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Low-level hydrogen sulfide and central nervous system dysfunction

Kaye H Kilburn[1], Jack D Thrasher[2] and Michael R Gray[3]

Abstract

Forty-nine adults living in Lovington, Tatum, and Artesia, the sour gas/oil sector of Southeastern New Mexico, were tested for neurobehavioral impairment. Contributing hydrogen sulfide were (1) an anaerobic sewage plant; (2) two oil refineries; (3) natural gas/oil wells and (4) a cheese-manufacturing plant and its waste lagoons. Comparisons were to unexposed Wickenburg, Arizona, adults. Neurobehavioral functions were measured in 26 Lovington adults including 23 people from Tatum and Artesia, New Mexico, and 42 unexposed Arizona people. Participants completed questionnaires including chemical exposures, symptom frequencies and the Profile of Mood States. Measurements included balance, reaction time, color discrimination, blink reflex, visual fields, grip strength, hearing, vibration, problem solving, verbal recall, long-term memory, peg placement, trail making and fingertip number writing errors (FTNWE). Average numbers of abnormalities and test scores were adjusted for age, gender, educational level, height and weight, expressed as percent predicted (% pred) and compared by analysis of variance (ANOVA). Ages and educational attainment of the three groups were not statistically significantly different (ssd). Mean values of Lovington residents were ssd from the unexposed Arizona people for simple and choice reaction times, balance with eyes open and closed, visual field score, hearing and grip strength. Culture Fair, digit symbol substitution, vocabulary, verbal recall, peg placement, trail making A and B, FTNWE, information, picture completion and similarities were also ssd. The Lovington adults who averaged 11.8 abnormalities were ssd from, Tatum–Artesia adults who had 3.6 and from unexposed subjects with 2.0. Multiple source community hydrogen sulfide exposures impaired neurobehavioral functions.

Keywords

neurobehavioral, encephalopathy, reduce sulfur gases, sewage

Introduction

Hydrogen sulfide (H_2S) has caused coma and death in sewer workers (Christison, 1845). In a sour natural gas pollution incident in Poza Rica, Mexico, 320 people living around the refineries were hospitalized and 22 died (McCabe and Clayton, 1950). H_2S attacks the lungs, cardiovascular system and central nervous system (CNS; Beauchamp et al., 1984; Burnett et al., 1977; McCabe and Clayton, 1950). Acute exposure can result in loss of consciousness and upon recovery neurological symptoms occur: persistent headache, loss of balance, dizziness, agitation, amnesia and cognitive dysfunction (Arnold et al., 1985; Guidotti, 1994). Initially, it was believed that individuals who lost consciousness fully recovered without neurological sequelae. However, a follow-up in six patients 5 years after H_2S poisoning demonstrated motor and memory dysfunction, with one case of dementia. (Tvedt, Edland et al., 1991; Tvedt, Skyberg et al., 1991). After another incident, it was recommended that patients manifesting neurotoxicity should undergo neurological and neuropsychological testing for at least 5 years (Snyder et al., 1995). Further reports of physiological deficits: abnormal balance,

[1] Neuro-test Inc., University of Southern California, Keck School of Medicine, Laboratory for Environmental Sciences, ret., California, USA
[2] Citrus Heights, California, USA
[3] Progressive Health Care, Benson, Arizona, USA

Corresponding author:
Kaye H, Kilburn, Neuro-test Inc., University of Southern California, Keck School of Medicine, Laboratory for Environmental Sciences, ret., 3250 Mesaloa Lane, Pasadena, California 91107, USA
Email: khkilburn@sbcglobal.net

reaction time, color discrimination and visual field performance made it clear that brain damage was permanent with objective measures of a prolonged P300 latency (Wasch et al., 1989) and decreased performance in a battery of tests for neurophysiological/psychological functions (Kilburn and Warshaw 1995a).

Animal studies have shown several specific adverse effects of H_2S on the CNS. Repeated exposure to H_2S (25 to 100 parts per million [ppm]) produced a cumulative effect in the rat hippocampus, resulting in an increase in the total theta power activity in a dose-dependent manner (Skrajny et al., 1996). Following a daily 1-hour exposure to 7 ppm, rat cerebral cortices showed axonal swelling and demyelination, neuronal cell death, intensified endocytosis, oligodenroglial damage and increased protein synthesis (Solnyshkova, 2003; Solnyshkova et al., 2002; Solnyshkova and Shakhlamov, 2002). H_2S also maybe a developmental CNS toxin causing abnormal growth of cerebellar Purkinje cells after in utero exposure in rats (Hanna and Roth, 1991). In addition, in utero and postnatal treatment of rat pups caused an increase in neurotransmitters (serotonin, epinephrine, aspartate, GABA and glutamate) in the frontal cortex and developing cerebellum (Roth et al., 1995; Skrajny et al., 1992). Among the mechanisms proposed for toxicity are interference with sodium currents in cells (Warenycia et al., 1989), overloading of the H_2S gaseous transmitter system (Wang, 2002), inhibition of cytochrome oxidase that was cumulative (Savolainen et al., 1980) and production of reactive sulfur species depleting glutathione with formation of reactive oxygen species (ROS; Truong et al., 2006). H_2S exposures have cumulative effects in animals (Partlo et al., 2001; Skrajny et al., 1996).

Historically, exposure to low concentrations of H_2S and other reduced sulfur compounds from industrial and non-industrial sources has been considered a nuisance. As such, H_2S was removed from the Clean Air, 1990 under pressure from the American Petroleum Institute (Morris, 1997). This occurred in opposition to the recommendation of the Agency for Toxic Substances and Disease Registry (ATSDR) to set a chronic reference dose (RfC) of 0.010 ppm in the draft on the Toxicological Profile for H_2S (2004). Several reports demonstrate the need for stricter controls on H_2S releases. Emissions of malodorous sulfur compounds (24 hours of H_2S at 35–45 μg^3) from a pulp mill were associated with increased respiratory and neuropsychological symptoms (anxiety and depression; Haahatela et al., 1992; Partti-Pellinen et al., 1995). Exposure to H_2S emitted from open ponds from industrial waste (24-hour average of H_2S < 3–49 $\mu g/m^3$) and geothermal releases (peak H_2S < 300–400 parts per billion [ppb]) resulted in increased odds ratio for central nervous and respiratory symptoms (Legator et al., 2001). Moreover, increased risks for diseases of the respiratory and nervous system were reported in residents of Rotorua, New Zealand, living on an active geothermal field (Bates et al., 2002). Subsurface leakage in the sour gas field of SW Iran contains reactive sulfur compounds equal to 0.023 $\pm$ 0.002 ppm of SO_2. Reports on residents have shown elevated scores for depression and hopelessness (Saadat, Bahaoddini et al., 2004); increased rates of suicide (Saadat, Zendeh-Boodi et al., 2004) and decreased absolute white blood cell counts, while RBC, hematocrit, hemoglobin and platelets were elevated (Saadat and Bahaoddini, 2004). Finally, objective measurements of permanent neuropsychological and neurophysiological deficits (e.g. balance, memory, word recall, trail making, peg placement, visual scores, etc.) have demonstrated numerous deficits in individuals exposed to low concentrations of reduced sulfur compounds from refineries (Kilburn, 1999; Kilburn and Warshaw, 1995), oil field workers (Kilburn, 1997), natural gas and hog lagoons (Kilburn, 1999), leakage into homes from gas and petroleum deposits (Kilburn, 2003) and a refinery explosion (Kilburn, 1999).

We reasoned that adverse effects from H_2S might occur to people in the middle of a sour gas/oil field of Lea and Eddy Counties in S.E. New Mexico. The region has several oil refineries and a malodorous desulphurization plant for natural gas that precipitated complaints from residents. In addition, Lovington had an outmoded waste water treatment plant (WWTP) that went anaerobic because of excessive discharge of heavy oil and wax waste from a local refinery and fat from a cheese-whey manufacturer. These materials prevented aeration of waste. After being consulted by four residents with severe health complaints, we invited residents of three towns in Southeastern New Mexico to participate in an investigation.

