawaii (*n* = 97)		Total exposed population (*n* = 223)		Midlothian, Texas (*n* = 58)		Waxahachie, Texas (*n* = 54)		Hilo, Hawaii (*n* = 58)		Total reference population (*n* = 170)	
Characteristic	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Age (y)														
Mean	51.7		48.2		50		49.6		63.7		55.2		56.2	
Range	14–83		17–78		14–83		16–76		29–86		18–86		16–86	
Under 40	33	27*	22	23	55	25	15	26	5	9	5	9	25	15
40–59	39	32*	63	65	102	47	27	46	16	30	33	57	76	45
60+	50	41*	12	12	62	28	16	28	33	61	20	34	69	41
Male	46	37	36	37	82	37	20	34	24	44	22	38	66	39
Female	80	63	61	63	141	63	38	66	30	56	38	62	104	61
Ethnicity														
White-Non-Hispanic	2	2	74	76	76	34	55	95	54	100	33	57	142	84
African-American	87	69	0	0	87	39	0	0	0	0	1	2	1	0.6
Hispanic	37	29	4	4	41	18	2	3	0	0	1	2	3	2
Other	0	0	19	20	19	9	1	2	0	0	23	40	24	14
Years at residence														
< 10	2	2*	53	55	55	25	17	29	3	5	27	47	47	28
10–29	33	28*	42	43	75	35	26	45	16	30	20	34	62	36
30+	85	71*	2	2	87	40	15	26	35	65	11	19	61	36
Smokers†	38	30	20	21	58	26	11	20†	9	17†	12	21	32	19

*Age was unavailable for 4 Odessa participants, and years at residence for 6 Odessa participants were unavailable.
†Smoking information was unavailable for 2 participants in Midlothian and for 2 participants in Waxahachie.

Table 3.—Self-Reported Symptoms in Various System Categories: Total Exposed (*n* = 223) Versus Total References (*n* = 170)

	Total exposed Puna/Odessa		Total reference Midlothian/Waxahachie/Hilo				
System categories	*n*	%	*n*	%	Iterated OR	95% CI	Fisher's Exact Probability
Central nervous system	194	87	58	34	12.7	7.59, 22.09	< .001
Ear/nose/throat	194	87	81	48	7.24	4.37, 12.42	< .001
Respiratory*	112	68	13	15	11.92	6.03, 25.72	< .001
Muscle/bone	137	61	58	34	3.06	1.99, 4.77	< .001
Skin	114	51	38	22	3.6	2.27, 5.82	< .001
Immune	134	60	37	22	5.35	3.36, 8.74	< .001
Cardiovascular	131	59	70	41	2.03	1.33, 3.12	< .001
Digestive	95	43	26	15	4.05	2.44, 6.96	< .001
Teeth/gums	86	39	15	9	6.31	3.46, 12.32	< .001
Urinary	63	28	23	14	2.48	1.44, 4.42	< .001
Blood	60	27	7	4	8.07	3.64, 21.18	< .001
Endocrine†	44	20	21	19	1.06	0.58, 1.98	.88

Notes. OR = odds ratio, and CI = confidence interval.
*In the respiratory comparison, Midlothian was excluded from the reference group, data from smokers were excluded from the respiratory comparison, and smoking information was unavailable for 2 participants in Midlothian and for 2 participants in Waxahachie.
†In the endrocrine comparison, Hilo was excluded from the reference group.

erence communities, similar differences were reported, with the endocrine category being the only category that was not statistically different. Nine of the 12 symptom categories resulted in odds ratios that exceeded 3.0. Symptom categories with the highest odds ratios were the CNS category (OR = 12.7; 95% CI = 7.59, 22.09), the respiratory category (OR = 11.92; 95% CI = 6.03, 25.72), and the blood category (OR = 8.07; 95% CI = 3.64, 21.18). In Figures 1–3, a breakdown of these three categories is presented.

