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Worker Exposure to Volatile Organic Compounds in the Vehicle Repair Industry

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This study evaluated exposures among vehicle repair technicians to hexane, acetone, toluene, and total volatile organic compounds (VOCs). On randomly selected workdays, we observed a characteristic pattern of solvent use among 36 technicians employed in 10 repair shops, each of which used an aerosol solvent product. We obtained quantitative exposure measurements from a subset of nine technicians (employed in three of these shops) who used an aerosol product containing hexane (25–35%), acetone (45–55%), and toluene (5–10%). The time-weighted average (TWA) exposure concentration for task-length breathing zone (BZ) samples ($n = 23$) was 36 mg/m^3 for hexane, 50 mg/m^3 for acetone, and 10 mg/m^3 for toluene. The TWA area concentrations ($n = 49$) obtained contemporaneously with BZ samples ranged from 25% to 35% of the BZ concentrations. The solvent emission rate (grams emitted/task time) was correlated with the total VOC exposure concentration ($R^2 = 0.45$). The proportions of VOCs in the BZ samples were highly correlated ($r = 0.89$ to 0.95) and were similar to those of the bulk product. Continuous exposure measurements for total VOCs ($n = 1238$) during 26 tasks produced a mean BZ VOC "pulse" of 394 mg/m^3 within 1 min following initiation of solvent spraying. The geometric mean air speed was 5.2 meters/min in the work areas ($n = 870$) and was associated with 0.8 air changes per minute in the BZ. The findings suggest that vehicle repair technicians who use aerosol solvent products experience episodic, inhalation exposures to the VOCs contained in these products, and the proportions of VOCs in the breathing zone are similar to those of the bulk product. Because acetone appears to amplify the severity and duration of the neurotoxic effects of n-hexane, products formulated with both hexane and acetone should be avoided. Further evaluation of exposures to VOCs is needed in this industry, along with information on effective alternatives to aerosol solvent products.

Keywords automotive repair, exposure assessment, hexane, organic solvents, volatile organic compounds

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INTRODUCTION

Repair and maintenance of the mechanical function of automobiles and trucks is typically a solvent-intensive process that is performed without the benefit of engineering controls or respiratory protection; the nature of solvent exposures among workers in this industry, however, has yet to be investigated.(1) A recent case report described three vehicle repair technicians with symptoms of peripheral neuropathy that resulted from their use of an "aerosol" brake cleaning product formulated primarily with hexane, acetone, and toluene.(2) These products are commercially available and consist of disposable, pressured cans containing 400 to 600 grams of mixed organic solvents.

During the period 1990 to 2002, aerosol products containing hexane, acetone, and toluene were used extensively in the vehicle repair industry. Commercial-grade hexane is a mixture of isomers, of which 20–80% consists of the neurotoxic isomer n-hexane.(3–6) Exposure to n-hexane can produce symptoms of peripheral neuropathy. Products formulated with both hexane and acetone are of particular concern because the severity and duration of the neurotoxic effects of n-hexane appear to be amplified by acetone.

The present study was undertaken to characterize general worker practices with respect to the use of aerosol solvent products and to quantify exposures to hexane, acetone, and toluene during typical vehicle repair tasks. Thirty-six technicians in 10 repair shops were observed; a subset of 9 technicians in three shops that used a commercially available aerosol product containing hexane, acetone, and toluene (Product #1) participated in quantitative exposure measurements. The hexane fraction of Product #1 consisted of 50% n-hexane. The term "hexane" as used herein therefore refers to commercial-grade hexane that consists of 50% n-hexane.

Some attention is given to California in this study because the first cases of n-hexane-induced peripheral neuropathy in the vehicle repair industry were identified in the San Francisco Bay Area and because air quality rules in that state inadvertently created a market in this industry for solvent products formulated with hexane (beginning in 1990) and hexane-acetone blends (beginning in 1997).(7) Although introduced in California, vehicle repair aerosol products blended with both hexane and acetone were marketed nationally in this industry during the period 1990 to 2002.(7)

Employment in the Vehicle Repair Industry

Employment in the vehicle repair sector is large and growing. About 818,000 vehicle repair technicians were employed in the United States in 2002.(8) The majority of these individuals worked for automotive dealerships, independent vehicle repair shops, or vehicle service facilities at retail department stores. Others worked for gasoline service stations; taxicab and automobile leasing companies; and local, state, and federal governmental agencies. In California, 80,100 vehicle repair technicians (SOC code 49-3023) were employed in 2000, with a projected employment of 100,600 by 2010.(9) The job category of "automotive mechanic" was one of several occupations with the greatest projected job growth in California for the period 2000 to 2010.(9)

Solvent Use in the Vehicle Repair Industry

Volatile organic solvents are used in the vehicle repair industry for removing oil, grime, and grease from work surfaces, and commercially available, disposable aerosol spray cans are the most popular solvent delivery system. In fiscal year 1997, 12,413 metric tons of aerosol cleaning products were sold in California.(10) These consisted of 4258 metric tons of brake cleaner, 4924 metric tons of engine degreaser, and 3231 metric tons of carburetor cleaner.

