

VOC Concentrations of Interest in North American Offices and Homes

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Summary: *Indoor air quality investigators often sample many volatile organic chemicals but with insufficient knowledge of their potential impacts on occupants. Studies performed in North American offices and residences since 1990 were reviewed and central tendency and maximum VOC concentrations were summarized by building type. These concentrations were assessed relative to various guideline values for odor, sensory irritancy and noncancer chronic toxicity to identify compounds that may reach levels of concern. These comparisons revealed that less than one-fifth of the 106 VOCs studied reached levels that were $\geq 10\%$ of guideline values. Guidelines are needed for other VOCs and other health endpoints.*

Keywords: *Indoor exposure, Guidelines, Chronic toxicity, Sensory Irritancy, Odor thresholds*

1. Introduction

Consideration of indoor exposures to air pollutants is critical to health hazard assessments. For many toxic volatile organic compounds (VOCs), indoor concentrations exceed outdoor concentrations due to numerous indoor sources, limited dilution volumes, and relatively low ventilation rates. The decade since 1990 has witnessed increased concern about the environmental consequences and adverse health effects of air pollution. In the U.S., the 1990 Clean Air Act (CAA) Amendments established programs to regulate emissions of air pollutants associated with cancer, reproductive harm, and other serious illnesses. Nearly 200 substances are classified as hazardous air pollutants (HAPs). Industry is regulated to reduce their emissions of HAPs and cleaner fuels and engines have been mandated. It is possible that indoor as well as outdoor exposure concentrations for some HAPs have been reduced as direct or indirect results of these programs.

Indoor VOC concentrations in residential and commercial buildings from about 1978 through 1990 have been summarized in several reviews. Much of this data is from North America (NA). We have updated this information by compiling and summarizing the data on the central tendency and upper limit indoor VOC concentrations measured in NA from 1990 through 2001 [1]. Data from existing residences, new residences and large office buildings were treated separately. Our primary objective was to generate a database of typical and maximum VOC concentrations that can be used as a comparative basis for evaluating measured concentrations.

In a companion paper [2], we assessed the summarized VOC concentrations in residences and office buildings with respect to odor thresholds,

sensory irritation levels for the general population and noncancer chronic health risks. Our objective was to identify and broadly classify VOCs that are most likely to result in comfort and/or health concerns. We excluded cancer from consideration, as the risk assessment approach and the time period of interest for cancer are substantially different. Other effects, such as immunological responses, were not considered due to insufficient toxicological data. This assessment, while revealing the limitations of the available concentration data and present knowledge regarding health outcomes, can provide guidance for prioritizing indoor air pollutants for monitoring and for efforts to limit indoor exposures through combinations of ventilation and source controls.

2. Methods

We defined VOCs as chemical compounds with carbon chains or rings and vapor pressures greater than ~ 1 Pa at room temperature. Papers were gathered from journal literature with several exceptions. We focused solely on reported measurements made in NA residences, both new and existing, and office buildings from 1990 through 2001. Only cross-sectional studies that investigated five or more buildings were considered. Investigations of unusual environments or pollutant sources were excluded. In total, we identified 13 papers presenting the results for 12 studies of existing residences, 2 papers for new residences, and 3 papers for office buildings. Limited data editing was performed. Concentrations given as mass per unit volume ($\mu\text{g}/\text{m}^3$) were converted to ppb concentrations assuming standard indoor conditions. 106 VOCs were identified (see Table 1). Broad ranges of chemical functionality and volatility were represented. Central tendency and upper limit

concentrations were summarized separately for residences and office buildings.

Odor Thresholds

Standardized human odor thresholds (OTs) for VOCs were obtained from Devos *et al.* [3]. One hundred percent odor detection thresholds were obtained from the Cometto-Muñiz and Cain research group [4]. These were divided by 10 to adjust for the difference between 100% recognition criteria and an assumed 50% recognition threshold for the Devos *et al.* values. For VOCs with OTs from both sources, we assumed the adjusted Cometto-Muñiz *et al.* values were more reliable because they were determined with a consistent contemporary methodology.

Sensory Irritants

Exposures to high levels of sensory irritants stimulate a response through the trigeminal nerve and cause a reflex change in breathing pattern. A mouse bioassay exploits this change as a measure of sensory irritancy. The procedure calculates the concentration producing a 50% decrease in frequency. These RD50s have been reported for a large number of individual VOCs. Human nasal pungency thresholds (NPTs) are a measure of the trigeminal response of the nose when exposed to airborne sensory irritants. The Cometto-Muñiz and Cain group has employed a uniform methodology with groups of anosmic subjects to determine NPTs for VOCs in different classes.

