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Regulated Workplace Ketones and Their Interference in the PFBHA Method for Aldehydes

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Ketones are the major positive interferences for an aldehyde dynamic air sampler that consists of 200-mg 20 percent (w/w) O-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine hydrochloride (PFBHA) on Tenax TA contained in a Pyrex tube 7-mm OD, 5-mm ID, and 70-mm in length, that utilizes a personal battery-powered pump at 10–50 mL/min. The ketone O-oxime derivatives were synthesized to allow absolute quantitation of O-oximes formed during sampling. Wet spiking allowed ketone recoveries to be found. Ketone vapors of known concentrations were generated statically in Tedlar gas bags. The O-oximes were desorbed with hexane, and an aliquot injected for gas chromatographic analysis on a nonpolar capillary column with mass spectrometric or electron capture detection. Gas phase recoveries up to 200 ppm-hour loadings exceeded 75 percent at 25°C for chloroacetone, cyclohexanone, diacetone alcohol, diethyl ketone, dipropyl ketone, ethyl butyl ketone, methyl amyl ketone, methyl butyl ketone, 2-methylcyclohexanone, methyl ethyl ketone, methyl isobutyl ketone, methyl isopropyl ketone, and methyl propyl ketone. The recoveries for acetophenone, 2-chloroacetophenone, and ethyl amyl ketone were lower than 75 percent, and were caused by steric hindrance. Sampling for both aldehydes and ketones is recommended at 10 mL/min for TLV concentrations.

Keywords Dynamic Sampling, Ketone, Solid Sorbent Sampling, Adsorption, Oxime, Gas Chromatography

Ketones (R_1-(C=O)-R_2 where R_1 and R_2 are alkyl, aromatic, or alicyclic functional groups) are widely used industrial chemicals. They are used as solvents, chemical intermediates, cleaning fluids, dewaxers, and reaction enhancers, as well as in paints, hydraulic fluids, cleaning fluids, inks, pharmaceuticals, cosmetics, and dopes.[1,2] Probably the most prevalent exposures in workplaces are during painting and lacquering operations, in paint factories, and in chemical laboratories during solvent dispensing. Commercially important ketones include acetone, diacetone, methyl ethyl ketone, methyl propyl ketone, and methyl isobutyl ketone.[2] Ketones are also environmental products of photooxidation. For example, methyl ethyl ketone can be produced in outdoor air by the photooxidation of such air pollutants as butane and other hydrocarbons.[3] Methyl ethyl ketone has also been found in drinking water and surface waters,[4] and is also a product of metabolism.[5] Ketones are emitted as products of bacterial spoilage[6] and oxidative combustion,[7] and are important markers of lipid peroxidation, metabolic status, and diabetic status,[8] as measured through breath sampling.[5] Water-soluble ketones dehydrate and then abrade the skin after contact, allowing enhanced skin permeation of other exposing chemicals.

Ketones are mucous membrane irritants and activate the trigeminal nerve endings in the eyes and nose ("sensory irritation"), but are not as potent as their closely related aldehyde analogs of the same number of carbon atoms. Overexposure can cause narcosis, headache, nausea, light-headedness, dizziness, and incoordination. Methyl butyl ketone is oxidized to the same neurotoxic metabolite (2,4-hexanedione) as is *n*-hexane, and peripheral and central neuropathy are caused in rats after time-weighted average (TWA) exposure to 1,300 ppm.[2]

Methods for personal sampling of ketone vapors usually involve dynamic air sampling with solid sorbents.[9] The National Institute of Occupational Safety and Health (NIOSH) recommends several methods like charcoal tube sampling for acetone, cyclohexanone, diisobutyl ketone, 2-hexanone, methyl isobutyl ketone, and 2-pentanone.[10] However, CS_2 desorption of the more nonpolar ketones on charcoal tubes is inefficient. A desorbing mixture of 1 percent methanol in CS_2 improves desorption of camphor, mesityl oxide, 5-methyl-3-heptanone, methyl-(*n*-amyl) ketone, and ethyl butyl ketone.[11] Methyl ethyl ketone is sampled on beaded carbon before desorption by CS_2.[12] 2-, 3-, and 4-methyl cycloheanone are sampled on Porapak Q, desorbed with acetone, and analyzed by GC.[13] Thermal desorption from graphitized carbon and carbon molecular sieves is used for ppb concentrations of ketone vapors.[14]

The 2,4-dinitrophenylhydrazine (2,4-DNPH) solid sorbent method is recommended by the United States Environmental