The percentages for the individual symptoms within the CNS category are shown in Figure 1. Statistical anal-

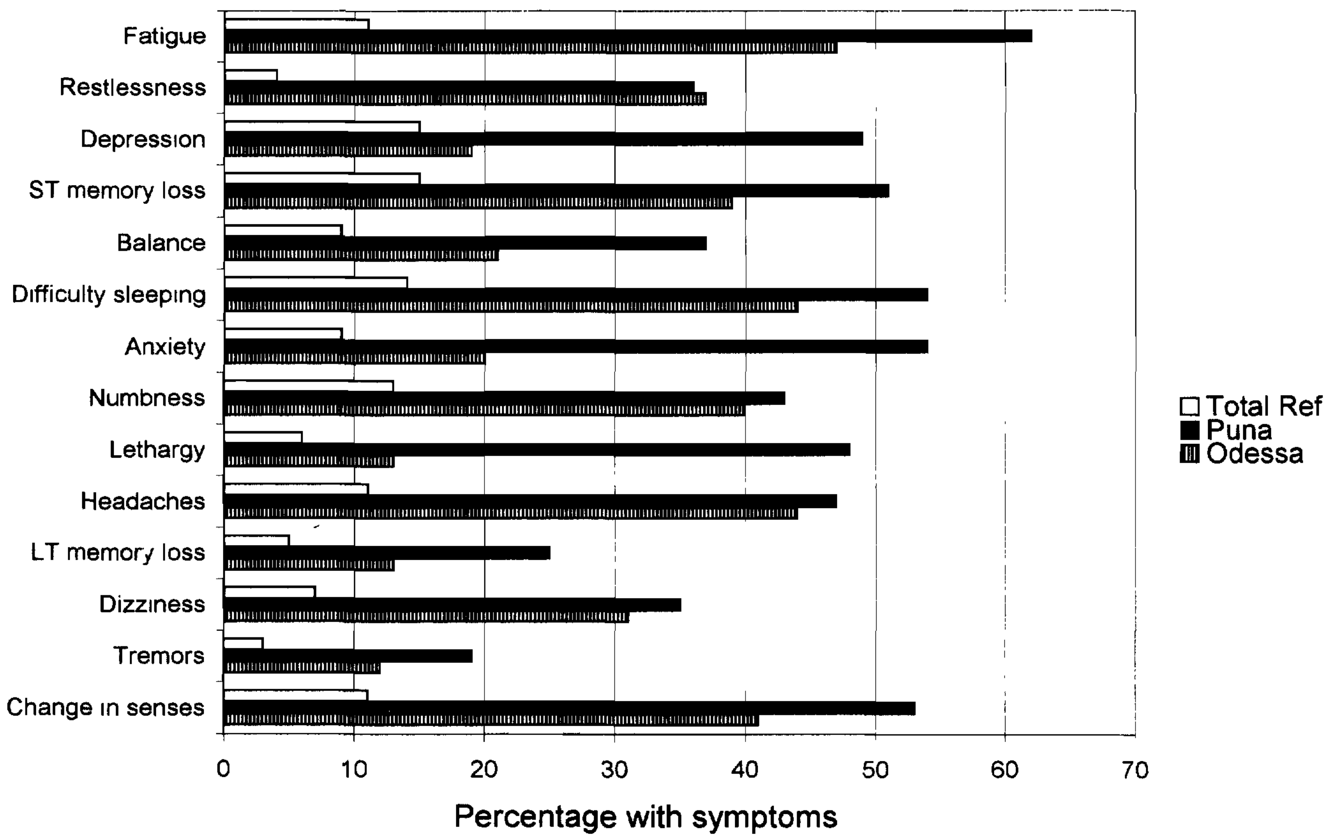

Fig. 1. Comparison of percentage of central nervous system symptoms among the combined reference populations and the hydrogen-sulfide-exposed Puna and Odessa populations. ST = short-term, and LT = long-term.