Among brake cleaners, 56% of sales consisted of nonchlorinated solvent blends and 44% of sales consisted of chlorinated blends (primarily perchloroethylene).(11) Nearly all sales of brake cleaners were to vehicle repair facilities; consumer sales comprised less than 10% of total.(12) In 2000, the California Air Resources Board reported that 73% of repair facilities in California that performed brake repair used aerosol solvent products.(13) From 1990 to 2002, 30 to 65% of sales of nonchlorinated aerosol brake cleaning products in California were formulated using between 25–90% hexane.(7) In fiscal year 2000, an estimated 3.7 million cans of aerosol brake cleaning products formulated with both hexane and acetone were sold in California.(7)

Hexane Toxicity

Among the nonchlorinated brake cleaning products, those formulated with hexane and acetone are of particular concern.(5,14) Following inhalation, the n-hexane isomer of commercial-grade hexane is mediated by P-450 enzymes to a neurotoxic species, 2,5-hexanedione (2,5-HD).(15,16) The neurotoxicity of 2,5-HD appears to be related to protein cross-linking mediated by pyrrole intermediates.(17,18)

The most widely reported health effect of human exposure to n-hexane is peripheral neuropathy, a disease process characterized by a gradual reduction in sensory and motor function of the limbs that can advance to muscle atrophy.(19,20) Cases of peripheral neuropathy among workers exposed to n-hexane have been reported in numerous industries.(21–29) Testicular damage in males may be a second health endpoint of exposure to hexane. Hexane-induced testicular toxicity has been observed in rats(30–34) but not in mice.(35) Animal studies suggest that both the severity and duration of the neurotoxic effects of n-hexane are amplified when exposure occurs simultaneously with acetone(36–41) or methyl ethyl ketone.(42–45)

Study Overview

This study employed qualitative and quantitative methods to characterize solvent exposures among vehicle repair technicians during typical repair tasks.(46–48) Thirty-six technicians in 10 repair shops were observed; a subset of nine technicians in three shops that used a commercially available aerosol product containing hexane, acetone, and toluene (Product #1) participated in quantitative exposure measurements. These measurements included task length, integrated breathing zone ($n = 23$), and area ($n = 49$) samples for hexane, acetone, toluene, methyl ethyl ketone (MEK) and mixed xylenes; measurement of the solvent mass emitted during each task ($n = 23$); continuous measurement sampling of breathing zone volatile organic compounds (VOCs) ($n = 1238$); measurement of air speed in the work areas ($n = 780$); and approximation of the breathing zone air exchange rate.

METHODS

Description of the Study Sites

Thirty-six technicians employed in five, medium-sized, independent vehicle repair facilities and five large dealerships were observed during one to five randomly selected workdays. All 10 facilities used aerosol brake cleaning products of various types. A subset of nine technicians employed at three of the medium-sized shops participated in quantitative exposure measurements (Table I). These shops (Shops A, B, and C) were selected because their workers, owners, and managers agreed to participate in the assessment and because each shop used Product #1.

The material safety data sheet (MSDS) indicated that Product #1 contained hexane 25–35%, acetone 45–55%, toluene 5–10%, methanol <5%, MEK <2%, mixed xylenes <2%, isopropanol <2%, and carbon dioxide 5–7%. Manufacturer data indicated that 50% of the hexane fraction of Product #1 consisted of n-hexane. The design of the participating shops was typical among the 10 shops visited during the study: Shops A and B had one complete wall consisting of roll-up doors,

TABLE I. Site Characteristics

Shop ID	Internal Volume, m^3	Vehicle Capacity	Technicians Employed	Study Participants (%)
A	1064	6	5	3 (60)
B	806	5	4	4 (100)
C	2549	6	4	2 (50)

whereas Shop C had a single roll-up door at the end of a rectangular shop space.

Integrated Breathing Zone and Area Sampling

In Shops A, B, and C, integrated breathing zone and area samples were obtained for hexane, acetone, toluene, MEK, and mixed xylenes using 6 mm diameter, coconut shell charcoal sorbent tubes.(49) All breathing zone and area samples were obtained during normal working conditions. Over a period of 9 workdays, task-length breathing zone samples were obtained from nine technicians performing 23 separate tasks. Three task categories were sampled: brake maintenance and repair ($n = 13$), scheduled service ($n = 6$), and engine/power-train repair ($n = 4$). Brake maintenance and repair included inspection of both front and rear brakes on all sampled tasks. Some vehicles had rear drum brakes and some had rear disc brakes.

Scheduled service was performed on vehicles with 60,000 miles or more and included changing of engine oil. In the engine/power-train category, the following tasks were sampled: transmission work ($n = 1$), transfer case work ($n = 1$), and replacement of the head gasket ($n = 2$). For quality assurance purposes, six (26%) breathing zone samples included two charcoal tubes in dual samplers (model 800148; Gilian, Sensidyne Inc., Clearwater, Fla.).

Area samples were obtained on 49 charcoal tubes contemporaneously with 15 of the breathing zone samples. Area samplers were placed at the following locations: the center of the undercarriage of the work vehicle, 1 m from each side of the vehicle, 2 m from the front of the vehicle, and 1 m from the rear of the vehicle. Area samplers were also placed in adjacent bays at 4 m and 8 meters away from the work vehicle. All area samplers were placed at a height of 1.5–2.0 m above the shop floor, with the work vehicle raised on the shop's hydraulic lift. For quality assurance purposes, six (12%) area samples included two charcoal tubes in dual samplers.