The California EPA Office of Environmental Health Hazard Assessment (OEHHA) has developed acute Reference Exposure Levels (RELs) for some hazardous airborne pollutants [5]. An acute REL is an exposure concentration unlikely to cause adverse effects in humans, including sensitive individuals, exposed to the concentration for one hour. Guidelines to protect workers from the adverse effects of exposure to chemicals have been developed over many years. Threshold Limit Values (TLVs) constitute one of the most widely used sets of occupational exposures levels (OELs) in the U.S. and elsewhere. TLVs are intended to protect workers for an eight-hour workday assuming a typical 40-h workweek.

We endeavored to place the measures of sensory irritancy onto a comparable scale. Others have estimated sensory irritation effects in humans by applying an uncertainty factor to RD50s. These studies generally support an early proposal for estimating TLVs by setting them 1.5 orders of magnitude below their RD50s on a log scale. NPTs occur at elevated concentrations approximately equivalent to RD50s. Various agencies have attempted to establish inhalation exposure guidelines for the general population by applying uncertainty factors to TLVs and other OELs. Based on the work of Nielsen *et al.* [6] and others, we adopted the approach of adjusting the TLVs of

compounds with irritancy as the sole or principal effect by dividing by 10 to account for sensitive sub-populations. By extension, RD50s were adjusted by 2.5 orders of magnitude (*i.e.*, 1.5 orders of magnitude factor to equate RD50s with TLVs plus a factor of 10 for sensitive groups). The same factor was applied to NPTs. We assumed that sensory irritation response was best characterized by human measures (NPTs, TLVs, and RELs); that among the human measures NPTs were the most directly applicable; and, that acute RELs represented more current and thorough reviews of the literature on human response than TLVs.

Chronic Noncancer Effects

Several NA agencies have established health-based, noncancer guidelines for chronic exposures of the general population to toxic air pollutants. The U.S. EPA has developed noncancer, inhalation reference concentrations (RfCs) for some HAPs. The RfCs are concentrations to which it is believed humans including sensitive groups can be exposed over long periods without effects. The Environmental Health Directorate, Health Canada has developed analogous tolerable concentrations for inhalation for some VOCs. The U.S. Agency for Toxic Substances and Disease Registry (ATSDR) has developed acute, intermediate and chronic health effect guideline levels for inhalation exposures to a number of industrial chemicals. These Minimal Risk Levels (MRLs) are estimates of the daily human exposures unlikely to cause appreciable risk of adverse noncancer effects in sensitive populations over specified durations. For the ATSDR source, we selected the lowest inhalation MRLs derived for either the intermediate (>14 to 364 days) or the chronic (≥ 365 days) exposure period as the best measure. OEHHA has developed noncancer chronic RELs for 78 chemicals following the same general approach as used by the U.S. EPA for RfCs [5].

Noncancer chronic exposure guidance levels were estimated for the general population from TLVs that are not based on cancer or irritation as the primary effect. Following the suggestions of others, a factor of 1/40 was applied to account for the difference between a 40-h workweek and a constant 24-h a day exposure and including a factor of 10 uncertainty for sensitive groups. Then, a worst-case pharmacokinetic factor of 0.2 was applied to account for the lack of a recovery period for chemicals with a biological half-life of over eight hours. The total adjustment was TLV/200.

We assumed chronic REL, RfC and MRL concentrations were better measures of chronic toxicity than the TLV-based measures due to the uncertainty in the use of a universal adjustment factor with TLVs. We gave preference to the OEHHA chronic RELs since they generally were based on the most current toxicological literature

for the largest set of compounds. Our second preference was the lower of the two other measures.

Comparison with Guideline Values

We next compared the best estimates of odor thresholds and protective sensory irritation and noncancer chronic health levels for the general population to the VOC concentrations measured in residences and office buildings. This was accomplished by dividing maximum, or the derived 95th percentile (95thile), concentrations by the selected guideline values to produce indoor hazard quotients. Measured VOCs were classified with respect to the different effects based on these hazard quotients. We considered compounds with

quotients in excess of unity to be of primary concern. Quotients within one order of magnitude of unity defined the next level of concern. Since this was a screening level assessment, we did not ascribe any particular importance to compound ranking within or between the two categories of concern.