Materials and methods

Subjects

All subjects in this study lived and/or worked in the sour gas/oil fields located in South East New Mexico as follows: Two WWTP workers and their wives originally met with one of the authors. They brought videos depicting the anaerobic condition of the WWTP and raw sewage running down the streets of Lovington as well as data on H_2S testing. The four had severe balance problems when their eyes were closed and complaints of neurocognitive dysfunction. They and four other adults (3 men, one wife) with similar symptoms underwent detailed neurophysiological and neuropsychological testing.

Twenty-six women and men, including the original eight subjects (age: 45.9 ± 11.6; education: 11.2 ± 2 years) residing in Lovington, New Mexico, volunteered for testing after a public meeting and newspapers and TV coverage. Three children aged 5, 7, and 11 were also tested. Their data are not included in the tables of this communication. The estimated exposures to H_2S varied, but all had lived in Lovington 4 years or more, with the five workers and three wives having exposure data.

The 12 Tatum, New Mexico, people (located 32 km NE of Lovington) were recruited by community churches and matched to the Lovington subjects. Tatum is within the same sour gas/oil field as Lovington and had a natural gas desulfurization plant near the town. The Tatum subjects were tested intermixed with the Lovington people.

Eleven individuals from Artesia, New Mexico (104 km west of Lovington), were considered to be minimally exposed to H_2S. They were tested because of health complaints that they associated with H_2S and possibly volatile organic chemicals (VOC) exposure from an oil refinery near the center of town. They attributed their symptoms to H_2S, because they detected its odor at night and in the early morning hours. The mean age and educational level of the 23 of the lesser exposed group (Tatum + Artesia subjects) were 49.7 ± 16.6 and 12.9 ± 1.9 yrs, respectively.

All subjects were tested for neurobehavioral impairment, completed questionnaires and were interviewed to exclude occupational and residential exposure to neurotoxic chemicals and medical and neurological diseases (Kilburn and Warshaw, 1992). The 49 subjects were tested using the same neurobehavioral and pulmonary measurements by the team that tested eight initial Lovington subjects, the 11 adults in Artesia and the 42 unexposed adults in Arizona (Kilburn and Warshaw, 1995a, 1995b; Kilburn, 1999). The 42 Arizona unexposed subjects (age: 49 ± 21.7; education: 12.6 ± 2.3 years) comprised a 10-year follow-up of a random sample of 202 adults studied in 1993, 1996 and 2002 and used to produce regression equations to predict values for the 26 tests (Kilburn, Thornton, Hanscom 1998a). Subjects completed questionnaires on chemical exposures, medical and neurological histories and frequency of symptoms (Kilburn et al., 1999). They gave informed consent and the protocol was approved by the Human Studies Research Committee of the University of Southern California, Keck School of Medicine.

Exposure assessments – hydrogen sulfide and air quality

Hydrogen sulfide. The assessment of exposure to H_2S in Lovington was obtained via the following sources: (1) videos supplied by the Lovington WWTP workers showing Draeger tube measurements; (2) reports generated by the State of New Mexico Environment Department; (3) reports and test data by Callaway Safety Equipment Co, Hobbs, New Mexico; (4) interviews of the five workers and their wives; (5) interviews of individual residents of the community and (6) review of written complaints of citizens to the town council. The assessment of H_2S exposure for Tatum and Artesia residents was done by personal interviews (Tatum, Artesia), a visit to Artesia by the testing team and review of tests data from the State of New Mexico Environment Department on concentrations present in Eddy County, NM (Dubyk and Mustafa, 2002).

Air Quality VOCs, PM_{10} and $PM_{2.5}$. Review of U.S.E.P.A, historical Toxic Release Inventory (TRI) for VOCs, and PM_{10}, $PM_{2.5}$ for Lovington and Tatum (Lea County, NM), Artesia (Eddy County, NM) and Wickenburg (Maricopa County, AZ) was done through http://wwwscorecard.com and U.S.E.P.A. by zip codes. Lea and Eddy Counties, NM, are located in the sour gas/oil fields of SE New Mexico, while Wickenburg is a rural isolated town approximately 75 km NW of Phoenix that is devoid of major industry.

Description of the exposure and work conditions of the original eight individuals

Three of the original exposed male subjects were employees of the Lovington WWTP and three were their wives. Two other males were WWTP and pipeline workers with 12 years of exposure to leaks of a natural gas pipeline. On one occasion, a pipe line leak that measured 480 ppm of H_2S caused a knock-down and hospitalization of one worker. Durations of WWTP employment were 24, 21 and 4 years. These three men would frequently immerse themselves up to their arm pits in waste streams while repairing lift station pumps. Two of the wives were exposed along with their husbands while they held flashlights during repair and unclogging of sewer lines and WWTP clarifiers. The third wife was exposed as result of her husband's soiled clothing taken home (see below).

The sewage input was increased by waste from the oil refinery in 1992 and the cheese factory in 1995, resulting in anaerobic conditions of the primary and secondary clarifiers of the WWTP lasting into 2002. The waste stream from the refinery periodically had an odor of H_2S upon reception at the WWTP and would be shut down until the situation was rectified. Videos taken by two sewer plant workers revealed: (1) whey foam several inches thick spilling out of the primary and secondary clarifiers; (2) measurements of H_2S concentrations on the streets of Lovington; (3) raw sewage flowing down the main street of Lovington and (4) measurements of H_2S within the WWTP. The WWTP was cited and fined for deficiencies by the State of New Mexico Occupational Safety and Health Administration (OSHA) in January 2003. Two WWTP employees and their wives had filed a civil suit against the city, the refinery and the cheese/whey manufacturer in February 2001, which was settled in 2004.

Questionnaires

Completed questionnaires were checked by computer-guided reading so that subjects rectified all omissions on the day of the testing. Questionnaires included the frequencies of 35 common health complaints (Kilburn and Warshaw, 1992, 1993, 1995a, 1995b) rated from never as 1 to daily as 11, making a 10-point scale, the American Rheumatism Association 11 lupus erythematosus questions (Levin et al., 1984), a standard respiratory questionnaire (Ferris, 1978). Included were occupational and other exposures to chemicals, pesticides and herbicides, tobacco, alcohol and drug use (prescription and illicit), unconsciousness, anesthesia, and head trauma and neurologic and medical histories (Kilburn and Warshaw, 1992). The questionnaires and the neurophysiological and neuropsychological test battery had evolved through previous studies for formaldehyde effects on histology technicians (Kilburn and Warshaw, 1992) of people exposed to thermolysis products of polychlorinated biophenyls (PCBs) (Kilburn, 2000) and people exposed to toluene-rich chemical waste (Kilburn and Warshaw, 1993) and included several groups of unexposed subjects (Kilburn, 2000; Kilburn et al., 1998a; Kilburn and Warshaw, 1995a). The symptom frequencies of each subject were averaged and a compared across groups. The questionnaire has been standardized in previous studies (Kilburn et al., 1998a; Kilburn and Warshaw, 1992; Kilburn and Warshaw, 1993).

Neurophysiological tests. Simple reaction time (SRT) and visual two choice reaction time (CRT) were measured from the appearance on the computer screen of a 10 cm block A to its cancellation by tapping a keypad A for simple and A or S for choice with a computerized instrument (Miller et al., 1989). The lowest median score of the last 7 in each of the two trials of 20 was accepted for SRT and for CRT. Body balance was measured with the subject standing erect with feet together. The position of the head was tracked by a sound-based position detector from a sound generating stylus on a head-band, processed in a computer and expressed as mean speed of sway in cm/sec (Kilburn and Warshaw, 1994). The minimal sway speed of three consecutive 20-second trials was the value used for sway with the eyes open and sway with the eyes closed.

The blink reflex was measured in 8 exposed and 11 control subjects with surface electromyographic electrodes (EMG) from lateral orbicularis oculi muscles bilaterally (Shahani and Young, 1972, Kilburn et al., 1998a) after tapping the right and left supraorbital notches with a light hammer, which triggered a recording computer. Ten firings of R-1 were averaged to find the mean response for each side and failures to respond were recorded (Kilburn et al., 1998b). Color confusion index was measured with the desaturated Lanthony 15 hue test under constant 1000 Lux illumination (Lanthony, 1978) and errors scored by the method of Bowman (1982). Hearing was measured in left and right ears with standard audiometers (model ML-AM Microaudiometrics, So. Daytona, Florida, USA) at stepped frequencies of 500 to 8,000 Hertz. The sum of deficits for each ear was the hearing score.