All integrated breathing zone and area samples were obtained using either Gilian Gilair 5 sampling pumps with constant low flow modules (Gilian, Sensidyne Inc.) or PAS-500 mini-pumps (Spectrex Inc., Cedar Grove, N.J.). The flow rate was 100 mL/min. All pumps were calibrated before and after each sampling day using a Gilibrator-2 Primary Flow Calibrator (Gilian, Sensidyne Inc.) with a representative charcoal tube sampler in line. Differences in pre- and postcalibration values were within 5% in all cases. Pre- and postcalibration values were averaged to calculate the volume of air sampled. At the end of each sample period, charcoal tubes were capped and transported to the laboratory, where they were stored at -20°C.

Analysis of Integrated Samples

Charcoal from the front section of each tube was emptied into 2-cc vials.(49) A precalibrated pipette was used to introduce 1 cc of carbon disulfide into each of the vials, which were then vibrated for 30 min on a developing vibrator (SKC, Inc., Eighty Four, Pa.) during desorption. Charcoal from the front and back sections was analyzed separately for all breathing zone samples and for 21 (38%) area samples that had been placed closest to the technicians' work areas. No breakthrough was observed except with acetone, which was identified in the back section of six (26%) of the breathing zone samples, with a mean breakthrough of 6.4%, and three (6%) of the area samples, with a mean breakthrough of 13.7%.

Analysis was performed for commercial-grade hexane, acetone, toluene, MEK, and mixed xylenes using a 30-m, 0.25 mm diameter DB-wax polar capillary column (J & W Scientific, Folsom, Calif.). Nineteen breathing zone and 46 area samples were analyzed using a Hewlett-Packard (HP; Palo Alto, Calif.) 5890 gas chromatograph with a flame ionization detector (GC/FID). Four breathing zone and three areas samples were analyzed using a HP 6890 gas chromatograph with a mass spectrometer (GC/MS). The GC/FID was operated with a deactivated, straight split/splitless liner (#1925-60540; Agilent, Inc., Palo Alto, Calif.) with a 33:1 split ratio. The GC/MS was operated with a deactivated, single taper, split/splitless liner (#5062-3587; Hewlett Packard, Inc.) with a 24:1 split ratio. Hewlett Packard Chemstation software was used for management of GC operations.

Reagent grade calibration standards were prepared at seven concentration levels for hexane and acetone and five concentration levels for toluene, MEK, and mixed xylenes. High concentration calibration standards were prepared for hexane and acetone only. The GC peak area was plotted against the concentration of the calibration standards for each analyte. The coefficient of determination (R^2) of the calibration standards met or exceeded 0.999 prior to the analysis of samples. Calibration standards were also analyzed after every sixth sample over the duration of each sample run. The averaged R^2 values for these standards met or exceeded 0.999 in each sample run. Evaporative changes in the calibration standards over the duration of each sample run were $<1\%$.

For each calibration standard, the lowest concentration within the linear portion of the calibration curve was used as the limit of quantitation (LOQ).(49,50) For the GC/FID, these were hexane (33 μg/mL), acetone (39 μg/mL), toluene (43 μg/mL), MEK (40 μg/mL), and mixed xylenes (44 μg/mL). For the GC/MS, these were hexane (16 μg/mL), acetone (20 μg/mL), toluene (22 μg/mL), MEK (20 μg/mL), and mixed xylenes (22 μg/mL).

The exposure concentration represented by each charcoal tube sample was derived by dividing the micrograms of solvent collected by the volume of air sampled, in liters. All exposure concentration values were within the calibration range for each analyte. Results were adjusted to reflect desorption efficiencies of 100%, 92%, 94%, 76%, and 91% for hexane, acetone, toluene, MEK, and mixed xylenes, respectively. A total of 20 field blanks, 11 laboratory blanks, and 19 reagent blanks produced zero signal for all analytes. The total coefficient of variation (CV) contributed by the sampling pumps and laboratory instruments together ranged from 5.5 to 11.6%.(51)

Analysis of Bulk Samples

Bulk samples were obtained from five randomly selected cans of Product #1 and analyzed for hexane, acetone, toluene, MEK, and mixed xylenes using a Hewlett-Packard 5890 gas chromatograph with a flame ionization detector (GC/FID). The GC/FID was operated as described above. Although MEK is a minor constituent in Product #1, it was evaluated because it is reported to amplify the neurotoxic effects of n-hexane. Mixed xylenes were evaluated because of their neurotoxicity. Methanol and isopropanol were not evaluated because they have no known interaction with n-hexane and are minor constituents in Product #1.

Measurement of Solvent Mass Emitted

The total mass of solvent emitted (grams) during each of the 23 sampled tasks was measured using an electronic balance (model 5000; Ohaus Inc., Pine Brook, N.J.) to weigh the technician's can of Product #1 before and at the completion of the sampled task. The balance was factory calibrated immediately prior to the study period and was calibrated before and after each sampling day using a factory-supplied 2 kg weight. The balance was reported by the manufacturer to have a linear range of 0–5000 g with accuracy within ±2 g. Differences in pre- and postcalibration values were within 1% in all cases.