Protection Agency (EPA)[15] to determine aldehydes and ketones in ambient air. The 2,4-DNPH method potentially allows relatively selective quantitation of different aldehydes and ketones through high-performance liquid chromatography (HPLC)/ultraviolet detection (UVD) of their hydrazones but not by GC because many hydrazones decompose at high temperatures.[9] 2,4-DNPH does not react quantitatively with conjugated aliphatic aldehydes, can be light sensitive, is prone to ozone interference, and variable recoveries occur on liquid spiking.[9] Some passive samplers have been developed for the lower molecular weight aldehydes and ketones based on liquid systems.[16,17] Solid sorbent DNPH passive samplers are available.[18–21]

O-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine hydrochloride (PFBHA) has been used to analyze aldehydes in ozonated water[22] because of its fast quantitative reaction to form O-oximes that can be detected at the picogram (pg) level by gas chromatography/mass spectrometry (GC/MS) and gas chromatography/electron capture detection (GC/ECD).[23] The PFBHA method has been used to chemisorb aldehyde vapors by dynamic sampling,[24,25] and by passive sampling.[26,27] In those studies, relative humidity RH (3 to 79%), temperature (4 to 48°C), intermittent exposures, shelf life (at least three months), and storage stability (at least six months) were shown to have no effects on aldehyde O-oxime recoveries, and thus the method shows promise. The present study extends the PFBHA dynamic sampling method for aldehydes to selected regulated ketones, the major positive interferences of the aldehydes.

EXPERIMENTAL METHODS

Materials

The ketones from Aldrich, Milwaukee, Wisconsin, were: acetophenone (99%), butyl ethyl ketone or 3-heptanone (98%), chloroacetone or chloro-2-propanone (95%), 2-chloroacetophenone or phenacyl chloride (99%), diacetone alcohol or 4-hydroxy-4-methyl-2-pentanone (99%), di propyl ketone or 4-heptanone (98%), cyclohexanone (99.8%), diethyl ketone or 3-pentanone (99+%), ethyl amyl ketone or 3-octanone (98+%), methyl amyl ketone or 2-heptanone (98%), methyl butyl ketone or 2-hexanone (98%), 2-methylcyclohexanone (99%), methyl ethyl ketone or 2-butanone (99+%), methyl isobutyl ketone or 4-methyl-2-pentanone (99.5+%), methyl isopropyl ketone or 3-methyl 2-butanone (99%), and methyl propyl ketone or 2-pentanone (99.5%). Internal standard decafluorobiphenyl (99%) was also from Aldrich. Hexane (Optima), methanol (Optima), nitric acid, activated charcoal, molecular sieves, and indicating Drierite were from Fisher Scientific, Tustin, California. O-(2,3,4,5,6-Pentafluorobenzyl)hydroxylamine hydrochloride (PFBHA) was from Lancaster Laboratories, Lancaster, Pennsylvania. Tenax TA (80/100 mesh) was from Alltech Associates, Deerfield, Illinois. Chromatographic grade helium, nitrogen, and 5% methane/argon were from Alphagaz, Los Angeles, California.

Equipment

Pyrex tubing (7-mm OD, 5-mm ID), Pyrex glass wool, 4-mL Kimble vials with PTFE-lined screw caps, 10-μL Hamilton syringes for chromatographic injections, gas-tight Hamilton syringes, Soxhlett-extraction apparatus, calibrated temperature/relative humidity (RH) meter/recorder, and a hair dryer to vaporize liquids and homogenize atmospheres in gas bags were from Fisher Scientific. Pocket pumps (Model No. 210-1002), rotameters, and Tedlar gas bags were from SKC West, Fullerton, California. A Whatman Zero Air generator was from Balston, Haverhill, Massachusetts. AM-5 Mini-Buck calibrator for flow rate measurement was from Buck Scientific, East Norwalk, Connecticut. A Goldstar Multiwave microwave oven facilitated O-oxime syntheses.

GC/MS was done with a Hewlett-Packard 5890 gas chromatograph (Hewlett-Packard, Palo Alto, California) equipped with a 30-m $\times$0.32-mm ID DB-1701 chemically bonded (1-μm thick film) fused-silica capillary column. The temperature for the injector and link was 250°C. The column temperature program was: solvent delay 5 min at 105°C, 105°C for 0.5 minutes, 105°C to 200°C at 10°C/minute, and holding then until all peaks eluted. The Hewlett-Packard 5988A quadrupole positive ion electron impact mass spectrometer had an electron multiplier detector, and the 70-eV ion source temperature was 250°C. Selected ion monitoring (SIM) used m/z 181 and m/z 334. Total ion monitoring (TIC) utilized m/z 50–500. The areas of both *E*- and *Z*-isomers were utilized for quantitations.