3. Results and Discussion

Table 1 lists 106 VOCs for which concentration data were obtained. They are organized by chemical class and ordered by decreasing volatility within class. The U.S. EPA classifies 35 of these as HAPs.

Table 1. VOCs reported since 1990 for North American existing and new residences and office buildings, organized by chemical class and decreasing boiling point within class.

Chem. Class	Compound (CAS No.)
Alcohols	Ethanol (64-17-5), 2-propanol (67-63-0), 1-butanol (71-36-3), phenol (108-95-2), 2-Ethyl-1-hexanol (104-76-7), 1-octanol (111-87-5), butylated hydroxytoluene (128-37-0)
Ethers	<i>t</i> -Butyl methyl ether (1634-04-4), 1,4-dioxane (123-91-1)
Glycols	Ethylene glycol (107-21-1), 2-butoxyethanol (111-76-2), 1,2-propanediol (57-55-6), 2-(2-butoxyethoxy)ethanol (112-34-5)
Ketones	2-Propanone (67-64-1), 2-butanone (78-93-3), 4-methyl-2-pentanone (108-10-1), cyclohexanone (108-94-1), 1-phenylethanone (98-86-2)
Aldehydes	Formaldehyde (50-00-0), acetaldehyde (75-07-0), propionaldehyde (127-38-6), acrolein (107-02-8), butanal (123-72-8), 3-methylbutanal (590-86-3), pentanal (110-62-3), hexanal (66-25-1), heptanal (111-71-7), 2-furaldehyde (98-01-1), octanal (124-13-0), benzaldehyde (100-52-7), nonanal (124-19-6)
Esters	Ethyl acetate (141-78-6), butyl acetate (123-86-4), 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (25265-77-4), 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (6846-50-0), diethylphthalate (84-66-2)
Acids	Formic acid (64-18-6), acetic acid (64-19-7), hexanoic acid (142-62-1)
Alkane HCs	n-Pentane (109-66-0), 2-methylpentane (107-83-5), 3-methylpentane (96-14-0), n-hexane (110-54-3), 3-methylhexane (589-34-4), n-heptane (142-82-5), 2,2,5-trimethylhexane (3522-94-9), n-octane (111-65-9), n-nonane (111-84-2), n-decane (124-18-5), n-undecane (1120-21-4), n-dodecane (112-40-3), n-tridecane (629-50-5), n-tetradecane (629-59-4), n-pentadecane (629-62-9), n-hexadecane (544-76-3)
Cyclic HCs	Methylcyclopentane (96-37-7), cyclohexane (110-82-7), methylcyclohexane (108-87-2), propylcyclohexane (1678-92-8), butylcyclohexane (1678-93-9)
Alkene & terpene HCs	1,3-Butadiene (106-99-0), isoprene (78-79-5), α -pinene (7785-70-8), camphene (5794-04-7), 3-carene (13466-78-9), β -pinene (18172-67-3), d-limonene (5989-27-5), p-cymene (99-87-6)
Aromatic HCs	Benzene (71-43-2), toluene (108-88-3), ethylbenzene (100-41-4), m/p-xylene, o-xylene (95-47-6), styrene (100-42-5), cumene (98-82-8), propylbenzene (103-65-1), 3/4-ethyltoluene, 4-ethyltoluene (622-96-8), 2-ethyltoluene (611-14-3), 1,3,5-trimethylbenzene (108-67-8), 1,2,4-trimethylbenzene (95-63-6), 1,2,3-trimethylbenzene (526-73-8), buylbenzene (104-51-8), naphthalene (91-20-3), 4-phenylcyclohexene (4994-16-5)
Halocarbons	Vinyl chloride (75-01-4), bromomethane (74-83-9), trichlorofluoromethane (75-69-4), dichloromethane (75-09-2), trichlorotrifluoromethane (76-13-1), chloroform (67-66-3), 1,1,1-trichloroethane (71-55-6), carbon tetrachloride (56-23-5), 1,2-dichloroethane (107-06-2), trichloroethene (79-01-6), tetrachloroethene (127-18-4), chlorobenzene (108-90-7), 1,4-dichlorobenzene (106-46-7), 1,2-dichlorobenzene (95-50-1), 1,2,4-trichlorobezene (120-82-1)
Miscellaneous	Carbon disulfide (75-15-0), acrylonitrile (107-13-1), pyridine (110-86-1), octamethylcyclotetrasiloxane (556-67-2), decamethylcyclopentasiloxane (541-02-6), benzothiazole (95-16-9)