Continuous Measurement of VOC Exposure Levels

Total breathing zone VOCs were measured using a photoionization detector (PID) (#DL-101; Hnu Systems, Inc., Newton Highlands, Mass.) during 4 days in Shop A and 2 days in Shop B, simultaneously with air speed measurements. Twenty-six separate tasks performed by nine technicians were sampled, generating a total of 1238 individual breathing zone samples lasting 15 sec each. Sampling periods ranged from 5.0 to 31.5 min. The PID was zeroed outside the shop in fresh air prior to each of the 26 sampled tasks. Sampling was initiated immediately before the technician began spraying Product #1.

To capture breathing zone VOCs, the tip of the PID probe was placed over the technician's shoulder at chin level. Sampling was discontinued when the PID showed a breathing zone VOC concentration equivalent to shop background levels for at least 2 min. The PID was equipped with a 10.2 eV ultraviolet (UV) lamp; quantitation was based on pentane equivalents. For each sampling period, the PID was programmed to record 15-sec concentration values for total VOCs, the sample-length TWA concentration, the maximum 15-sec concentration, and the peak 3-sec concentration. The PID was factory calibrated immediately prior to the study and was calibrated before and after each sampling day using factory-supplied 100 ppm pentane.

The PID was reported by the manufacturer to have a linear range of 0.1 ppm to 400 ppm total VOC (0.30–1210 mg/m^3 for Product #1) with ±1% repeatability and a 90% response rate in <3 seconds. All 15-sec samples were within the PID linear range. Fourteen (54%) peak 3-sec samples exceeded the PID linear range by 0.25% (1213 mg/m^3) to 27% (1539 mg/m^3). Differences in pre- and postpentane calibration values were within 2% in all cases.

Measurement of Air Speed

An electronic anemometer (model 8384; TSI Inc., Shoreview, Minn.) was used to measure air speed simultaneously with continuous VOC measurements. On each of the sample days, the roll-up doors in both shops were fully opened. A total of 30 randomly selected air speed measurements lasting 10-sec each was obtained during each of the 26 tasks ($n = 780$). Samples were obtained in the front, middle, and rear shop areas where technicians performed their work. All air speed measurements were obtained within 1 m of a working technician. The anemometer was factory calibrated immediately prior to the study period and was reported by the manufacturer to function properly within an air speed range of <0.3 to 3048 m/min (1 to 9999 ft/min) with accuracy of ±1 m/min (3 ft/min) and a response time of 200 milliseconds.

RESULTS

Observation of the Work Process

In the 10 shops observed, ambient air movement through large, roll-up doors served as the primary source of ventilation in the work areas. None of the 10 shops used local exhaust ventilation (LEV) for removal of solvent vapors from the work areas, and no technician was observed using respiratory protection during aerosol solvent spraying. Solvent products labeled as brake cleaners were used for all cleaning purposes, not simply those related to brake work. Most technicians wore latex gloves during repair work, which reduced contact with grease and grime but did not serve as an effective barrier against dermal contact with solvents. (On the recommendation of the researchers, all shops switched their glove type to a more solvent-resistant material during the course of the study.)

The day-to-day work of the technicians usually involved some combination of tasks from three different groups:

- Group 1: Servicing of brakes, transmissions, differentials, and steering systems
- Group 2: Tune-ups and scheduled service
- Group 3: Diagnosis and repair of electrical, cooling, and heating systems.

Solvents were used extensively in Task Groups 1 and 2 and rarely in Group 3. We found that technicians in the medium-sized shops typically performed any combination of tasks in Groups 1, 2, and 3 on a daily basis, whereas technicians in the large dealerships tended to specialize in a single task, such as brake work, transmission repair, or electrical work, which they performed repeatedly each day. Based on these observations, we concluded that solvent exposures due to direct use of aerosol products would tend to be concentrated among a subset of technicians employed in large dealerships and more evenly distributed among technicians employed in small to medium-sized shops. Shops A, B, and C were typical of medium-sized vehicle repair operations in that the technicians employed in these shops usually performed tasks from Groups 1, 2, and 3 on a daily basis.

TABLE II. Solvent Use Patterns

Task	Solvent Use	Total Spray Duration, sec
Inspection	Light	2 to 10
Disassembly	Moderate	10 to 30
Reinspection	Heavy	30 to 90
Repair/maintenance	Moderate	10 to 30
Reassembly	Light	2 to 10
Reinspection	Light	2 to 10
Removal of oil and grease marks	Light	2 to 10

Notes: Thirty-six technicians employed in five, medium-sized, independent vehicle repair facilities and five large dealerships were observed during 1 to 5 randomly selected workdays. All 10 facilities used aerosol brake cleaning solvent products of various types.

The volume of aerosol solvent sprayed during a task depended on the task type, the work practices of the technician, and the condition of the work vehicle. In general, the technicians used these products in spray bursts lasting from 2 to 90 sec, with a typical burst lasting about 30 sec. The work pattern and volume of solvent used during most tasks followed a characteristic pattern, with the highest solvent use occurring during the "re-inspection" period (Table II). Based on these observations, we concluded that the exposure profile to VOCs in this industry is episodic, as compared with continuous, both within tasks and across workdays.