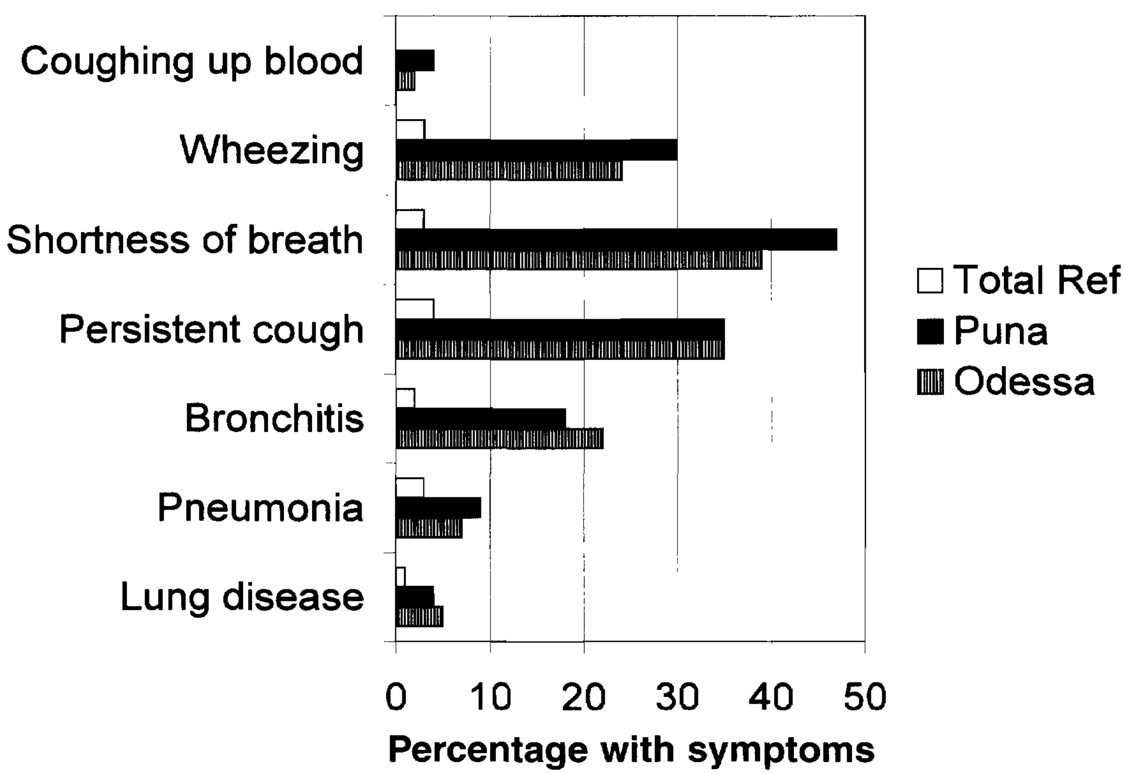

Fig. 2. Comparison of percentage of respiratory symptoms among the combined reference populations and the hydrogen-sulfide-exposed Puna and Odessa populations.