Threshold testing of visual field performance used a computerized automated perimeter which mapped the central 30° of right and left eyes individually (Neuro-Test, Inc. Pasadena, California, USA). The visual field score for each eye was the sum of abnormal quadrants with two or more points detected at 2 or more steps of illuminance greater than others in that a circle (Anderson, 1987).

Neuropsychological tests. Immediate memory or recall was measured with two stories from Wechsler's Memory Scale–Revised (1981). Culture Fair tested non-verbal non-arithmetical intelligence based on the selection of designs for similarity, for difference, for completion and for pattern recognition and transfer (Cattell, 1951; Cattell et al., 1941). Culture Fair resembles Raven's progressive matrices (Raven, 1988). The 46-word vocabulary test was from the multidimensional aptitude battery (Jackson, 1985). Digit symbol substitution from the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1981) tested attention and integrative capacity. Information, picture completion and similarities were also from the WAIS-R, tested long-term (embedded) memory. Time needed to place 25 pegs in the Lafayette slotted pegboard was measured as were times to complete Trail making A and B. These tests from the Halstead-Reitan battery (Reitan, 1958; Reitan, 1966) measured dexterity, coordination and decision making. Peripheral sensation perception was measured with fingertip number writing errors. Subjects' moods were appraised by responses to 65 terms describing emotional status for the week using the Profile of Mood States ((McNair, Lorr et al, POMS; 1981) POMS; 1981). Recall of the Rey 15 forms tested whether recall was appropriate or suggested malingering (Rey, 1964).

Respiratory tests. Respiratory flows and vital capacities were measured from a full inspiration while subjects stood and blew forcefully into a QRS Diagnostic (Venturi) spirometer which was calibrated against the volume displacement (Ohio) spirometer used at Artesia. Their volumes and profiles of flow were equal. All subjects used a nose clip. This maneuver was repeated until two forced expirations agreed within 5% (ATS, 1987). Records of volume and flows were measured by a computer and printed. Prediction equations adjusted for height, age, sex and years of cigarette smoking (Miller et al., 1986).

Statistical analysis

Age, educational level and other factors affecting each function were adjusted for each subject before comparisons were made as percentage predicted of control values. Scores and computed data were entered into an IBM compatible microcomputer. Descriptive and analytical computations adjusted for differences in age, education, sex, height and weight using stepwise linear regression modeling that used Stata Statistical Software (1993; Stata Corporation, College Station, Texas, USA). These prediction equations were based on measurements of functions of 202 subjects. Each was symmetrically distributed (Kilburn et al., 1998) or was transformed mathematically for symmetry before modeling. The observed measurements and scores for each patient were compared to his/her individual predicted values and expressed as percentage predicted. Then the exposed group's percentage predicted values were compared to the control group by analysis of variance (ANOVA) and expressed as p values (other factors such as family income, hours of general anesthesia, POMS score and depression score were tested for influence in regression equations but excluded because their coefficients were not significant). Statistical significance was defined as $p < 0.05$. Complaints of groups of subjects were compared as means of frequencies of 35 symptoms for each subject (Table 1) and means of POMS score compared (Table 4). Abnormalities for each were counted (Table 5) after assigning most bilateral tests, a value of 0.5 per side, for example hearing. Visual scores were 1 per side if 2 or more quadrants had zones of diminished recognition or scotoma, and balance was assigned 1 for the eyes open test and 1 for the eyes closed one. Two exposure variables, duration and latency from exposure to testing and profile of mode states score and depression score were tested for influence on total abnormalities and specific measurements, that is, balance with eyes closed using regression analysis.

Results

Hydrogen sulfide, VOCs, PM_{10}, and $PM_{2.5}$ in Lovington

Analysis of 21 grab samples for H_2S in the waste-treatment plant ranged from 2 to 74 ppm. Levels fell to 12 to 16 ppm when the wind was 25 to 35 mph. Six readings on 11 April 2001 ranged from 12 to 49, median 30 ppm. Near the waste water clarifier readings were 170, 35 in the breathing zone and 15–20 ppm compared to at the outlet. Inside the cab of one worker's pick-up truck, while surveying the sewage in the streets of Lovington, readings were 8–15 ppm and were 6–8 ppm in the WWTP during pump repair. Levels of 20–30 ppm were found in the ambulance

Table 1. Age and education with frequency of symptoms of 26 hydrogen sulfide-exposed subjects compared to 12 Tatum and 11 Artesia who were less exposed and 42 Wickenburg unexposed controls as percentage predicted by analysis of variance (ANOVA)

		A-Lovington exposed ($N = 26$)	B-Tatum–Artesia less exposed ($N = 12 + 11$)	A versus B p values	C-Wickenburg unexposed ($N = 42$)	A versus C p values
	Age	45.9 ± 11.6	49.7 ± 16.6	0.357	48.0 ± 21.7	0.653
	Education	11.2 ± 3.9	12.9 ± 1.9	0.077	12.6 ± 2.3	0.072
	Symptoms					
1.	Skin itch/red	6.9	6.1	0.467	3.2	0.0001
2.	Fingernail change	5.6	2.4	0.003	2.0	0.0001
3.	Chest tightness	5.8	5.0	0.645	2.4	0.0001
4.	Palpitations	5.3	3.3	0.05	2.2	0.0001
5.	Pain or burning in chest	5.3	4.1	0.370	1.8	0.0001
6.	Shortness of breath	6.3	4.6	0.104	3.0	0.0001
7.	Dry cough	5.5	3.9	0.144	2.4	0.0001
8.	Cough with mucous	5.9	4.1	0.122	3.3	0.0002
9.	Cough with blood tinged mucous	2.0	1.3	0.136	1.3	0.009
10.	Tingling navel	2.8	1.2	0.026	1.0	0.0004
11.	Dryness of mouth, nose, throat	7.4	6.1	0.131	3.4	0.0001
12.	Throat irritation	6.5	5.3	0.354	3.0	0.0001
13.	Eye irritation	7.5	5.4	0.022	3.1	0.0001
14.	Reduced sense of smell	6.2	3.8	0.033	2.3	0.0001
15.	Headache	8.0	5.5	0.038	3.9	0.0001
16.	Nausea	4.9	3.1	0.036	2.4	0.0001
17.	Dizziness	6.1	4.7	0.287	2.6	0.0001
18.	Lightheadedness	6.1	4.2	0.150	2.7	0.0001
19.	Unusual exhilaration	4.0	1.3	0.002	1.5	0.0001
20.	Itchy gums	1.8	1.1	0.021	1.2	0.006
21.	Loss of balance	6.5	4.4	0.079	2.3	0.0001
22.	Loss of consciousness	1.9	1.3	0.320	1.1	0.032
23.	Extreme fatigue	9.2	6.9	0.091	3.3	0.0001
24.	Somnolence	6.3	4.1	0.115	2.2	0.0001
25.	Insomnia-can't fall asleep	6.7	3.4	0.002	2.6	0.0001
26.	Insomnia-wake up frequently	7.9	5.1	0.017	2.5	0.0001
27.	Insomnia-sleep soundly, few hours	7.1	4.9	0.021	2.4	0.0001
28.	Irritability	8.1	5.7	0.039	3.1	0.0001
29.	Lack of concentration	8.3	6.5	0.086	3.3	0.0001
30.	Recent memory loss	7.9	6.6	0.263	3.0	0.0001
31.	Long term memory loss	6.3	5.5	0.758	2.5	0.0001
32.	Instability of mood	6.9	4.6	0.075	2.4	0.0001
33.	Decreased libido	7.7	5.0	0.063	2.8	0.0001
34.	Decreased alcohol tolerance	2.3	2.8	0.344	2.4	0.935
35.	Indigestion	6.0	5.8	0.745	3.5	0.0008
36.	Loss of appetite	4.4	2.8	0.058	2.6	0.007
37.	Stomach swells or is bloated	6.8	5.7	0.414	2.6	0.0001
Frequency of symptoms-mean		6.0	4.3	0.018	2.6	0.0001

transporting one worker to the hospital. Callaway Safety Equipment Co., Hobbs, New Mexico, on 24 July 2002 reported H_2S concentrations taken with a Draeger pump and tubes in the waste treatment facility as follows: (1) primary clarifier output (170 ppm) and breathing zone (35 ppm); (2) downwind of outlet box by 10 feet (20 ppm) and (3) air surrounding primary clarifier (2–3 ppm). The H_2S alarm at the waste-treatment plant was set to go off at 10 ppm. The alarms at the waste treatment plant were ordered silenced during the night because too many residents in the area complained of lost sleep.