Integrated Breathing Zone Samples

The sample time for the 23 task-based breathing zone samples ranged from 18 to 145 min, with an average time of 94 min. Each sample represented the time necessary for the technician to initiate and complete the repair task. Hexane, acetone, and toluene were identified in all 23 breathing zone samples (Table III and Figure 1). The proportions of hexane, acetone, and toluene in each sample were correlated in the 23 samples (hexane and acetone, r = 0.95; hexane and toluene, r = 0.89) (Figure 2). MEK and mixed xylenes were below the level of quantitation in all breathing zone samples.

Integrated Area Sample

Hexane and acetone were identified in all 49 task-length, integrated area samples; toluene was identified in 37 area samples (Figure 3). MEK and mixed xylenes were below the level of quantitation in all area samples. As in the breathing

TABLE III. Breathing Zone Exposure Concentration Values for Task-Based, Integrated Samples

Sample	Task Category	Worker ID	Shop ID	Hexane (mg/m^3)	Acetone (mg/m^3)	Toluene (mg/m^3)	Total VOC (mg/m^3)	Task Time (min)	Emission Rate (g/min)
1	Brake inspection	1	A	12	9	3	24	133	5
2	Brake inspection	1	A	31	41	10	82	89	7
3	Brake inspection	2	A	15	21	6	41	145	4
4	Brake inspection	2	A	8	9	3	21	119	2
5	Brake inspection	2	A	96	146	17	258	46	10
6	Brake inspection	3	A	50	38	20	108	76	6
7	Brake inspection	4	B	55	112	15	182	104	7
8	Brake inspection	4	B	49	85	17	151	52	6
9	Brake inspection	5	B	43	90	19	152	18	9
10	Brake inspection	7	B	20	37	11	68	26	9
11	Brake inspection	8	C	31	32	6	69	109	11
12	Brake inspection	8	C	100	148	21	269	108	18
13	Brake inspection	9	C	23	24	5	51	110	1
14	Scheduled service	1	A	21	29	6	56	128	3
15	Scheduled service	2	A	2	2	2	6	128	1
16	Scheduled service	9	C	51	68	11	130	103	2
17	Scheduled service	3	A	14	22	6	42	115	5
18	Scheduled service	2	A	21	19	6	46	96	1
19	Scheduled service	1	A	60	86	20	101	112	5
20	Engine work	1	A	47	44	10	143	105	10
21	Engine work	6	B	49	83	11	146	84	6
22	Engine work	2	A	49	84	13	99	112	9
23	Engine work	1	A	31	48	20	166	52	8

Notes: Total VOC represents the sum of breathing zone exposure concentrations of hexane, acetone, and toluene. Emission rate represents total mass (g) of solvent emitted during the task over the total task time in minutes.

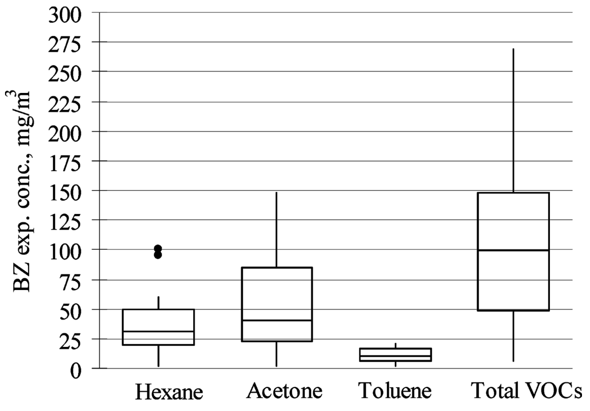

FIGURE 1. Breathing zone (BZ) exposure concentration values (mg/m^3) for task-based, integrated samples (n = 23). Each box represents the interquartile, or the central 50% of the distribution. The middle line in each box represents the median. Whiskers depict the upper and lower range of the data, to a maximum of 1.5 times the interquartile range. Data exceeding this limit are represented by a solid dot (moderate outliers), unless they exceed 3 times the interquartile range, at which point they are represented by an open dot (extreme outliers). No extreme outliers are shown.

zone samples, the proportions of hexane, acetone, and toluene in the area samples were correlated (hexane and acetone, r = 0.73; hexane and toluene, r = 0.83). The aggregate TWA area concentrations were 33%, 28%, and 40% of the TWA breathing zone concentrations for hexane, acetone, and toluene, respectively.

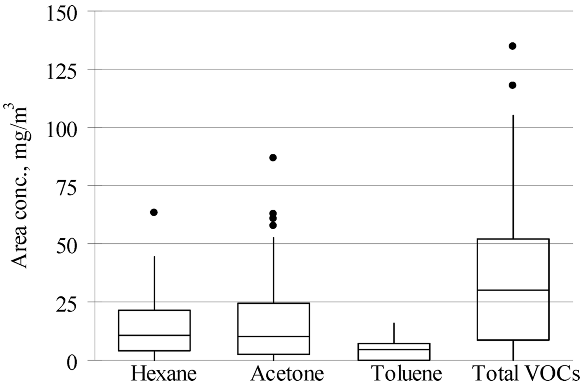

FIGURE 3. Area concentration values (mg/m^3) for task-based, integrated samples (n = 49). Area samples were obtained contemporaneously with 15 breathing zone samples. Each box represents the interquartile, or the central 50% of the distribution. The middle line in each box represents the median. Whiskers depict the upper and lower range of the data, to a maximum of 1.5 times the interquartile range. Data exceeding this limit are represented by a solid dot (moderate outliers), unless they exceed 3 times the interquartile range, at which point they are represented by an open dot (extreme outliers). No extreme outliers are shown. Note scale difference between breathing zone and area samples.