The same column, temperature, and peak quantitation conditions were used for Hewlett-Packard 5890 capillary GC/^{63}Ni-electron capture detection (ECD) with 5 percent methane/argon carrier flow of 3.0 $\pm$ 0.4 mL/min. The detector temperature was 250°C. The flows for the septum purge, anode, and make-up carrier gas were 3.0 $\pm$ 0.2, 4.0 $\pm$ 0.3, and 40 $\pm$ 3 mL/min, respectively. The signal was visualized with a Hewlett-Packard 3396 integrator. As for GC/MS, the injection volume was 2 μL.

Methods

After the synthesis of the new pure ketone O-oximes of PFBHA to provide absolute quantitations, the sampling tubes were prepared. Spiked ketones (neat or in methanol) at guideline equivalent mass levels allowed calculation of wet spiking recoveries. Known ketone vapor concentrations generated in Tedlar gas bags allowed determination of vapor recoveries when a known volume was sampled.

Synthesis of PFBHA O-Oximes

The PFBHA O-oximes are not commercially available. They were synthesized in triplicate by methods detailed elsewhere.[22,24,28] All the PFBHA O-oximes synthesized for this work in Table I are new, except those for methyl amyl ketone, acetophenone, 2-methylcyclohexanone, and acetone, these being synthesized before.[28] Each derivative in hexane at a total

TABLE I
Ketone PFBHA O-oxime GC/MS yields for triplicate syntheses, and SIM linear dynamic ranges

Ketone	Yield[A] (%)	Oxime linear dynamic range (ng in 2-μL injection)
Chloroacetone	98.4 ± 1.5	0.10–10
Diethyl ketone	98.91 ± 0.17	4.5–18
Methyl isopropyl ketone	98.33 ± 0.36	5.0–20
Methyl ethyl ketone	97.8 ± 1.4	5.0–20
Methyl propyl ketone	98.1 ± 1.3	5.0–20
Methyl *n*-amyl ketone	98.7 ± 1.1	5.0–20
Cyclohexanone	98.4 ± 1.6	5.0–20
Methyl *n*-butyl ketone	98.67 ± 0.14	5.0–20
Acetophenone	98.1 ± 1.9	4.5–18
Methyl isobutyl ketone	99.2 ± 1.0	4.5–18
Ethyl amyl ketone	99.58 ± 0.55	4.5–18
2-Chloroacetophenone	97.2 ± 1.4	0.10–10
2-Methylcyclohexanone	99.63 ± 0.16	5.0–20
Ethyl butyl ketone	98.3 ± 2.8	4.5–20
Dipropyl ketone	98.71 ± 0.67	5.0–20
Diacetone alcohol	99.56 ± 0.98	5.0–20

[A]corrected for GC/MS purity.

injection mass of about 1 μg in 2 μL was subjected to GC/MS investigation in the total ion current (TIC) mode for purity. The areas of both *E*- and *Z*-isomers of the PFBHA O-oximes were utilized for quantitation purposes. TIC-GC/MS corrected for the presence of pentafluorobenzaldehyde, pentafluorobenzyl alcohol, excess PFBHA in the O-oximes, any other aldehydes, and other peaks not attributable to the reagents and solvents.[22] Yields were corrected for GC/MS purity. Other spectroscopic criteria of purity (ultraviolet, infrared, mass spectra, and ^{1}H- and ^{13}C-nuclear magnetic resonance) for the four ketones already synthesized before this study are also available.[28] Quantitations utilized the selected ion monitoring (SIM) mode at m/z 181. GC/^{63}Ni-ECD was also used with the same capillary column, temperature program, and column flow rates.

Sampler preparation. The Tenax TA and glass wool were separately Soxhlett-extracted overnight with methanol, and then hexane. Both were dried to constant weight in a vacuum desiccator containing indicating Drierite. PFBHA (0.7500 g) was dissolved in 25 mL methanol and added to 3.0 g Tenax TA in a preweighed 250-ml 24/40 pyrex ground glass round-bottom flask to produce a 20% w/w PFBHA coating. The methanol was removed by rotary/vacuum evaporation at 55°C until the solid flowed. The container was then left in a vacuum desiccator until constant weight of the solid product.

Pyrex tubing was cut into 70-mm lengths, the ends fire-polished, acid-cleaned, and dried. After inserting a 5.0-mm glass wool plug at one end, 200 mg of the coated solid sorbent was packed uniformly into the tube using the vibrator. Once the upper distance of the sorbent top to the end of the tube was constant on continued vibration, another 5.0-mm glass wool plug was inserted at the upper surface. The ends were capped for storage in a vacuum desiccator at room temperature.