Table 2. Neurophysiological and neuropsychological functions of 26 hydrogen sulfide-exposed subjects compared to 42 Wickenburg controls as percentage predicted by analysis of variance (ANOVA)

Measurement	Exposed (Lovington; $N \leq 26$)	Unexposed (Wickenburg; ($N \leq 42$)	p Values
Simple reaction time	106.6 ± 6.7	99.8 ± 3.8	0.0001
Choice reaction time	104.4 ± 4.8	100.8 ± 2.8	0.0002
Balance sway speed			
Eyes open	209.4 ± 115.6	108.9 ± 35.0	0.0001
Eyes closed	263.7 ± 162.6	114.1 ± 30.8	0.0001
Blink reflex latency R-1*			
Right	106.6 ± 17.3	106.1 ± 12.0	0.856
Left	104.8 ± 44.9	95.0 ± 15.1	0.394
Color discrimination errors			
Right	63.4 ± 55.3	71.0 ± 44.4	0.519
Left	70.1 ± 62.0	77.5 ± 48.8	0.585
Visual field performance*			
Right	100.6 ± 30.9	97.0 ± 15.7	0.603
Left	99.9 ± 43.5	97.3 ± 17.5	0.763
Visual field score	5.3 ± 2.8	1.2 ± 1.9	0.0001
Hearing			
Right	126.2 ± 41.4	97.0 ± 15.4	0.0001
Left	126.4 ± 41.4	97.7 ± 18.1	0.0002
Grip strength			
Right	64.2 ± 20.1	93.5 ± 21.7	0.0001
Left	65.3 ± 23.5	97.5 ± 17.7	0.0001
Psychological cognitive			
Culture Fair	83.1 ± 23.2	113.6 ± 27.7	0.0001
Digit symbol	87.7 ± 13.7	94.8 ± 8.7	0.011
Vocabulary	60.4 ± 26.0	102.7 ± 34.2	0.0001
Verbal recall			
Immediate	61.1 ± 26.3	98.1 ± 28.1	0.0001
Delayed	48.2 ± 37.7	95.0 ± 41.0	0.0001
Attention/Coordination			
Peg placement	74.4 ± 28.5	100.3 ± 23.1	0.0001
Trail making A	108.6 ± 16.6	98.5 ± 7.2	0.001
Trail making B	107.2 ± 8.9	110.3 ± 7.9	0.002
Finger writing errors – right	110.2 ± 10.5	98.0 ± 9.7	0.0001
Finger writing errors – left	111.3 ± 10.7	98.9 ± 9.8	0.0001
Long-term memory			
Information	56.0 ± 67.7	111.8 ± 35.0	0.0001
Picture completion	67.6 ± 44.0	107.5 ± 34.9	0.0001
Similarities	63.5 ± 37.2	105.4 ± 33.6	0.0001

*$p < 0.05$.

One incident involved a rupture of a natural gas pipeline. The H_2S at the site measured 480 ppm. One worker experienced a knockdown and was transported to the local hospital emergency room (E.R.). In the E.R., when his contaminated clothes were placed in a plastic bag with his H_2S monitor attached, the alarm set at 10 ppm went off.

The wife of one of the WWTP workers described her husband's H_2S monitor going off after work clothing was placed in the family clothes hamper. Two wives often held flashlights in the WWTP and in the field, while husbands did emergency repairs on the pumps. The 18 towns' people tested did not live in the immediate vicinity of the sewer plant, cheese factory or refineries but often detected rotten eggs smell day and night.

Review of the Score Card and U.S.E.P.A.TRI data revealed two major contributors to waste in

Table 3. Neurophysiological and neuropsychological functions of 26 hydrogen sulfide-exposed subjects compared to 23 New Mexico 'oil patch' people: 12 Tatum and 11 Artesia as percentage predicted by analysis of variance (ANOVA)

Measurement	Exposed Lovington ($N \leq 26$)	Lesser exposed Tatum–Artesia ($N \leq 23$)	p Values
Simple reaction time	106.6 ± 6.7	100.5 ± 5.0	0.001
Choice reaction time	104.4 ± 4.8	100.9 ± 3.1	0.004
Balance sway speed			
Eyes open	209.4 ± 115.6	129.9 ± 52.4	0.004
Eyes closed	263.7 ± 162.6	135.2 ± 46.4	0.001
Blink reflex latency R-1*			
Right	106.6 ± 17.3	112.6 ± 8.7	0.353
Left	104.8 ± 44.9	117.7 ± 2.3	0.394
Color discrimination errors			
Right	63.4 ± 55.3	82.0 ± 48.2	0.219
Left	70.1 ± 62.0	87.2 ± 48.7	0.292
Visual field performance*			
Right	100.6 ± 30.9	97.0 ± 15.7	0.603
Left	99.9 ± 43.5	97.3 ± 17.5	0.763
Visual field score	5.3 ± 2.8	3.4 ± 2.2	0.042
Hearing			
Right	126.2 ± 41.4	105.8 ± 21.7	0.119
Left	126.4 ± 41.4	109.8 ± 11.4	0.183
Grip strength			
Right	64.2 ± 20.1	97.6 ± 15.8	0.0001
Left	65.3 ± 23.5	98.8 ± 17.4	0.0001
Cognitive			
Culture Fair	83.1 ± 23.2	99.9 ± 22.5	0.014
Digit symbol	87.7 ± 13.7	99.6 ± 8.2	0.001
Vocabulary	60.4 ± 26.0	88.5 ± 26.0	0.001
Verbal recall			
Immediate	61.1 ± 26.3	89.5 ± 26.7	0.001
Delayed	48.2 ± 37.7	84.9 ± 31.6	0.001
Attention/Coordination			
Peg placement	74.4 ± 28.5	101.1 ± 21.6	0.001
Trail making A	108.6 ± 16.6	95.9 ± 19.2	0.016
Trail making B	107.2 ± 8.9	98.4 ± 9.6	0.016
Finger writing errors – right	110.2 ± 10.5	105.0 ± 9.0	0.071
Finger writing errors –left	111.3 ± 10.7	105.2 ± 7.5	0.029
Long-term memory			
Information	56.3 ± 67.7	71.1 ± 32.0	0.332
Picture completion	67.6 ± 44.0	88.7 ± 39.3	0.085
Similarities	63.5 ± 37.2	72.6 ± 27.3	0.340

*$p < 0.05$.

Lovington were the cheese/whey manufacturer and the local refinery. The waste from the cheese/whey plant was eventually placed into onsite ponds that became anaerobic, releasing malodorous H_2S. No measurements were possible since the property was fenced and private. The refinery had air releases of VOCs from 1994 to 2002, ranging from 24,900 to 30,500 pounds per year. For the year 2002, the total released neurotoxins were 30,043 pounds per year. Lovington zip code (88260) for 1999 showed total air emissions of BTEX, cyclohexane, *n*-hexane and naphthalene of 17,814 lbs/year for all industrial facilities. In contrast, contribution to VOCs in Lea County from internal combustion engines, industrial petroleum and solvent evaporation was estimated at 285.85 tons in 1999. The 24-hour average for PM_{10} and $PM_{2.5}$ for Lea County were 36 and 7 $\mu g/m^3$ for the same period

Table 4. Profile of mood states (POMS) of 26 hydrogen sulfide-exposed subjects compared to 12 Tatum and 11 Artesia controls and 42 Wickenburg controls