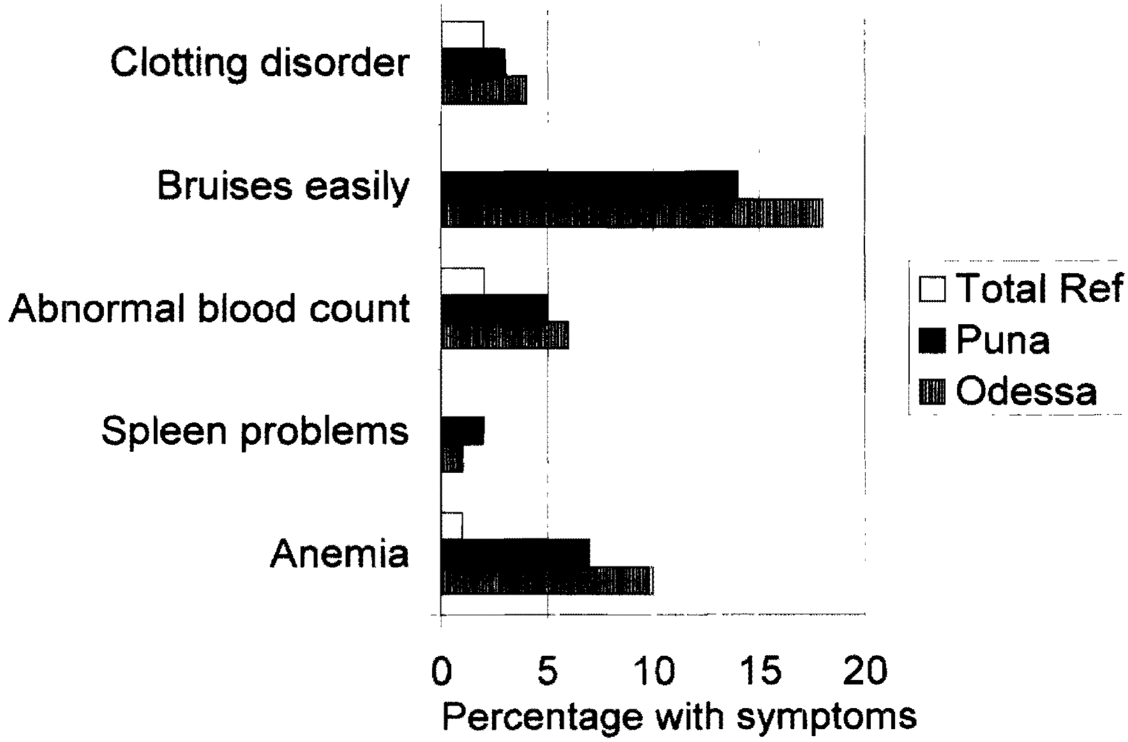

Fig. 3. Comparison of percentage of blood-related symptoms among the combined reference populations and the hydrogen-sulfide-exposed Puna and Odessa populations.

ysis of the data revealed that when we compared the Odessa and Puna communities, they were significantly different ($p < .05$) in 6 of 14 individual categories (i.e., long-term memory loss, lethargy, anxiety, balance, depression, and fatigue). The two exposed communities were compared separately to the combined reference communities. For the exposed population in Odessa, the odds ratio for each of the individual symptoms was elevated significantly over the symptoms reported by the combined reference populations ($p < .05$)—except for depression. For the exposed population in Puna, the odds ratios for all individual symptoms were significantly elevated over the combined reference populations ($p < .01$). It should be noted that neuropsychological evaluations were also conducted on the participants from Puna. These objective measurements supported and confirmed the CNS findings of this health-symptom survey.[20]

Individual respiratory symptoms are compared and summarized in Figure 2. For both exposed populations, the same four respiratory symptoms (i.e., bronchitis, persistent cough, shortness of breath, and wheezing) were significantly different from the combined reference populations ($p < .001$). In a comparison of the two exposed communities, the odds ratios were not significantly different for any of the individual categories.

The comparisons of individual symptoms in the blood category are shown in Figure 3. In both exposed communities, the same two symptoms (i.e., anemia and bruises easily) were significantly different from the reference group ($p < .05$). All other individual blood symptoms were not significantly different. The odds ratios for the two exposed communities were not significantly different from each other for any of the individual categories.

Discussion

In this multi-symptom health survey, we identified a variety of adverse health symptoms that appear to be associated with chronic exposure to low levels of H_2S. In this study, self-reported, adverse effects in every category analyzed, except the endocrine system, are documented. Within the broader health categories, a number of specific symptoms were reported, with significantly higher frequencies in the two exposed groups than in the reference communities. Although some differences were noted between the two exposed populations, the findings in these two independent groups were generally very similar. Additional strengths of this study include the consistency of the interviewing process and the use of identical questionnaires for all subjects in our study. There were also several objective neuropsychological tests and measurements that were performed on subjects in the exposed Puna and the reference Hilo communities.[20] The results of these tests support findings within the important CNS symptom category.

There were also limitations in our study. Surveys of self-reported symptoms may be susceptible to response enhancement bias (i.e., an increase in reported symptoms resulting from the fact that respondents are aware of, and sensitized to, the fact that they are exposed). Our study was vulnerable in this area given the rather intense political controversy that characterized the history of

H_2S exposure in the Puna community. In Odessa, the community was involved in a lawsuit related to H_2S exposure, and this involvement may have contributed to a potential response bias for this group. However, the results of a recent study indicate that plaintiffs in a legal case may be no more likely to "enhance" answers than the general population.[21] Also, the survey results for Puna and Odessa were very similar, even for symptoms that the community respondents would likely have not expected to be related to H_2S exposure.