Bulk Samples

The mean fractions of hexane, acetone, and toluene in the breathing zone and area samples were similar to those of the bulk samples for Product #1 (Table IV).

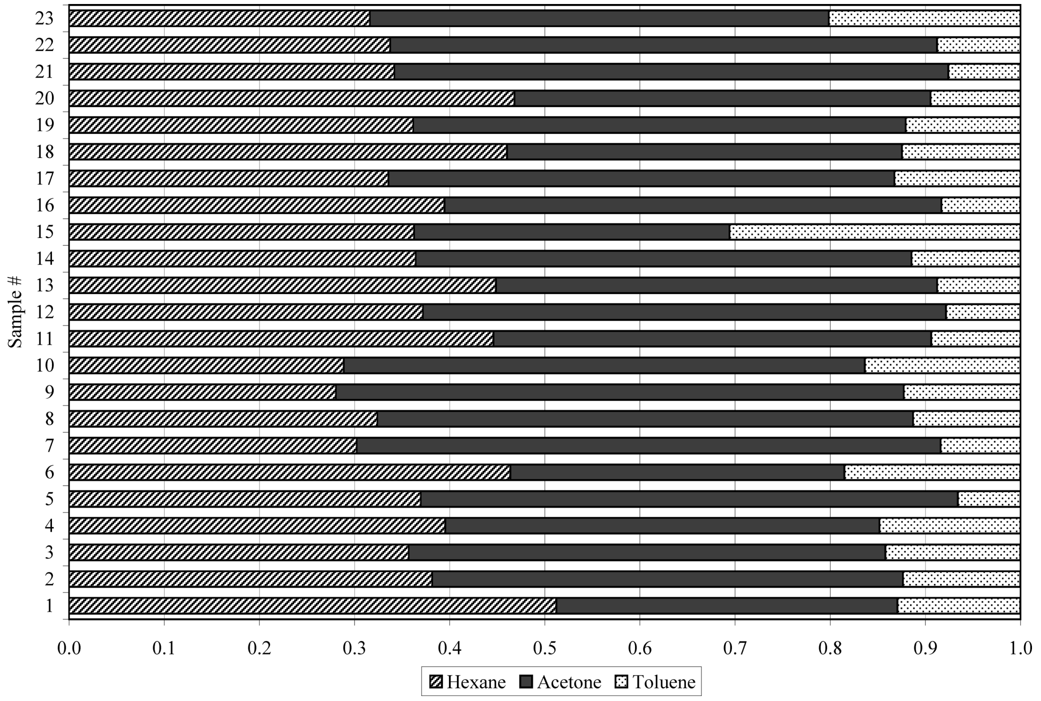

FIGURE 2. Fractions of hexane, acetone, and toluene in integrated breathing zone samples (n = 23). The fractions of hexane, acetone, and toluene in each sample were correlated (r = 0.95 for hexane and acetone; r = 0.89 for hexane and toluene).

TABLE IV. VOC Fractions in Breathing Zone and Area Samples Compared with the Bulk Product

	Fraction in Shop Samples				Fraction in Bulk Samples	
	BZ (n = 23)		Area (n = 49)		Range (n = 5)	
	Mean	SD	Mean	SD	Lower	Upper
Hexane	0.38	0.09	0.45	0.25	0.39	0.42
Acetone	0.51	0.14	0.41	0.25	0.35	0.38
Toluene	0.13	0.05	0.14	0.13	0.18	0.21

Solvent Mass Emitted

In the 23 integrated breathing zone samples, the mass of solvent emitted over the duration of the task (g/min) was correlated with the breathing zone exposure concentration for total VOCs (mg/m^3) (Figure 4). In a simple linear regression model, g/min explained 45% of the variability in the total VOC component of variance ($R^2 = 0.45$) ($y = 12x + 29$; 95% CI = ±6.0 mg/m^3).

Continuous Measurement of VOC Exposure Levels

The PID measurements supported the observation that exposure to VOCs was episodic over the duration of a task and highest during the initial minutes of solvent spraying. In the 26 tasks sampled with the PID, the maximum 15-sec value exceeded the sample length TWA by 5.1 times on average. The peak 3-sec value exceeded the sample-length TWA by 8.4 times on average. Aggregated PID data from the first 4.75 min of the re-inspection phase of the 26 tasks (during which solvent spraying occurred for the first 30 to 90 sec) showed an average VOC exposure "pulse" of 394 mg/m^3 (95% CI = 337, 452 mg/m^3) at 75 sec that declined to 114 mg/m^3 (95% CI = 56, 171 mg/m^3) at 165 sec (Figure 5). Median exposure values closely tracked those of the mean.