	26 A Lovington exposed	23 (12 + 11) B Tatum–Artesia unexposed	B versus C p^2 values	42 C Wickenburg unexposed	A versus C p^1 values	A versus B p^3 values
POMS score	99.4 ± 65.0	55.9 ± 47.8	0.0001	27.8 ± 27.9	0.007	0.006
Tension	20.0 ± 9.9	14.9 ± 8.5	0.0001	10.4 ± 6.3	0.045	0.025
Depression	29.4 ± 19.3	14.8 ± 13.4	0.0001	10.0 ± 8.6	0.003	0.129
Anger	24.1 ± 15.9	12.8 ± 10.1	0.0001	8.4 ± 5.0	0.004	0.033
Fatigue	20.6 ± 8.2	15.8 ± 8.7	0.0001	9.2 ± 5.7	0.043	0.001
Vigor	9.7 ± 7.5	13.0 ± 7.3	0.0001	17.2 ± 6.1	0.057	0.010
Confusion	15.0 ± 8.7	10.1 ± 6.2	0.0001	7.1 ± 4.0	0.018	0.020
Frequencies of symptoms	6.0 ± 2.2	4.3 ± 1.7	0.0001	2.6 ± 0.9	0.002	0.0001

Table 5. Prevalence of neurobehavioral abnormalities in 26 hydrogen sulfide-exposed Lovington compared to 12 Tatum and 11 Artesia 'controls' and 42 Wickenburg referents

Tests	26 Lovington mean	23 (12 + 11) Tatum–Artesia mean	42 Wickenburg mean
Verbal recall – delayed	77	26	17
Visual field score	77	69[a]	17
Balance eyes closed	73	65[a]	30
Grip – right	72	9	10
Grip – left	72	9	5
Fingertip number writing – right	69	26	17
Balance – eyes open	69	48[a]	20
Information	69	39[a]	7
Verbal recall – immediate	65	22	17
Peg placement	65	13	11
Reaction time – simple	62	4	13
Reaction time – choice	62	26	24
Fingertip number writing – left	62	30	20
Vocabulary	60	36[a]	13
Trail making B	58	9	22
Hearing – left	54	33	14
Color discrimination – right	54	35	28
Picture completion	50	43	17
Color discrimination – left	46	35	35
Digit symbol	46	13	33
Culture Fair	44	26	7
Trail making A	42	17	9
Hearing – right	31	17	7
Similarities	31	30[a]	17
Total abnormalities mean ± SD	11.8 ± 6.1	3.6 ± 2.8	2.0 ± 2.0

[a] Six measurements that are not different.

of time. Score Card rated the air quality in Lea County as good for 95% of the days of 1999.

Hydrogen sulfide, VOCs and PM_{10}, $PM_{2.5}$ in Tatum

The 12 Tatum subjects occasionally smelled H_2S in their community but concentrations were about the Draeger tube threshold of 0.02 ppm. Tatum was in the same sour gas/oil field as Lovington with a desulphurization plant approximately 16 km away. Tatum is 32 km north of Lovington at the juncture of highways 380 and 206. In addition, one of the authors had driven east on Highway 380 in the daylight when few wells were pumping and west in the evening, 7:30 p.m. At dusk, most wells were pumping. The automobile was clean in the daylight hours but covered with black oily slick at dusk and the windshield had to be cleaned. An odor of petroleum was detected. Tatum zip codes 88213 and 88261 showed no data for TRI on-site and off-site disposal or release for chemicals. Therefore, the only data for VOCs, PM_{10} and $PM_{2.5}$ are those for Lea County as described for Lovington.

Hydrogen sulfide, VOCs, PM_{10} and $PM_{2.5}$ in Artesia

The 11 Artesia subjects complained of H_2S odor from an oil refinery located near the center of town that completed refining petroleum products from the Lovington refinery. Spot samples measured using Draeger tubes (0.2 ppm sensitivity) failed to detect H_2S in the early evening hours. However, the testing team detected the odor of H_2S in the early morning hours, suggesting nighttime release of chemicals. In addition, the State of New Mexico Environment Department on 18–22 March 2002 tested for H_2S and reported daytime levels of 1 to 1600 ppb from spot sampling coming from two Artesia refineries. Values ranged from 0 to 14 ppb (Dubyk and Mustafa, 2002).

Review of Score Card U.S.E.P.A. data TRI revealed that the two major contributors of VOCs for the city of Artesia were Navajo Refinery (1374 tons/year) and GPM Gas (90 tons/year). Information on total air releases was not available for GPM Gas, while Navajo refinery air releases ranged from 62,660 to 254,826 lbs/year from 1988 to 2002. Neurotoxin releases totaled 148,976 lbs in 2002. The total emissions of VOCs (BTEX, trimethylbenzene, cresol, cumene, cyclohexane, *n*-hexane, naphthalene and Trichloroethylene for the year 1999 was 164,351 lbs for Artesia (zip code 88210). There was no TRI data for zip code 88211 for PM_{10} and $PM_{2.5}$ for Eddy County. When compared to Lea County, the total releases for Eddy County were 13% greater for PM_{10} and 51% greater for $PM_{2.5}$ but not exceeding NAAQS acceptable 24-hour averages. The Score Card rating for air quality showed good for 98% of year for Eddy County.

Hydrogen sulfide VOCs, PM_{10} and $PM_{2.5}$ in Wickenburg, AZ

Search of the Score Card and U.S.E.P.A. records for Wickenburg, AZ (zip codes 85358 and 85390) revealed no data for TRI on-site and off-site chemicals by all industries for 1999.

Age, education and symptoms

The approximate population of each town were Lovington (9000); Tatum (800), Artesia (10,000) and Wickenberg, Arizona (5000). The mean ages of each group were similar with a wide range, 17 to 83 (Table 1). Educational attainment, years of school completed were not significantly different. Means were Lovington (11), Tatum (12.1), Artesia (13.7) and Wickenburg (12.6).

Pulmonary symptoms and function

The frequency of chest tightness, chest burning, shortness of breath, cough with mucus, blood tinged mucus and throat irritation in Lovington as compared to the Wickenburg groups were significantly elevated ($p <$ 0.0001–0.0002, Table 1). Lovington and the Tatum–Artesia groups showed the same symptoms were not significantly different (Table 1) but Tatum–Artesia group compared to the Wickenburg unexposed group was significantly different (data not shown).

Comparison of pulmonary function of Lovington subjects with Wickenburg subjects showed decreased $FEF_{75\text{-}85}$ and decreased FEV_1/FVC, signs of small airways obstruction. The small differences between the 26 Lovington subjects and 23 Tatum–Artesia subjects were not significant (data not shown). Comparison of the Tatum–Artesia group to Wickenburg subjects revealed a significantly greater increase in small airway obstruction, that is, decreased $FEF_{75\text{-}85}$. Wheezing, shortness of breath at rest, while walking and when climbing stairs were significantly more frequent in Lovington adults than in the unexposed adults from Wickenburg. Alveolar alcohol levels were all zero and the few elevated carbon monoxide levels were appropriate for subject's cigarette smoking for both exposed groups.

There were no significant differences in the frequency of symptoms in the Tatum and the Artesia participants (data not shown), allowing them to be combined as a single group, Tatum–Artesia for comparisons. The frequencies of the 35 symptoms (on a 10-point scale) was greatest for the Lovington subjects (mean 6.0) followed by the Tatum–Artesia group (mean 4.3) and the Wickenburg reference group (mean 2.6), Table 1. The differences were significant as follows: Lovington versus Tatum–Artesia groups ($p < 0.018$), Lovington versus Wickenburg groups ($p < 0.0001$) and Tatum–Artesia versus and Wickenburg groups ($p < 0.0001$). Lovington people had 34 of 35 symptoms more frequent than Wickenburg subjects. Of 35 symptoms, 13 were more frequent in Lovington people versus the Tatum– Artesia group. Only 'decreased alcohol tolerance' was not different. Lovington and Tatum–Artesia groups had higher respiratory, neurological and limbic symptoms than unexposed, Wickenburg people and differed in neurophysiological and neuropsychological impairments and POM scores.

The only psychiatric diagnosis was depression and it was no more frequent in Lovington subjects than in the Wickenburg group and use of tranquilizer-anti-depressant drugs was similar. Occupational and domestic chemical exposures were similar among the three groups (data not shown).