A standard problem in studies that use subjective questionnaires is the potential for recall bias. In our study, we used a detailed questionnaire with internal checks to help control for this bias. It is impossible, however, with only subjective data, to completely avoid this problem, but we minimized the effect by using identical questionnaires for all of the subjects in all groups. There is also the potential for interviewers to introduce systematic errors in the data if there is a special way they ask certain questions, encourage certain responses, or if there are differences in the ways they interpret and transcribe answers. The design and methodology of this survey minimized the potential for this type of error or bias in at least two important ways. First, the use of computerized, menu-driven questionnaires, which allowed for direct input of data into the computers, enhanced the accuracy and consistency of the interviews. Second, the extensive training of the interviewers included supervised mock interviews, and the study coordinator also carefully supervised the actual subject interviews.

There were several possible confounders that could affect the findings of our study. Differences were observed in age, smoking behavior, and ethnicity between the exposed and reference groups. As noted in Table 1, Puna (a 76% white, non-Hispanic community) and Odessa (primarily an African-American and Hispanic community) differed significantly in terms of their ethnicity. However, there were no statistically significant differences in the responses of the subjects in these two communities in the broader symptom categories. It appears, therefore, that any potential ethnic effects were not sufficiently great to influence the major findings of this investigation. With respect to age, the mean age for the reference group (56.2 y) was slightly higher than that of the exposed group (50 y). Given that older individuals might have a higher number of adverse health symptoms, we would expect that any age effect in this study would have resulted in an underestimate of the true differences between the exposed and reference groups. As noted previously, to minimize the possible confounding effects of smoking in this study, we removed smokers from the analyses of all respiratory symptoms.

A final limiting factor that should be noted is often present in environmental studies of this type. In the Puna community, only a portion of the monitoring data from the fixed, elevated monitors was available for this investigation, thus making exposure difficult to analyze. Concurrent exposures to other chemicals, in addition to H_2S, in the Odessa community also clouded the exposure picture. Hence, it was impossible for us to know what the "true" exposure was for each individual, or even for groups of individuals, who lived in a certain area.

Despite the listed limitations, the two potentially exposed communities were very similar in terms of adverse health symptoms reported within each broad category. They were also very similar in the subcategories of respiratory and blood symptoms. Some differences were noted in individual symptoms in the CNS category, but the exact reason for this difference is unclear. Perhaps the difference may result, in part, from the stressful atmosphere in Puna that is related to the intense political dissension about geothermal development in that area.

On the basis of information contained in the available literature about acute toxic effects of H_2S exposure, increased health effects in the exposed populations (e.g., CNS, respiratory, and ear, nose, and throat symptoms) could be anticipated.[11–13,22] Other categorical symptoms in the exposed groups are less commonly associated with H_2S exposure. Information exists, however, that supports some of our unique findings. For example, changes in enzymes involved in heme metabolism have occurred in individuals exposed to H_2S.[23,24] Alterations in iron metabolism have also been noted.[25] There is also evidence from studies in rats that H_2S interferes with bacterial inactivation in the lung.[26] Studies in humans have also indicated that, as levels of sulfur compounds[13] decrease, the incidence of respiratory infections in individuals also decreases.[27]

This study, like all community-based observations, requires extension and confirmation. However, our results, providing evidence of the elevated prevalence of adverse health symptoms in communities potentially exposed to low levels of H_2S, emphasize the need for further studies on the effects of this toxin.

Given that we still do not know whether adverse effects are associated with low-level exposure to industrial chemicals in residential settings, studies such as this multi-symptom, community-health survey should prove valuable. However, community-based epidemiological studies, even conducted under the best of circumstances, do have important limitations, as discussed above. Despite these limitations, we anticipate that studies such as this one will play an ever-increasing role in identifying potential health problems related to chronic exposures to toxic substances. A committee of the National Academy of Science recognized the limitations of traditional environmental epidemiological studies, but it asserted that a community symptom survey, coupled with pertinent knowledge gained from laboratory studies, could lead to "causal inference" about the effect of potentially toxic chemicals on human populations.[28] The findings in our study, taken together with previously reported data concerning adverse responses to H_2S, strongly mandate the need for continued research on the possible detrimental effects of chronic exposure to this toxic agent. This is of decided public health significance, given the relatively large segment of the population that is regularly exposed to low levels of H_2S.

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