Classification of Measured Indoor Volatile Organic Compounds Based on Noncancer Health and Comfort Considerations

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Abstract

Building occupants are exposed to complex mixtures of air pollutants including many volatile organic compounds (VOCs). A recent review summarized the central tendency and upper limit indoor VOC concentrations measured in North American residences and office buildings since 1990. Although this database is limited in many respects, it serves as a useful starting point for evaluating the potential health and comfort effects of indoor VOC exposures. Excluding cancer and birth defects, the primary concern is chronic inhalation exposure to toxicants that can cause serious health problems. Additionally, building occupants react to the quality of indoor air through their sensory perceptions and frequently experience unpleasant odors and irritation of the eyes and upper respiratory tract.

In this paper, we conduct a simple screening-level assessment of indoor VOC concentrations. We compare measured VOC concentrations to published odor thresholds, sensory irritation levels derived for the general population, and noncancer chronic health guidelines. Hazard quotients are individually calculated for these three effects by dividing maximum or derived 95th percentile VOC concentrations by our selected best estimates of guidance levels for the general population. These results provide a basis for broadly classifying commonly encountered VOCs into groups according to the likelihood that they will produce effects among building occupants.

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This methodology shows that only a small number of the more than 100 reported VOCs exceed levels that are likely to be of concern with respect to the health and comfort endpoints considered. Although data is lacking for a number of odorous compounds potentially present in buildings, the results indicate that carboxylic acids, higher molecular weight aldehydes and less volatile aromatic hydrocarbons are most likely to be perceived by olfaction and that there is more probability of detection in residences than in offices. Sensory irritation levels were approached or exceed by only a very small number of relatively potent, reactive VOCs. Of these, acrolein was by far the most potent irritant. Although more detailed consideration of the underlying toxicological data is needed, the results suggest that only a small number of commonly measured VOCs, when considered singly, are likely to produce serious irreversible health effects not associated with cancer. These compounds include lower molecular weight aldehydes, and several aromatic hydrocarbons. Again, acrolein stands out as the most potent compound.

Based on these results, we recommend that studies to characterize indoor VOC concentrations and exposures focus their resources on compounds that are most likely to impact occupants as determined by the study objectives. For a very few compounds, such as acrolein and formaldehyde, the evidence based on sensory irritation and chronic toxicity appears sufficient to warrant efforts to reduce and control sources of these compounds in buildings.

Introduction

The number of air pollutants of concern with respect to potential human health effects significantly expanded in 1990 with the introduction of the U.S. Clean Air Act (CAA) Amendments. This law established Federal and State programs to regulate the ambient emissions of 188 (originally 189) hazardous air pollutants (HAPs), consisting of chemical substances including many volatile organic compounds (VOCs) that can cause cancer, reproductive harm, other serious illness or environmental damage (U.S. EPA, 1994). The interest in the outdoor environment and cancer risk has dominated governmental regulatory efforts.

It is widely recognized, however, that indoor exposures to VOCs and other air pollutants are at least as, if not more, important, than ambient exposures. Time activity studies show that individuals spend, on average 87% of their time indoors (Jenkins *et al*., 1992; Klepeis *et al*, 2001). Most VOCs of outdoor origin penetrate indoors through ventilation and infiltration. Numerous indoor VOC sources in residential, commercial and public buildings add to indoor concentrations and exposures. Furthermore, the relatively low rates of outdoor air ventilation in buildings prevent the rapid dispersal of indoor generated pollutants (Lai *et al*., 2000). Numerous building studies confirm that indoor air concentrations of many toxic VOCs are significantly higher than outdoor concentrations (*e.g.*, Daisey *et al*., 1994; Shields *et al*., 1996).

Indoor VOC data collected in North America and western Europe from about 1978 through the 1980's were summarized in several reviews (Shah and Singh, 1988; Brown *et al*., 1994; Holcomb and Seabrook, 1995). Central tendency and upper limit indoor VOC concentrations measured in North America from 1990 through the present recently have been reviewed (Hodgson and Levin, 2003). Twelve of the post-1989 studies were cross sectional investigations of existing residences. Three cross sectional office building studies were identified. The summary tables in the review list concentration data for more than 100 VOCs of which 35 are classified as HAPs. An analysis of historical trends suggests that average indoor concentrations of some HAPs, such as benzene, 1,2-dichloroethane, 1,1,1-trichloroethane and tetrachloroethene, may have decreased since the 1980's. In addition, the use of alternate VOCs in products with indoor applications may have increased over the same time period. Due to such changes, the more recent data have greater relevancy for assessments of potential occupant effects.