Neurophysiological and neuropsychological functions

Compared to Wickenburg controls, neurophysiological test scores for Lovington people (Table 2) were significantly different for simple reaction times (SRTs) and choice reaction times (CRTs), balance-sway speed with eyes open and with eyes closed, visual field score, hearing and grip strength ($p < 0.0001$). In addition, cognitive functions: Culture Fair, digit symbol substitution, vocabulary and verbal recall (immediate and delayed); Attention/Coordination: peg placement, trail making A and B and finger writing errors right and left were significantly decreased. Also long-term memory (information, picture completion, similarities) were all significantly decreased in the Lovington compared to the Wickenburg groups (Table 2). Blink reflex latency (right and left), color discrimination errors (right and left), and visual field performance (right and left) were not significantly different. (Asterisks after blink reflex and visual field performance reflect values for the 8 initial subjects.)

Comparison of Lovington to Tatum–Artesia groups (Table 3) show significant differences: SRTs and CRTs ($p < 0.001$ and 0.004, respectively); balance sway speed with eyes open ($p < 0.004$) and closed (p 0.001); grip strength right ($p < 0.001$ and left ($p < 0.001$). Cognitive functions significantly different were Culture Fair ($p < 0.014$); digit symbol substitution ($p < 0.001$); vocabulary ($p < 0.001$) recall memory, verbal recall immediate ($p < 0.001$) and delayed ($p <0.001$); and the measures for Attention/Coordination – peg placement ($p < 0.001$), trail making A ($p < 0.016$ and B ($p < 0.016$) and left fingertip number writing ($p < 0.029$). The long-term memory dysfunctions (information, picture completion and similarities) in the Tatum–Artesia group in comparison to the Lovington group were not different (Table 3).

A comparison between the Tatum–Artesia and Wickenburg groups was also done (data not shown). The significant differences between the two groups were balance (sway speed) with eyes open ($p <$ 0.021) and closed ($p < 0.014$); left blink reflex latency ($p < 0.001$); hearing right ($p < 0.09$) and left (0.034; one cognitive function, digit symbol substitution differed ($p < 0.016$) Attention/Coordination right and left fingertip number writing errors differed by $p < 0.005$ and 0.013, respectively; and long-term memory, information differed by $p < 0.001$ and similarities by $p < 0.001$. Thus, the Tatum–Artesia group was impaired in several functions, but not as severely as of the Lovington group

Three Lovington children aged 5, 7 and 11 had total abnormality scores of 7, 7 and 8, which indicated CNS impairment.

Profile of mood states

The scores of the Lovington group 99.4 ($p < 0.007$) and Tatum–Artesia group 55.9 ($p < 0.001$) were different from the Wickenburg controls of 27.8 (Table 4), Lovington ($p^2 < 0.007$) and Tatum–Artesia ($p^1 < 0.001$). Lovington versus Wickenburg had significant differences for all six moods. Significant differences for tension, vigor, anger, confusion and fatigue but not for depression ($p < .129$) were found for the Lovington versus the Tatum–Artesia comparison. Comparison of the Tatum–Artesia group to the Wickenburg controls showed significant differences for POMS score ($p < 0.007$); tension ($p < 0.045$); depression <0.003; anger $p < 0.004$; fatigue ($p <$ 0.043); confusion ($p < 0.018$) but not vigor ($p <$ 0.057). The POMS scores paralleled differences in neurophysiological-neuropsychological testing. The Tatum–Artesia group was different from the Wickenburg controls but less so than the Lovington group.

Prevalence of neurobehavioral abnormalities

The relative number of abnormal scores, as percentages of the exposed and control groups, showed differences for 18 tests (Table 5), only six were not different. At the top of the list are verbal recall delayed, grip strength, visual field score, balance eyes open and closed that were abnormal for the greatest number of exposed people and are the most sensitive indicators of exposure applicable to both New Mexico groups. Also, information, vocabulary and picture

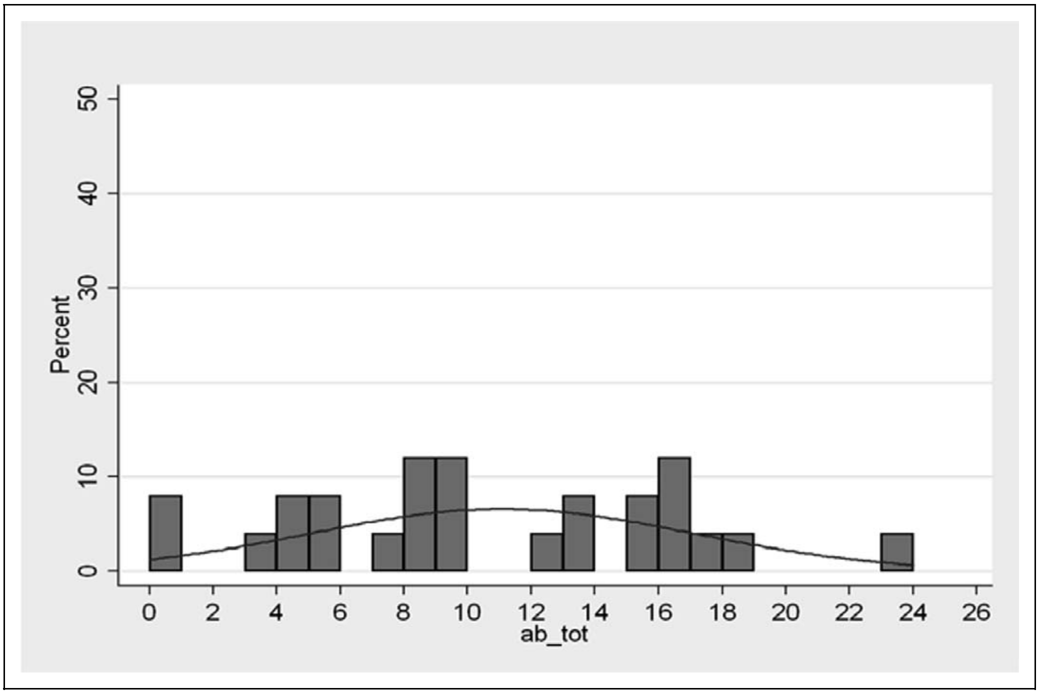

Figure 1. Individual abnormality frequencies in 26 Lovington adults exposed, mean 11.8 and symmetrically distributed.

completion were abnormal in over 50% of Lovington subjects. As these three tests reflect well embedded, multi-factorial memory that has been least susceptible to reduction by chemical exposure (Ryan et al., 1987, Kilburn 2002), it shows the high impact of the Lovington exposures.

Occupational exposures that could have adversely influenced neurobehavioral function were uncommon in Lovington adults (0 to 19.2%) and not different from reference Wickenburg subjects (0 to 16.7%) so had little likelihood of affecting the outcome.

Comparison of eight initial Lovington subjects

The eight original Lovington subjects (five workers, three wives) were retested and the test results were compared to their initial scores (Table 6). Six of the subjects were retested at 16 months and two at 3 months following the initial testing. The retest showed a statistically significant greater degree of abnormality for balance with eyes open ($p < 0.016$), visual field score ($p < 0.001$), hearing on the left ($p < 0.047$), peg placement ($p < 0.045$) and right and left finger writing errors ($p < 0.006$ and 0.001, respectively). These data suggested deterioration of function with increased exposure.

Comparison of neurobehavioral abnormalities of each group

Neurobehavioral abnormalities totaled 11.8 in Lovington and were distributed symmetrically (Figure 1). Tatum–Artesia, shown in Figure 2, were also distributed symmetrically while in the 2.0 in Wickenburg, Figure 3, the distribution was skewed to the left, which was typical of unexposed people (Table 7) and differences were statistically significant. POMS score means 99.4, 57.8 and 27.8 and frequency of symptoms means 6.0, 4.3 and 2.6 paralleled the neurobehavioral abnormalities and fit a hierarchy from Wickenburg as a reference normal.