Desorption efficiency. Specific volumes of ketone or ketone/methanol solution containing known weights of ketone equivalent to the target threshold limit value (TLV®)-TWA ppm-hour (except for chloroacetone which was the only ketone examined that had a ceiling limit where 0.25 × ceiling limit ppm was spiked) were spiked onto the tubes in triplicate as shown in Table II. After standing overnight, desorption was done with 3 mL hexane in a capped scintillation vial by two-min manual agitation at 25°C.[25]

Sampling efficiency. Known concentrations of specific ketones were prepared in triplicate in 10-L Tedlar gas bags statically by injecting known volumes[24] of ketones into purified compressed air of 1 percent RH,[25–27] and heating the mixture with a hair dryer to facilitate complete ketone evaporation and

TABLE II
Desorption efficiency after methanol spikes of the test ketones in triplicate

Ketone (1996 TLV-TWA in ppm, STEL in ppm)	Spiked ketone (μmol)	Efficiency (%)
Chloroacetone (1 C)	0.031	96.1 ± 5.8
Diethyl ketone (200,-)	4.89	91.1 ± 3.9
Methyl isopropyl ketone (200,-)	4.94	92.8 ± 5.6
Methyl ethyl ketone (200,300)	4.50	90.0 ± 4.0
Methyl propyl ketone (200,250)	4.94	92.5 ± 2.6
Methyl amyl ketone (50,-)	1.23	93.3 ± 2.7
Cyclohexanone (25,-)	4.90	87.2 ± 7.0
Methyl butyl ketone (5,-)	0.99	107.00 ± 0.14
Acetophenone (10,-)	2.00	91.5 ± 9.1
Methyl isobutyl ketone (50,-)	1.24	98.2 ± 3.5
Ethyl amyl ketone (25,-)	4.89	98.2 ± 2.4
2-Chloroacetophenone (0.05,-)	0.011	95.4 ± 2.7
2-Methylcyclohexanone (50,75)	1.23	99.7 ± 2.3
Ethyl butyl ketone (50,-)	1.23	98.0 ± 3.2
Dipropyl ketone (25,-)	1.23	95.5 ± 6.5
Diacetone alcohol (50,-)	1.20	101.0 ± 4.5
Acetone (750,1000)[A]	294[B]	42.1 ± 6.8
	39[C]	72.6 ± 3.4

C = Ceiling (15-min).
[A]1999 TLV-TWA is 500 ppm and STEL is 750 ppm.
[B]equivalent to sampling double the TLV for 8 hr at 10 mL/min.
[C]equivalent to sampling the TLV for 2 hr at 10 mL/min.

mixing. The low RH was chosen as the most adverse RH condition because the aqueous solution reaction was known to be quantitative from the synthesis of the PFBHA O-oximes of the ketones at the beginning of the present study. Previous work gave similar results for the syntheses of aldehyde PFBHA O-oximes. Furthermore, there was no RH, temperature, and intermittent sampling dependence of vapor phase recoveries of the aldehydes, formaldehyde, n-valeraldehyde, and acrolein in terms of the expected PFBHA O-oxime formed.

The sampling tube was connected to the gas bag by Teflon tubing using Tygon collars and butt-to-butt joints. Sampling occurred at specific pump flow rates for known durations corresponding to TLV-TWA or ceiling limit exposures as appropriate (Table III). The sorbent was desorbed with 3 ml hexane by 2-min manual agitation at 25°C. Some experiments featured different sorbent weights and backup sections, and in certain cases more than triplicate sampling was utilized. This procedure allows a complete mass balance to calibrate the static sampling method.[24]

Capacity testing. Chloroacetone was selected as one representative ketone as it had the lowest American Conference of Governmental Industrial Hygienists (ACGIH®) sample loading (ceiling limit of 1 ppm), and it was not sterically hindered.[28] Specific concentrations were generated in 10-L Tedlar gas bags at 1 percent RH (Tables IV–VI). Sampling occurred at average flow rates of 48.90 ± 0.64 mL/min, 9.83 ± 0.66 mL/min, and 2.04 ± 0.12 mL/min at different gas bag concentrations and sampling times. Thus, the 48.9 mL/min data were obtained from chloroacetone concentrations of 1.0, 5.0, and 10 ppm sampled at times ranging from 15 min to 315 min. The 9.83 mL/min data were from chloroacetone concentrations of 5, 50, 100, and 250 ppm sampled at times ranging from 80 to 160 min. The sorbent was then desorbed by 3 mL hexane with agitation for 2 min at 25°C for GC analysis. A similar protocol to that used for chloroacetone was employed to evaluate acetone, the ketone with the highest TLV-TWA and one that is also not sterically hindered. The selection of the extremes of the capacity spectrum as a screening tool for all aldehydes has been discussed previously.[26]