Air Speed

Air speed data were lognormally distributed (n = 780). The geometric mean (GM) air speed ranged from 2.6 to 8.6 m/min (8.6 to 28.3 ft/min). The geometric mean for all 6 sampling days was 5.2 m/min (GSD 0.91) (17 ft/min, GSD 3.0). In general, air speed was slower in work areas located in the rear of the shops compared with front areas, which were closer to the roll-up doors ($p < 0.05$). The GM air speed was 3 and 4 m/min (10 to12 ft/min) in rear and middle work areas, respectively, and 12 m/min (38 ft/min) in front work areas.

Breathing Zone Air Exchange Rate

We used the continuous VOC measurement data to approximate the effective breathing zone air exchange rate, as described by the solvent vapor decay region occurring between

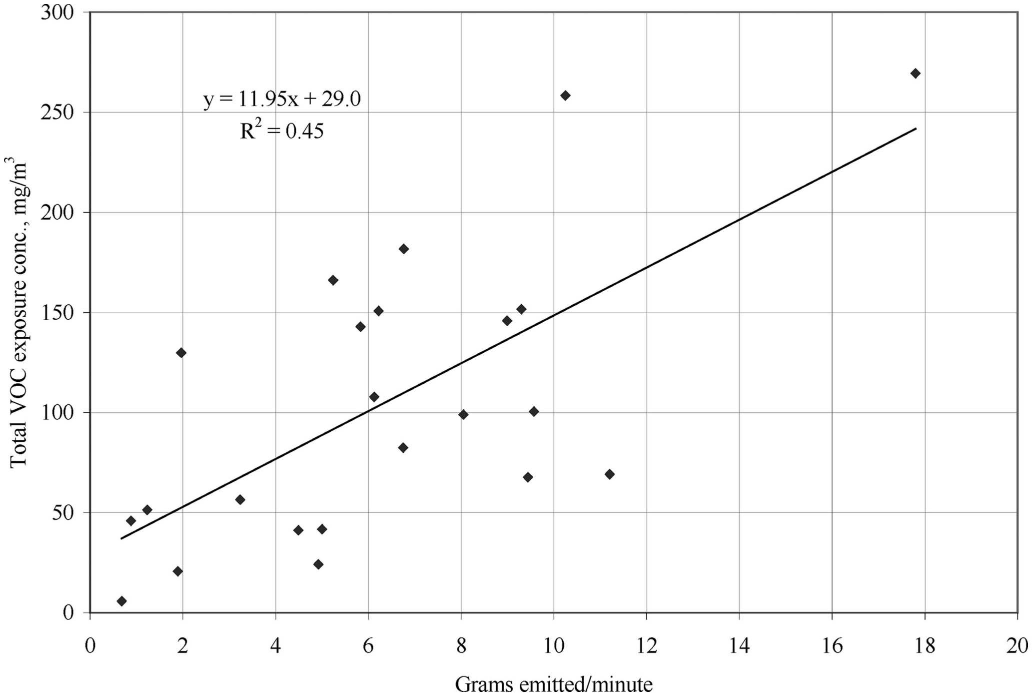

FIGURE 4. Solvent emission rate (g/min) and exposure to VOCs (mg/m^3). The solvent emission rate (g/min) and exposure to volatile organic compounds (VOCs), mg/m^3 in task-based breathing zone samples during the use of Product #1 ($p < 0.01$) (n = 23). Each data point represents the total grams of VOCs emitted by a worker during a task, over the total task time (95% CI = ±6.0 mg/m^3).