Discussion

The TRI data revealed five differences in the rural communities. **Number 1:** Lovington, Tatum and Artesia are in the sour gas/oil field of Southern and New Mexico that has air concentrations of H_2S up to 1600 ppb with daily averages of 0–14 ppb (Dubyk Mussafa 2002). In contrast, rural Wickenburg probably has a background of this chemical equivalent to the U.S. averages of 0.02 to 0.07 ppb; **Number 2:** the towns of S.E. New Mexico contain natural gas and oil fineries that emit VOCs, including neurotoxins, while

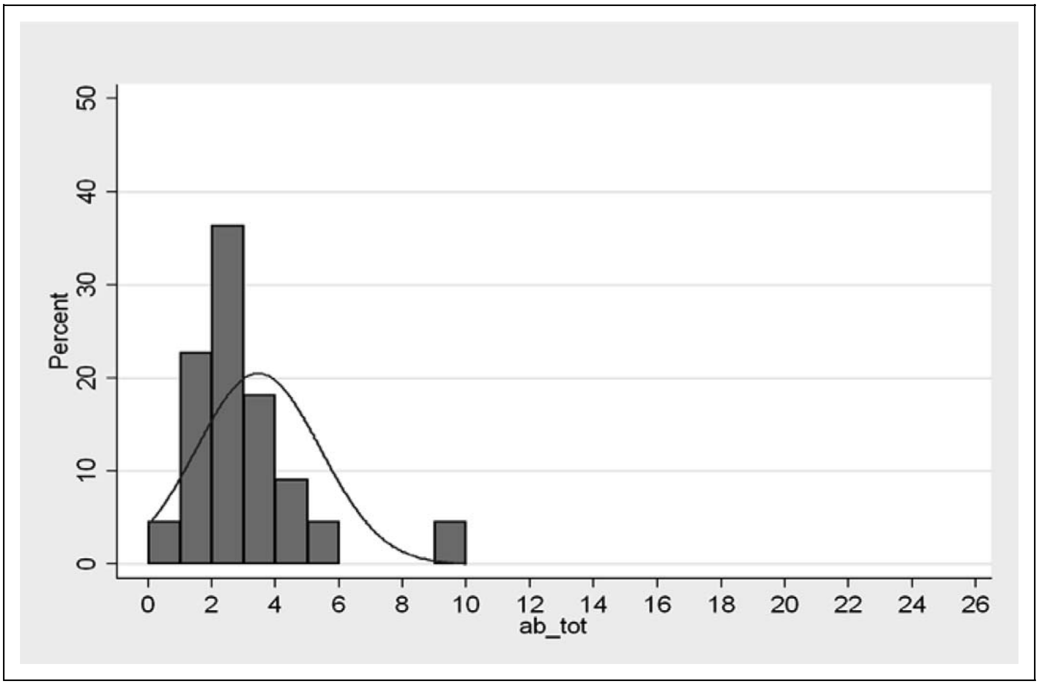

Figure 2. Individual abnormality frequencies in 23 Tatum–Artesia adult controls, mean 3.6 with the distribution skewed to the left.

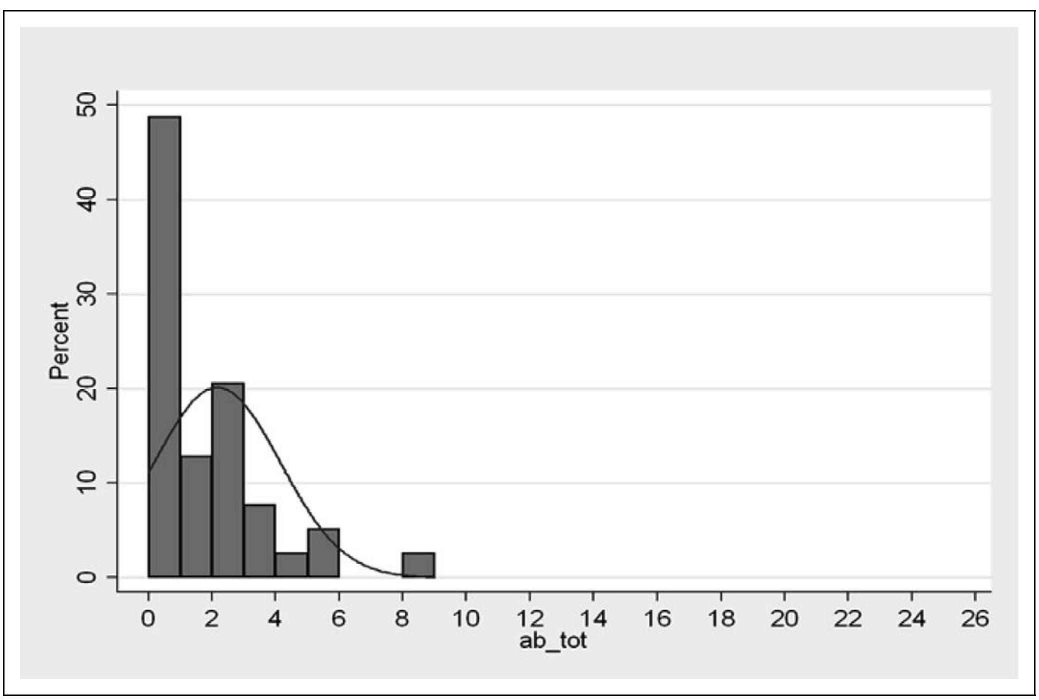

Figure 3. Individual abnormality frequencies in 42 Wickenburg three adult controls, mean 2.0 with the distribution skewed to the left.

Wickenburg without these and other industries that release reportable TRI toxins. The quantities of released VOC are greater for Artesia when compared to Lovington and possibly Tatum; **Number 3:** Lovington differed from the other three communities in that it experienced anaerobic conditions of it WWTP for several years before our testing. In addition, spot testing in 2002 demonstrated concentrations of H_2S at various locations

Table 6. Neurophysiological and neuropsychological functions of 8 hydrogen sulfide exposed subjects before compared to after 15 months as percentage predicted by analysis of variance (ANOVA)

	Exposed (3 f/5 m)	Retest	*p* Values
Age (years)	46.6 ± 2.3	47.3 ± 2.2	0.589
Educational level (years)	9.4 ± 3.1	9.4 ± 3.1	1.000
Simple reaction time	109.7 ± 6.6	112.6 ± 6.3	0.385
Choice reaction time	106.1 ± 4.0	108.4 ± 5.7	0.356
Balance sway speed			
Eyes open	185.8 ± 86.0	322.2 ± 110.9	0.016[a]
Eyes closed	378.9 ± 206.8	401.4 ± 113.5	0.791
Blink reflex latency R – 1			
Right	106.6 ± 17.3	(112.6 ± 8.7)	0.353
Left	104.8 ± 44.9	(117.7 ± 2.3)	0.394
Color discrimination errors			
Right	20.9 ± 18.6	18.4 ± 26.9	0.833
Left	24.4 ± 21.8	18.5 ± 19.0	0.572
Visual field performance			
Right	100.6 ± 30.9	97.0 ± 15.7	0.603
Left	99.9 ± 43.5	97.3 ± 17.5	0.763
Visual field score	2.3 ± 3.6	7.8 ± 0.7	0.001[a]
Hearing			
Right	133.7 ± 33.8	172.5 ± 45.4	0.073
Left	121.2 ± 33.8	166.1 ± 47.5	0.047[a]
Grip			
Right	73.1 ± 26.5	55.2 ± 27.8	0.209
Left	72.8 ± 32.4	52.6 ± 30.6	0.222
Cognitive			
Culture Fair	77.2 ± 22.9	70.5 ± 23.2	0.576
Digit symbol	76.2 ± 15.6	74.4 ± 16.2	0.827
Vocabulary	39.9 ± 24.2	43.1 ± 27.0	0.808
Verbal recall			
Immediate	60.0 ± 30.7	52.2 ± 17.0	0.541
Delayed	34.6 ± 27.1	23.1 ± 15.6	0.318
Attention/Coordination			
Peg placement	69.7 ± 21.1	50.2 ± 13.4	0.045[a]
Trail making A	114.6 ± 13.1	120.6 ± 19.5	0.483
Trail making B	107.4 ± 10.2	111.5 ± 6.3	0.348
Finger writing errors – right	105.5 ± 6.3	117.6 ± 4.4	0.0006[a]
Finger writing errors – left	106.1 ± 3.7	120.8 ± 4.5	0.0001[a]
Long-term memory			
Information	50.6 ± 26.3	38.4 ± 23.1	0.341
Picture completion	60.1 ± 42.9	56.7 ± 44.3	0.878
Similarities	62.6 ± 42.4	39.2 ± 30.0	0.223