Statistics

All internal statistical comparisons were subjected to analysis of variance types I and II, and to detect significant differences at $p \leq 0.05$ and significant statistical interactions, as well as Student t tests for differences of means.[29]

RESULTS AND DISCUSSION

Table I shows the yields for O-oxime syntheses, corrected for GC/MS TIC purities. All yields are greater than 97.2 percent, based on 1:1 stoichiometry. Because the yields for methyl isopropyl ketone and acetone were also acceptable, and those for diisopropyl ketone and for 2,4-hexanedione were not,[28] the wet chemical syntheses were of high yield except when the alkyl parts of the ketone were substituted at both β-carbons from the carbonyl carbon.

TABLE III
Sampling efficiencies for test ketone vapors in triplicate at specific flow rates, sampling times, and concentrations

Ketone	Gas bag concentration (ppm)	Pump flow rate (mL/min)	Sampling time (min)	Sampling efficiency (%)
Chloroacetone	1.00	49.4 ± 0.64	15	104.7 ± 2.2
Diethyl ketone	199	9.90 ± 0.47	60	95.6 ± 8.5
Methyl isopropyl ketone	200	10.01 ± 0.51	60	78.9 ± 4.8
Methyl ethyl ketone	197	9.71 ± 0.43	60	100.1 ± 6.7
Methyl propyl ketone	198	9.6 ± 1.2	60	83.8 ± 4.3
Methyl amyl ketone	49.6	10.08 ± 0.54	60	93.5 ± 4.5
Cyclohexanone	198	9.98 ± 0.11	60	95.5 ± 0.11
Methyl butyl ketone	42.2	9.87 ± 0.22	60	83.8 ± 4.1
Acetophenone	78.4	9.67 ± 0.36	60	26.7 ± 4.8
	9.41	10.10 ± 0.57	60	36.3 ± 2.7
Methyl isobutyl ketone	48.5	10.11 ± 0.10	60	96.2 ± 4.4
Ethyl amyl ketone	200	10.11 ± 0.17	60	30.4 ± 2.8
2-Chloroacetophenone	0.44	9.94 ± 0.30	60	36.3 ± 2.7
o-Methylcyclohexanone	53.7	10.37 ± 0.71	60	84.9 ± 3.6
Ethyl butyl ketone	50.8	9.94 ± 0.20	60	97.9 ± 3.2
Dipropyl ketone	49.0	9.81 ± 0.24	60	99.5 ± 4.1
Diacetone alcohol	50.6	9.93 ± 0.24	60	86.2 ± 2.4
Acetone	736	9.740 ± 0.044	120	33.2 ± 2.4

TABLE IV
Sampler capacity test for chloroacetone at a flow rate of 48.90 ± 0.64 mL/min in triplicate experiments

Molar ratio (PFBHA: chloroacetone)	Concentration × sampling time (ppm × min)	Sampling efficiency (%)
5280:1	15	109.2 ± 2.3
1780:1	45	97.7 ± 5.8
1320:1	60	98.8 ± 5.8
681:1	120	81.2 ± 3.1
539:1	150	90.5 ± 8.9
443:1	180	92.9 ± 6.4
385:1	210	100.7 ± 5.7
307:1	264	103.5 ± 3.0
292:1	276	101.8 ± 3.7
261:1	304	87.4 ± 5.4
220:1	365	88.2 ± 2.9
212:1	376	89.3 ± 3.1
154:1	518	81.8 ± 5.2
136:1	583	81.3 ± 1.6
126:1	634	79.7 ± 3.5
112:1	708	71.6 ± 1.8
102:1	778	72.2 ± 3.2
77:1	1046	71.6 ± 4.4
50:1	1585	60.7 ± 4.9
25:1	3158	55.6 ± 4.0

GC/MS TIC analysis shows the *E*- and *Z*-isomers of the PFBHA O-oximes to have the same molecular ion cluster and fragmentation pattern,[22] with a dominant m/z 181 base peak, the 2,3,4,5,6-pentafluorotropylium ion. Average linear dynamic ranges by GC/MS SIM were generally 4.5–20 ng, excepting 0.10–10 ng for chloroacetone (no *E*- and *Z*-isomers) and 2-chloroacetophenone (Table I). All these data are reported for the first time, except for methyl amyl ketone, acetophenone, 2-methylcyclohexanone, and acetone.[28] Generally GC/ECD linear dynamic ranges (not shown here) began at lower injected masses than 1 ng.