Unfortunately, the post-1989 database, like the previous summaries, is limited in many respects. The limitations are due, in part, to the relatively high costs of conducting field studies and to the restrictions imposed by the standard techniques that are employed for broad-spectrum VOC sampling and analysis. The following deficiencies in the database are notable and have been highlighted by others (*e.g.*, Wolkoff *et al*., 1997). Only relatively small numbers of building units are represented. In the current review, the maximum total number of residential

units for an individual VOC is about 1,000. Less than one-half of the reviewed studies employed a probability-based design for selecting building units. Data is lacking for many important indoor environments, such as schools, health-care facilities and small offices. Most studies measured a small number of compounds. In many cases, the focus was on a limited suite of aromatic and chlorinated hydrocarbons that are classified as carcinogens and are relatively easy to analyze by standard techniques. Most sampling schemes relied solely on short-term measurements made on a single day so that the range of variability within individual buildings was not captured. Spatial variability within buildings often was not addressed. Only in a few cases were personal exposure samples collected, so it is not possible to compare area concentrations with breathing-zone concentrations that may be significantly higher (Rodes *et al.*, 1991; Wallace, 1987).

The potential importance of indoor exposures to VOCs goes beyond the question of low level chronic exposures to toxicants. Building occupants initially react to the quality of indoor air through their sensory perceptions. Their impressions may be of unpleasant odors, irritation of the eyes and upper respiratory tract, or nonspecific sensations such as stuffiness. These sensory responses still serve as the basis for modern ventilation standards that attempt to achieve acceptable perceived air quality for a majority of occupants (ASHRAE, 1999). Viewed conversely, this approach assures that there will be dissatisfaction among a substantial fraction of building occupants even if code-minimum ventilation is provided. In fact, meta analyses of epidemiological studies show office workers commonly report relatively high frequencies of eye, nose, throat and lower respiratory tract symptoms that are associated with work (*i.e.*, improve when away from work) (Mendell 1993; Mendell *et al.*, 1996). Although the etiology of these sensory irritation and respiratory complaints among office workers has not been established, the symptoms are generally associated with ventilation rate such that symptom prevalence often decreases with increasing per person ventilation rate (Seppänen *et al.*, 1999). This relationship suggests that the causal agents are airborne.

Sensory irritation symptoms experienced by building occupants may be related to exposures to VOCs, which as a group contain a large number of irritant species. However, such symptoms are not associated with measures of total VOCs (Andersson *et al.*, 1997). Direct relationships between concentrations of individual VOCs and irritation symptoms also have not been established with a few exceptions such as formaldehyde (Liu *et al*., 1991). It has been suggested that these symptoms are caused by exposures to air pollutant components (either singly, in combination, or produced as the result of oxidative chemistry) that are associated with indoor sources of VOCs, but that are not easily measured (Ten Brinke *et al.* 1998; Wolkoff *et al.*, 1997; Wolkoff and Nielsen, 2001).

Odors in buildings caused by VOCs may not be of toxicological concern. However, the detection of unusual or unpleasant odors can cause occupants to feel threatened or to be concerned, precipitating complaints. Such complaints among office workers may be associated with absenteeism and decreased worker productivity. Other financial loses can be incurred due to expensive investigations and remedial actions.

The assessment of risks of serious health consequences associated with inhalation exposures to VOCs is highly developed for the ambient environment. The U.S. EPA's National Air Toxics Assessment program has quantified the risks of 32 common HAPs (plus diesel PM) in order to identify compounds that pose the greatest risk of cancer and adverse noncancer health effects on a regional and a national basis (U.S. EPA, 2000; Woodruff *et al*. 1998). A similar risk assessment has been performed for TACs in California (Morello-Frosch *et al.*, 2000). The general approach is to estimate ambient air concentrations by geographical region from source emissions data using a dispersion model that incorporates simulations of atmospheric processes. The modeled concentrations are compared to specified cancer risks and noncancer hazard levels. Cancer risks are presented as the lifetime risks of developing cancer over a 70-year lifetime. Noncancer risks are presented in terms of the ratio between exposure and a reference concentration (*i.e.*, a hazard quotient). The numbers of individuals exposed at these risk levels

are calculated to rank the HAPs and TACs that pose the greatest relative hazard on a regional scale.

This risk assessment methodology cannot be applied fully to the indoor environment because the indoor concentrations of HAPs/TACs are not well defined due to the noted deficiencies in the database. An alternate or complementary approach is to model indoor concentrations and exposures based on source characteristics including VOC emission rates, VOC removal mechanisms, building parameters and human activity patterns. Significant progress has been made in modeling VOC emissions from some indoor sources, but the assembly of all of the relevant variables into a model to predict population exposures to commonly occurring VOCs is a daunting task.

There have been several proposals and attempts to identify the compounds of most concern with respect to potential occupant effects in buildings. Mølhave (1998 and 2003) has called for the grouping of compounds according to their relevant toxicological principals as the first step in establishing a list of the most pertinent compounds. The categories of health outcomes of concern would include immunological, respiratory, cellular (cancer and reproductive), neurogenic and sensory, and cardiovascular effects. Nielsen and colleagues (Nielsen *et al.*, 1998a-c) also have defined the categories of human health and comfort effects attributable to air pollutants that are of concern in indoor environments. Following this system, they developed a toxicology-based evaluation procedure for recommending guideline values specifically for indoor air and applied this procedure to a small number of several VOCs including certain organic acids, aromatic alcohols and glycol ethers. They proposed that the evaluations should establish multiple values for each compound, an odor threshold, a sensory irritation threshold, and a value for all other non-genotoxic effects; and in addition, should consider genotoxic and carcinogenic effects. Similarly to the approach used by the U.S. EPA for developing inhalation reference concentrations (RfCs) for chronic exposures, the available literature on human and mammalian effects is to be critically assessed. Toxicokinetics are taken into account to recommend safety factors for continuous indoor exposures for the general population.