The complete VOC concentration summaries are shown in the original report [1]. For existing residences, both central tendency values (geometric mean (GM), median, and/or mean) and upper limits (90%ile, 95%ile, and/or maximum) were summarized. For new residences, GM and maximum values were summarized. For office buildings, central tendency (GM or median) and maximum VOC concentrations were determined. VOC concentrations in buildings had wide distributions. Residential studies often reported standard deviations for arithmetic average concentrations that were about the same magnitude as the average values. Typical GM standard deviations for distributions of VOC concentrations in both residences and office buildings were about 2.0-2.2. Maximum concentrations in all buildings uniformly were <1 ppm.

Figure 1 compares central tendency and maximum concentrations of selected VOCs between existing residences (12 studies) and office buildings (3 studies). Central tendency concentrations of n-dodecane, 1,1,1-trichloroethane, trichloroethene and tetrachloroethene were more than three times higher in office buildings. Residences had higher central tendency concentrations of pentanal, α -pinene, d-limonene, 1,4-dichlorobenzene, and dichloromethane. Maximum concentrations of the six aromatics were more than three times higher in residences.

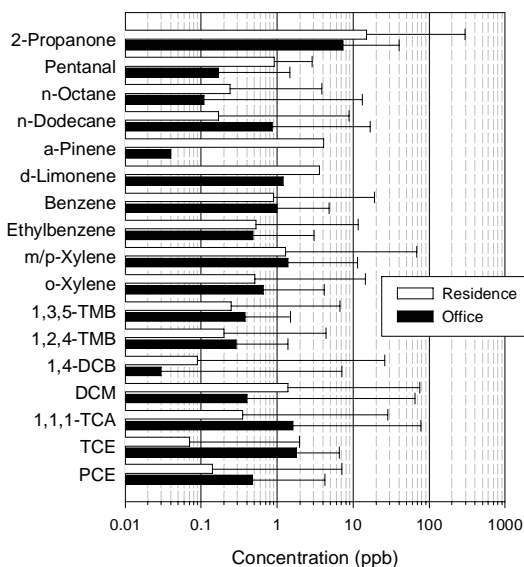


Figure 1. Comparison of central tendency and maximum concentrations (whiskers) of selected VOCs between existing residences and office buildings. TMB = trimethylbenzene, DCB = dichlorobenzene, DCM = dichloromethane, TCA = trichloroethane, TCE = trichloroethene, PCE = tetrachloroethene.

In Figure 2, the central tendency concentrations for existing residences from the current review summarized as unweighted GMs are compared with the U.S. EPA's TEAM study unweighted GM concentrations for 17 VOCs from nine residential studies conducted prior to 1990 [7]. The current 1,1,1-trichloroethane concentration is more than three times lower than the TEAM study value. Other compounds with similar differences are benzene, 1,2-dichloroethane and tetrachloroethene. Such changes with time likely are due to the increased environmental regulations of the CAA that have targeted these compounds.

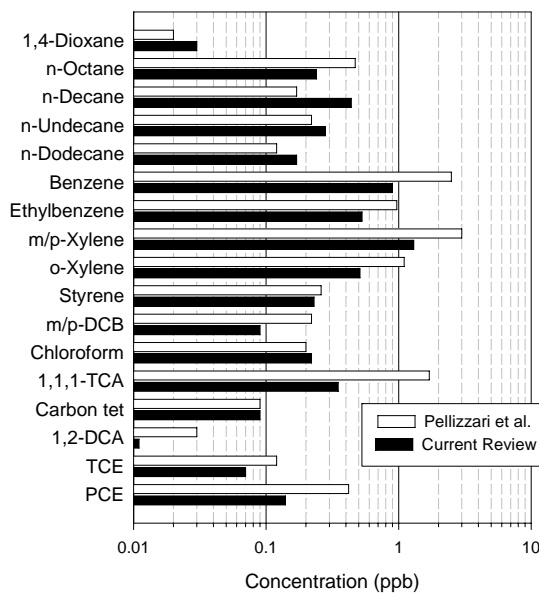


Figure 2. Comparison of geometric mean (GM) concentrations of 17 VOCs with GM concentrations from the U.S. EPA TEAM studies prior to 1990 as reported by Pellizzari et al. DCA = dichloroethane.