TABLE V
Sampler capacity for chloroacetone vapor at a flow rate of 9.83 ± 0.66 mL/min in triplicate experiments

Molar ratio (PFBHA: chloroacetone)	Concentration × sampling time (ppm × min)	Efficiency (%)
982:1	405	105.0 ± 9.7
52:1	7627	94.9 ± 9.4
33:1	13156	95.1 ± 4.3
26:1	15577	75.2 ± 1.2
15:1	26100	35.2 ± 4.5
10:1	39000	40.3 ± 7.7

TABLE VI
Sampler capacity for chloroacetone at flow rate 2.04 ± 0.12 mL/min in triplicate experiments

Molar ratio (PFBHA: chloroacetone)	Concentration × sampling time (ppm × min)	Efficiency (%)
25:1	77844	97.8 ± 5.3
14:1	128478	83.1 ± 5.6
10:1	196250	77.9 ± 5.1
5:1	378500	44.0 ± 9.4
1:1	1950000	10.2 ± 1.3

Table II shows the results of reaction efficiency/O-oxime recovery for wet spiking of ketones. All exceed 87 percent except for acetone. Acetone spiked at double its TLV-TWA sampled at 10 mL/min 8-hr equivalent was recovered at only 42 percent, but spiking equivalent to 200 ppm under the same conditions gave 73 percent recovery. This suggested that the capacity of the sorbent for quantitative sampling was limited to below 40 μmoles but was definitely quantitative at 5 μmoles or below. The theoretical capacity is 160 μmoles. These results agreed with those obtained previously with aldehydes,[24–27] and showed that wet spiking the coated tubes for ketones of TLV equivalent of 200 ppm or less would produce quantitative recoveries of PFBHA O-oximes for quantitation purposes, a vital aspect when no commercial standards are available for these O-oxime derivatives.

Initial vapor sampling over 1 hour at TLV-TWA equivalent conditions (that is, using concentrations of 8 × TLV-TWA) showed recovery problems for all ketones at 50 mL/min and 10 mL/min, except for cyclohexanone and methyl butyl ketone at 10 mL/min (Table III). Because these ketones have 1998 TLV-TWA of 25 ppm and 5 ppm and are not hindered sterically, the aldehyde technique at 10 mL/min can also be used to sample these two ketones in the 8-hour TWA mode, as well as chloroacetone under ceiling limit conditions at 50 mL/min. The aldehyde technique was acceptable for valeraldehyde (TLV of 50 ppm) but was best at 10 mL/min, because breakthrough occurred at 50 mL/min.[24] Thus, because most of the ketones had TLV-TWA values >25 ppm, further ketone vapor evaluations were done at about a flow rate of 10 mL/min, at the TLV sampled for 1 hour. Methyl ethyl ketone, methyl propyl ketone, and 2-methylcyclohexanone sampled under STEL conditions will be successfully sampled with the aldehyde vapor sampling technique.

Vapor sampling efficiencies for ketones at 10 mL/min flow rate for 1 hour in Table III exceeded 79 percent except for acetone, acetophenone, 2-chloroacetophenone, and ethyl amyl ketone where efficiencies varied between 27–36 percent. The low recoveries for acetophenone (TLV 10 ppm) and 2-chloroacetophenone (TLV 0.05 ppm) cannot be due to capacity because their TLVs were low. Instead, an inhibition of the gas phase/solid phase reaction relative to the efficient liquid phase/solid phase

and liquid phase reactions is implied, probably due to the large flat benzene ring, and restriction of access to the carbonyl group by the other alkyl group. As Table II implies, the wet spiking result for acetone was related to capacity, but the gas phase/solid reaction is only about 46 percent as efficient as the liquid/solid reaction since the acetone loading is about the same in Tables II and III experiments. Thus, the solid/vapor chemisorptive process differs from the wet chemical process. The result for ethyl amyl ketone is probably of similar origin.