[a] $p < 0.05$ or less after interval so that three measurements showed deterioration in 15 months or less.

from 2 to 480 ppm and prior to this the WWTP H_2S monitor and alarm were ordered silenced; (4) the daily air quality in the S.E. New Mexico communities was good for 95% to 98% of the year and (5) the release of VOCs was considerably greater in Artesia as compared to Lovington and Tatum. Thus, the residents of Wickenburg are considered a good reference population for comparison to communities that have potential air quality problems. The differences in the neurological and symptom patterns between Lovington and Tatum–Artesia are interpreted as resulting from an anaerobic condition of the Lovington WWTP from cheese whey that led to a contamination of the community with sewage. Finally, the neurological deficits observed in Lovington

Table 7. Total neurobehavioral abnormalities, profile of mood states (POMS) scores and symptom frequencies compared for people in the three sites

Site/Number	Total abnormalities (mean ± SD)	POMS (mean ± SD)	Frequency of symptoms mean ± SD
Wickenburg 42	2.0 ± 2.0	27.8 ± 27.9	2.6 ± 0.9
Artesia-Tatum 11-12	3.6 ± 2.8	51.8 ± 44.4	4.3 ± 1.7
Lovington 26	11.8 ± 6.1	99.4 ± 65.0	6.0 ± 2.2

and Tatum–Artesia were most likely caused by low level concentrations of H_2S rather than VOCs because the Artesia residents had the fewest abnormalities when compared to the Lovington and Tatum residents.

The Lovington people tested showed neurobehavioral impairment that was associated with airborne exposure to H_2S and other gases from oil refineries and sewage treatment. Greater impairment in Lovington subjects compared to those in Artesia 104 km away and Tatum at 32 km was consistent with measurements of H_2S concentrations. Tatum area spot samples were less than 0.2 ppm. Artesia samples were 0–2 ppm daytime, but 6–15 ppm from 12 p.m. to 4 a.m. Lovington ranging from 10 upward to probable spikes of 300 to 600 ppm is deduced from sewer workers being knockeddown (H_2S levels of 300 ppm and greater cause unconsciousness called knockdown; Kilburn 1997; Tvedt, Edland et al., 1991) Full characterizations need additional sampling at Tatum and Lovington.

These neurotoxic effects were more severe, averaging 11.8 abnormalities that exceeded the 9.2 found in 9 women and 10 men previously studied after occupational exposure to H_2S (Kilburn 1997). Their average impairment clearly exceeded that found in earlier studies of environmental exposure, 5.8 abnormalities (mean) in people exposed to waste lagoons from cattle hair removal in Nebraska, 4.3 in people near hog enclosure lagoons in Ohio and 8.8 in neighbors of sewer lift stations in Texas (personal observations, manuscripts submitted for publication).

The consistent findings in these three groups implied that environmental exposures to H_2S by living near one or several sources for years impairs neurobehavioral function, disturbs moods and increases frequencies of symptoms. Symptom frequencies were elevated in all eight categories: irritative, indigestion, respiratory, moods, sleep, balance, memory and limbic system. The absence of impairment of hearing, visual field performance and blink reflex latency was consistent with other groups environmentally exposed to H_2S (Kilburn, 1997; Kilburn, 1999; Kilburn, 2003; Kilburn and Warshaw, 1995a,). Impaired color discrimination and visual field score that measured of areas of decreased vision, which is scotoma, have been more sensitive to H_2S than is visual field performance (Kilburn, 1999). Two tests that measured well-entrenched, redundant memory were abnormal in more than 50% of subjects and one similarities score was reduced in 31%, indicating severe impairment (Ryan et al., 1987)

Strengths and limitations

Neurobehavioral impairment was associated with a community exposure thought to have peaked when sewers malfunctioned. Continuous exposure is postulated from the odor and spot sample data. Further exposure monitoring in the community and the refinery, sewer plant and other sources would quantify doses and contributions. To do this needs area sampling for H_2S indoors and outdoors for several months of exposure using a community network. Multiple recording samplers, running continuously for several days of different seasons, characterized zones of exposure in Dakota City NE (Kilburn 1999 and personal observation, manuscripts in preparation). When coupled with a daily wind rose and data collected for typical summer and winter conditions, reasonable estimates can be made. Much more data monitoring exposures and effects are needed. Peak concentrations were hard to relate to people's doses and there is no biological marker such as provided by blood lead level nor a specific sensor of H_2S effect. It appears that neurobehavioral impairments (abnormalities) are the best sensor marker. Unfortunately, it does not discriminate between effects of an acute exposure 100 ppm versus years of exposure at doses below 5 ppm. Duration of low exposure (below 10 ppm, the OSHA occupational standard) does not predict impairment (Kilburn, 1999). This dilemma is not peculiar to H_2S but applies to other gases: ammonia, chlorine and carbon monoxide (Kilburn, 1999).

A multiple recording sampler strategy applied in Lovington should sort out the relative contributions of the cheese factory and its lagoons, Navajo refinery, Davis refinery and the city sewer-treatment plant. These contributions would be needed to apportion responsibility for damage to the people in the several sectors of town. Because stopping releases completely is the objective, further measurements may be unnecessary and misleading.

The worsening function of the eight subjects after 16 months demonstrated serious permanent impairment. It appeared to be progressive in five workers and three wives who had continuing community exposure. Temporary effects from the Lovington environment, an intoxication cannot be excluded, because Tatum people were tested in Lovington 21 August 2004 at the same time as the 26 Lovington exposed people. Past community studies have not sought temporary or transient effects and brief human exposures to 5 to 10 ppm looked for pulmonary (Bhambhani et al., 1996) and cardiovascular effects (Bhambhani et al., 1997) but not sensitive neurobehavioral effects (Kilburn 1999; Feidler et al., 2008). So answering questions of permanence versus reversibility awaits further studies. Studies of children from Lovington compared to a clean community would help to define these effects.

The brain has been examined only a few times by computerized tomography after H_2S-induced encephalopathy. The pattern consists of lesions of the basal ganglia and white matter (Gaitonde et al., 1987) and of the lentiform nucleus on both sides (Matsuo et al., 1979). The pattern has been interpreted as resembling infarction and attributed to hypoxia and hypotension (Matsuo et al., 1979, De Reuck and Vender Eecken, 1978). Magnetic resonance imaging of people with severe functional impairments may help resolve this issue. Rats exposed by inhalation to 30 or 80 ppm H_2S for 7 days a week for 10 weeks lost olfactory neurons and had basal cell hyperplasia in the nose that would help explain human dysosmia and anosmia (Brenneman et al., 2000). More information is needed. Mechanisms for impaired brain function and brain damage include interference with electron transfer (Truong et al., 2006) and with sodium currents in the neurons (Warenycia et al., 1989) and overloading of the H_2S neurotransmitter that has been suggested to be the brain's third gaseous signaling system (Wang 2002). Also, rats exposed to H_2S showed cumulative effects on cytochrome oxidase and on the basal ganglion function (Savolainen et al., 1980). Abnormalities in monoamine levels and morphology have been described in rats exposed in utero to H_2S (Roth et al., 1995; Skrajny et al., 1992). Cattle confined in pens above manure pits died and necropsies of two euthanized steers revealed massive diffuse cerebral cortical laminar necrosis and edema (Hooser et al., 2000). Lesions of polioenephalomalacia were produced in calves fed with added sodium sulfate and other sulfur-yielding chemicals and attributed to producing excessive H_2S in the rumen (Gould et al., 1991).

The ambient exposure recommendation circulating for comment from the United States Environmental Protection Agency for H_2S is 0.01 ppm (toxicological profile). Clearly, this odorous gas harms brain function, hence inhalation must be avoided when it is detected by the human nose. Human subjects may be exposed from many sources such as natural gas and petroleum, animal wastes, chemical synthesis and sewer gas. The precautionary principle recommends that smelling this gas is a warning that should be heeded by people to evacuate quickly.

Conflict of Interest

None

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