The reported maximum concentrations of 14 VOCs approached levels of concern with respect to odor. As shown in Table 2, VOCs with odor quotients exceeding one, indicating likely olfactory perception, were hexanoic acid and the aldehydes hexanal, heptanal, octanal, and nonanal in new residences and acetic acid in existing and new residences. Compounds in residences and office buildings with odor quotients between 0.1 and 1 were 1-butanol, formaldehyde, acetaldehyde, propionaldehyde, 3-methylbutanal, m/p-xylene, naphthalene, and 1,4-dichlorobenzene.

Only three VOCs with summarized maximum concentrations in residences and office buildings were considered to be relatively potent sensory irritants at the reported concentrations. The maximum concentrations of these compounds are listed by building type along with their respective

sensory irritation quotients in Table 2. Due to its low sensory irritation threshold value, acrolein had the singularly highest quotient in residences. Formaldehyde and acetic acid with quotients near or in excess of unity also were indicated to be of relatively high concern with respect to sensory discomfort in residences.

Table 3 lists the central tendency concentrations and the chronic toxicity quotients for the most

potent VOCs in the review. VOCs with hazard quotients >1 were formaldehyde, acetaldehyde and acrolein, for which only residential data were available. Of these, acrolein had the singularly highest hazard quotient. VOCs with hazard quotients >0.1 were the aromatic hydrocarbons, benzene, toluene and naphthalene, and the chlorinated solvent tetrachloroethene.

Table 2. Maximum concentrations of VOCs of potential concern in existing and new residences and in office buildings with their odor and sensory irritation quotients (maximum conc./odor or sensory irritation threshold).

Compound	Maximum Conc. (ppb)			Odor Quotient			Sensory Irr. Quotient		
	Exist Res.	New Res.	Office Bldg.	Exist Res.	New Res.	Office Bldg.	Exist Res.	New Res.	Office Bldg.
1-Butanol		21	0.5		0.11	0.03			
Formaldehyde	180	62		0.21	0.07		2.3	0.81	
Acetaldehyde	16	43		0.08	0.23				
Acrolein	13						160		
Propionaldehyde	5.6	19		0.21	0.70				
3-Methylbutanal	1.2			0.55					
Hexanal		36	2.4		4.6	0.30			
Heptanal		4.9			1.5				
Octanal		7.2			18				
Nonanal		7.6	1.4		3.5	0.64			
Acetic acid	81	280		81	280		0.62	2.2	
Hexanoic acid		5.5			11				
m/p-Xylene	67	11	10	0.21	0.03	0.03			
Naphthalene	0.95		1.9			0.13			
1,4-Dichlorobenzene	26		7.0	0.54		0.15	0.05		0.01

Table 3. Central tendency and derived 95th percentile concentrations of selected VOCs in existing residences and in office buildings with their noncancer chronic toxicity quotients (derived 95thile conc./lowest chronic toxicity guideline).

Compound	Central Tend. Conc.		Derived 95 th ile Conc.		Chronic Tox. Quotient	
	Exist Res.	Office Bldg.	Exist Res.	Office Bldg.	Exist Res.	Office Bldg.
Formaldehyde	17		61		26	
Acetaldehyde	3.0		11		2.2	
Acrolein	1.8		6.5		217	
Benzene	0.9	1.0	3.2	3.6	0.17	0.19
Toluene	3.3	2.1	12	7.6	0.15	0.09
Naphthalene	0.09		3.2		0.19	
Tetrachloroethene	0.14	0.47	0.51	1.7	0.10	0.33

4. Conclusions

We have presented a methodology for classifying the relative importance of VOCs commonly present in indoor air with respect to their odor and sensory irritation potency and noncancer chronic toxicity. Although both the concentration distribution and the health effects data upon which this methodology was based are imperfect, only a small number of the more than 100 reported VOCs were shown to exceed levels of potential concern with respect to the comfort and health endpoints considered. We recommend future studies characterizing VOC concentrations and exposures in buildings focus their resources on measurements of those compounds most likely to impact occupants as determined by the objectives of the investigations. The lists of target compounds likely would be relatively small. In addition to the compounds identified here, other compounds with similar physicochemical properties should be included in monitoring studies. For a few compounds, such as acrolein and formaldehyde, the evidence likely is sufficient to warrant efforts to reduce and otherwise control their sources in buildings.

5. Acknowledgements

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