Ethyl and methyl ketones with alkyl straight chain groups from C_1 through C_5 were efficiently sampled for 60 min at their TLV concentrations, as were methyl ketones with isopropyl- and isobutyl-groups and also dipropyl ketone. The exception was the *n*-amyl alkyl group in ethyl amyl ketone where the yield was 30 percent at 200 ppm equivalent. Capacity cannot be the sole reason because 199 ppm equivalent diethyl ketone and methyl isopropyl-, ethyl-, and propyl-ketones between 197–200 ppm equivalent produced acceptable recoveries at the same sampling conditions. Probably, the β carbons of both chains are partially shielded in the gas phase/solid phase reaction though not in the liquid/solid wet spiking experiment. This implies that access of the carbonyl group to the hydroxylamine group of physically adsorbed PFBHA on the solid sorbent is limited for the gas/solid chemisorption of ethyl amyl ketone but not for methyl amyl ketone. Diisobutyl ketone and 2,4-hexanedione show low efficiencies on reaction with PFBHA in their wet chemistry.[28]

Previous work showed that the absolute recovery for *n*-valeraldehyde vapor in the dynamic method varied with flow rate, 10 mL/min being better (efficiency of about 100%) than 50 mL/min (efficiency 71–85%).[24–26] The *n*-valeraldehyde capacity in the gas phase/solid phase[24] was at least 13 μmoles, compared with a maximum of 5 μmoles for both cyclohexanone and methyl propyl ketone for quantitative recoveries in the present vapor phase study.

These results prompted an in-depth examination of the behavior of two unhindered ketones, acetone and chloroacetone, relative to concentration, flow rate, capacity, breakthrough, and sampler parameters.

A 200-mg front section/100-mg back section sampling configuration for 20 percent PFBHA sorbent showed 31.20 ± 0.44 percent overall recovery with 26–33 percent breakthrough after spiking 3 μL acetone (41 μmoles) and then drawing clean air through at 10 mL/min for 2 hr. The same configuration used to sample a 736 ppm gas bag for 2 hr at 9.74 mL/min showed an overall recovery of 49.6 ± 2.7 percent with breakthroughs of 31–37 percent. This proved a capacity problem existed for acetone. When 300-mg sorbent coated with 90 percent PFBHA was spiked with 21.7 μL acetone, the recovery was 58.9 ± 2.9 percent, an improvement relative to the corresponding 20 percent coated 200-mg sorbent data of 42.1 ± 6.8 percent in Table II. When the 90 percent sorbent was placed in a 300-mg front section/100-mg backup section configuration, spiked with 21.7 μL again, and clean air then drawn through at 10 mL/min for 2 hr, the overall efficiency decreased to 7.6 ± 1.1 percent with 10–42 percent breakthrough. The latter configuration was then used to sample 6009, 3000, and 755 ppm at 10 mL/min for 2-hr periods. The respective overall efficiencies/breakthroughs were: 2.80 ± 0.35 percent/22–32 percent; 3.21 ± 0.25 percent/25–58 percent; and 14.1 ± 1.2 percent/23–28 percent. Thus, increasing the PFBHA content did not solve the capacity problem for acetone, and neither did including a backup section because breakthrough also occurred through the latter. There appeared to be a complex capacity, flow dependence, challenge concentration, and PFBHA coating interactive dependence. The capacity and challenge concentration factors were minimized by using chloroacetone because it had only a ceiling value, and that concentration was low.

The chloroacetone results for efficiency E in percent from gas bag experiments are presented in Tables IV through VI for three different average flow rates (F), 48.9, 9.83, and 2.04 mL/min, respectively, at different ppm-min exposures P and PFBHA/ketone molar ratios (R). Assuming that the initial chemisorption adsorption isotherm can be described by a Henry (linear) type law indicative of strong adsorption, the best linear regression relationships for 48.9 mL/min in the R range 220 to 25 at $p < 0.05$ for $n = 10$ were (Table IV):

$$\text{Log } E = 0.227 \text{ log } R + 1.42 \quad r = 0.9791 \qquad [1]$$

$$\text{Log } E = -0.228 \text{ log } P + 2.53 \quad r = -0.9785 \qquad [2]$$

$$\text{Log } R = -1.0048 \text{ log } P + 4.91 \quad r = -1.000 \qquad [3]$$

Those for 9.83 mL/min in the R range 982 to 10 at $p < 0.05$ for $n = 6$ were (Table V):

$$\text{Log } E = 0.205 \text{ log } R + 1.50 \quad r = 0.7046 \qquad [4]$$

$$E = -0.0020\ P + 108 \quad r = -0.9160 \qquad [5]$$

$$\text{Log } R = -1.003 \text{ log } P + 5.61 \quad r = -0.9997 \qquad [6]$$

Equation (4) was not significant at $p < 0.05$ but was the best correlation, and is included to compare with Eqs. (1) and (7) for 48.9 and 2.04 mL/min, respectively.

Those for 2.04 mL/min in the R range 25 to 1 at $p < 0.05$ for $n = 5$ were (Table VI):

$$\text{Log } E = 0.735 \text{ log } R + 1.07 \quad r = 0.9796 \qquad [7]$$

$$\text{Log } E = -0.729 \text{ log } P + 5.65 \quad r = -0.9801 \qquad [8]$$

$$\text{Log } R = -0.992 \text{ log } P + 6.24 \quad r = -0.9996 \qquad [9]$$

The log/log relationship was consistently the most statistically significant for all F, except for the linear E versus P relationship for the 9.83 mL/min flow rate.