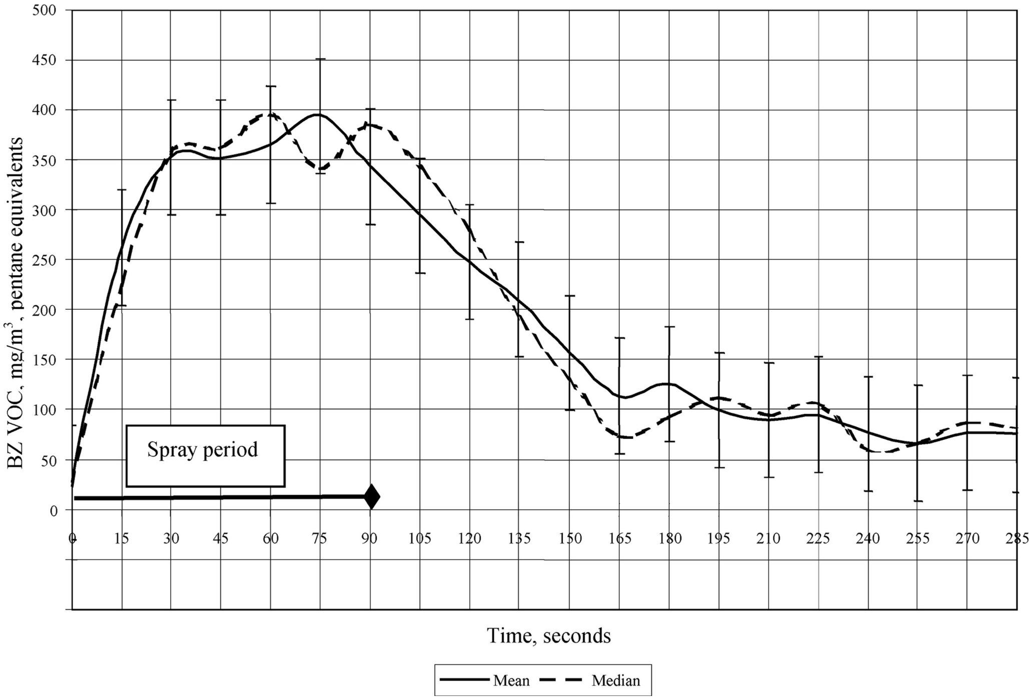

FIGURE 5. Continuous breathing zone exposure concentration to total VOCs, mg/m^3 (pentane equivalents). At time = 0, the technician initiated spraying of product # 1. Spraying lasted between 30 and 90 sec. Each data point represents the arithmetic mean of 26, 15-sec TWA breathing zone exposure values, obtained during 26 different tasks in Shop A (over 4 workdays) and Shop B (over 2 workdays). Median values and 95% CIs are also shown. Data were collected using a photoionization detector positioned in the technician's breathing zone.

75 and 165 sec (Figure 5). During this time period, the exposure concentration for total VOCs in the 26 tasks decreased from 394 mg/m^3 to 114 mg/m^3. The shape of the individual decay curves in the PID data suggested that the decay profile would be defined most appropriately using an exponential decay equation. This analysis produced a breathing zone air exchange rate of about 0.8 air changes per minute (95% CI = 0.61, 1.2). This breathing zone air change rate was associated with the geometric mean air speed of 5.2 m/min (17 ft/min).

DISCUSSION

This study characterized several aspects of exposure to VOCs among workers in the vehicle repair industry that are of practical value to public health and to exposure assessment for epidemiological research in this industry. With regard to public health, the study illustrates that workers in this industry use aerosol cleaning products under uncontrolled conditions. As a consequence, they receive an inhalation dose of VOCs during each use. This dose occurs in proportions that are approximately similar to those of the bulk product. This is of particular importance when the product mixture produces additive or synergistic effects, as in the case of hexane and acetone.

For epidemiological research, the study illustrates that (*a*) there is a characteristic pattern of aerosol solvent use that is largely independent of the task type, shop, or individual; (*b*) as a consequence, there is a correlation between the task-based solvent emission rate (g/min) and the breathing zone VOC exposure concentration (mg/m^3)($R^2 = 0.45$); (*c*) the greatest exposures occur in the first 1 to 2 min following initiation of spraying; and (*d*) the proportions of constituent solvents in both breathing zone and area integrated samples generally reflect those of the bulk product.

The results of the observations and continuous measurements demonstrate that VOC exposures are episodic during the use of aerosol solvent products. Presumably, exposure pulses such as these would be of greatest concern for substances that produce immediate health effects without the need for metabolic activation.(52) In the case of n-hexane, Perbellini(53) has demonstrated that the rate-limiting factor for peripheral neurotoxic effects is delivery of the n-hexane molecule to the liver, where it is activated to the neurotoxic metabolite, 2,5-hexanedione. It therefore appears that the risk of peripheral neurotoxic effects from inhalation of n-hexane would be similar under both episodic and continuous exposure conditions, assuming the total mass of inhaled n-hexane is similar.

The relationship of the emission rate (g/min) to the breathing zone exposure concentration (mg/m^3) for total VOCs would be expected to apply in most vehicle repair tasks because the mass of solvent applied over the duration of the task is the most important driver of exposure. Other exposure factors would not be expected to vary considerably among technicians, tasks, and shops. These are (*a*) the distance from the breathing zone to the sprayed surface (generally the length of the technician's arm); (*b*) the vapor pressure of the solvents used, which are fairly high and of similar range among nonchlorinated VOCs; and (*c*) the air change rate in the breathing zone, which in the absence of local exhaust ventilation or air moving fans is minimal.

This relationship can be of practical value in assessing exposure when the mass of solvent applied per unit time can be established. For example, in the case of brake work (n = 13), the average solvent emission rate was 7.0 g/min. The model produces an estimated task-length VOC exposure concentration of 113 mg/m^3(95% CI = 107, 119). The fraction analysis of Product #1 suggests that the proportions of the individual solvents within this VOC estimate can be approximated based on the formulation of the bulk product.

CONCLUSIONS

This study characterized exposures to mixed VOCs among vehicle repair technicians who used commercially available, nonchlorinated, aerosol, brake cleaning solvent products. Extensive use of these products in the absence of local exhaust ventilation or respiratory protection was observed during visits to 10 vehicle repair shops. Solvent use appeared to be concentrated among a subset of workers at the largest shops but distributed evenly among workers in medium-sized shops. Quantitative measurements among a subset of workers showed an episodic exposure profile, with ventilation conditions that did not prevent VOC vapors from entering the breathing zone. The study produced a number of findings that are of practical value to public health and epidemiological research. Further evaluation of exposures to VOCs is needed in this industry, along with information on effective alternatives to aerosol products that contain VOCs.

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