If 75 percent recovery is taken as the critical E,[30] the critical P/R are 746/101:1 [from Eqs. (2) and (1), respectively], 15577/26:1 (interpolated), and 200,000/10:1 (interpolated) for 48.9, 9.83, and 2.04 mL/min, respectively. The interpolated data were used because the actual data were close to the critical point, and Eq. (4) was not significant at $p < 0.05$. Regression analysis

showed that P or log P versus F, or P or log P versus R were not linear, as also were log R versus F and log R versus log F.

The only linear relationships at $p < 0.05$ for 200 mg of 20 percent PFBHA coated sorbent at 75 percent efficiency were:

$$R = 1.93\ F + 6.48 \quad r = 1.000 \qquad [10]$$

$$\text{Log } P = -1.76 \log F + 5.88 \quad r = -0.9990 \qquad [11]$$

$$\text{Log } P = -2.41 \log R + 7.67 \quad r = -0.9988 \qquad [12]$$

All intercepts are non-zero at $p < 0.05$. Equation (10) shows that R and F are linearly related. At $F = 0$, $R = 6.48$. In other work on n-valeraldehyde, R was 10.8, and log R versus F was linear, but with a very shallow slope.[25] For *n*-valeraldehyde, R did not vary much, being 12 at 10 mL/min and 17 at 50 mL/min, compared with 26 and 103 for these respective flow rates for chloroacetone from Eq. (10). If chloroacetone is representative of unhindered ketones as is n-valeraldehyde for aldehydes, ketones require a much greater excess of PFBHA for quantitative reaction at the same flow rates than do aldehydes. However, it is clear that the initial surface events do not have 1:1 stoichiometry but require at least 12- to 17-fold excess PFBHA molecules for aldehydes, and 26–100 excess for chloroacetone.

The less bulky carbonyl H of aldehydes allows much better access of the carbonyl group to the hydroxylamine group of surface-adsorbed PFBHA than does chloroacetone to form the initial activated tetrahedral intermediate. The intermediate can still be formed if there are enough excess surface PFBHA molecules at a given flow rate, or if ketone contact time is made longer by lowering F. However, the lower the flow rate, the higher must be the sensitivity of the analytical chemical method. The Tenax TA surface must also play a role in the process because merely increasing PFBHA relative to Tenax TA does not lead to increased efficiency, as illustrated by the acetone experiments when R was increased. The benzene ring in the acetophenone molecules, and functional groups substituted at both β carbons to the carbonyl group probably also do not allow ready access of the carbonyl group to the hydroxylamine group of the surface-bound PFBHA.

The extension of the previous aldehyde results to the related carbonyl compounds, the ketones, is not only important to be able to anticipate positive interferences to aldehyde analysis, but also for establishing an analytical method for ketones where the aldehydes may also be positive interferences. Not only is PFBHA a more potent reagent than DNPH because PFBHA reacts quantitatively with conjugated aldehydes and spiking data generally better match vapor spiking data, PFBHA-based analysis by GC/MS and GC/ECD is better placed for sensitivity and selectivity in a shorter analysis time than the HPLC analysis necessary for the DNPH derivatives. While the PFBHA method has a lower ketone capacity than does activated charcoal (typically >163 μmoles,[10]) the PFBHA method can still be used to sample ketones when capacity and steric effects are not problems and when more selectivity than in charcoal tube analysis is required.

CONCLUSIONS

The PFBHA aldehyde dynamic sampling technique was shown to sample ketone vapors also, so that ketones are positive interferences whose presence must be accounted for by the appropriate modification of chromatographic conditions during the chemical analysis step. The best recoveries for ketones occurred at 10 mL/min sampling pump flow rate rather than at 50 mL/min; this was especially true for ketones whose recommended TLV-TWAs exceeded 25 ppm but not above 200 ppm. Sampling flow rates at 10 mL/min will allow quantitative recoveries for all ketones at TLV-TWA conditions at 200 ppm for 1 hr (200 ppm-hr). Acetone sampling about its TLV or higher under TWA conditions caused breakthrough, while the recoveries of acetophenone, *o*-chloroacetophenone, and ethyl amyl ketone at 200 ppm-hr were affected by steric factors and did not exceed 75 percent sampling efficiency. To sample both aldehydes and ketones together at their TLV concentrations is best done at 10 mL/min flow rate.

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