In this paper, we conduct a simple screening-level assessment of VOC concentrations in residences and office buildings. We compare measured VOC concentrations to published odor thresholds, sensory irritation levels derived for the general population, and noncancer chronic health risk levels. Hazard quotients calculated for these effects are used to classify commonly encountered indoor VOCs into broad groups according to the likelihood that they will produce effects among building occupants as the result of inhalation exposures. We have excluded cancer from consideration as the risk assessment approach and the time period of interest (*i.e.*, a 70-year lifetime) for cancer are substantially different than from noncancer effects for which no adverse effect levels (NOAELs) can, at least theoretically, be determined. Other effects that may be related to VOC exposures, such as immunological responses, are not considered due to the lack of toxicological data. This assessment, while revealing the limitations of the available 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.

Methods

North American Indoor VOC Concentrations

Indoor VOC concentrations summarized from cross-sectional studies of North American residential and office buildings conducted from 1990 through the present (Hodgson and Levin, 2003, and herein termed the 'Review') serve as the database for this assessment. For all studies combined, 106 VOCs were identified. A broad range of chemical classes and volatility were represented. Central tendency and upper limit concentrations were summarized separately for residences and office buildings. In the accompanying tables, the compounds are grouped into chemical classes and then listed by increasing boiling point as a surrogate for volatility within each class. All concentrations are given in molar volume units of parts-per-billion (ppb) assuming standard indoor conditions (298^{o} K, 101.3 kPa).

Odor, Sensory Irritation and Noncancer Chronic Toxicity Values

Standardized human odor thresholds (OTs) for VOCs in the Review were obtained from Devos *et al.* (1990). This work compiled the scientific literature dating back to the late 1800's. For each compound, the source references were weighted based on their consistency with assumed good data sets and then averaged. These values presumably represent points of 50 or 75% odor detection (Cometto-Muñiz, 2000). One hundred percent odor detection thresholds were obtained from the Cometto-Muñiz research group (Cometto-Muñiz and Cain, 1990, 1991, 1993, 1994; Cometto-Muñiz *et al*., 1998a, 1998b). These studies employed uniform methodologies with small intensely studied groups of subjects to obtain OTs and nasal pungency effects (see below). We did not consider hedonistic odor tone.

The trigeminal nervous system with receptors in the facial area produces burning, tingling or stinging sensations in the eye nose, or throat when stimulated by airborne chemical irritants and functions as a warning system (Alarie, 1973). Exposures to high levels of sensory irritants result in a reflex change in the breathing pattern. This change is a characteristic pause following inspiration that results in a decrease in respiratory frequency. Alarie (1966) developed a bioassay to exploit this physiological change. Groups of four mice are exposed head-only to increasing concentrations of a sensory irritant. Their bodies are constrained in plethysomographs and pressure transducers record their breathing patterns and frequency. Sensory irritation is identified by the expiratory pause. Breathing frequency changes in proportion to the stimulus. The dose response is plotted on a logarithmic scale to calculate the concentration that produces a 50% decrease in frequency. This is termed the RD50. The procedure is described as ASTM standard method E 981 (ASTM, 2000). This method has been used to determine RD50s for a large number of individual sensory irritants, with emphasis on industrial chemicals. Schaper (1993) and Alarie *et al*. (2000) have summarized RD50s for 145 chemicals. Recent data for terpene hydrocarbons were obtained from Wolkoff *et al*. (2000).

Human nasal pungency thresholds (NPTs) are a measure of the trigeminal response of the nose when exposed to airborne sensory irritants. As noted above, the Cometto-Muñiz group has used a uniform methodology to measure OTs and NPTs for small groups of subjects. Their primary strategy has been to test homologous series of compounds in order to relate changes in physicochemical properties to the sensory outcomes for study groups with and without a sense of smell. In this way, they have been able to separate the trigeminal response from the olfactory response for a number of VOCs in different chemical classes.

The California EPA OEHHA has developed acute Reference Exposure Levels (RELs) for some hazardous airborne pollutants (Cal-EPA, 1999). An acute REL is an exposure concentration that is not likely to cause adverse effects in humans, including sensitive individuals that are exposed to the concentration for one hour on an intermittent basis. Acute RELs are all based on human studies and incorporate a one order of magnitude uncertainty factor to account for variability among individuals. Other factors are variously applied to adjust for the type of observed endpoint and the time difference by Haber's Law, which states that effect is determined by the cumulative dose determined as the product of concentration and exposure time. The severity of the effect is considered. Many of the acute RELs are based on sensory irritation, which is classified as a mild effect.

Guidelines to protect workers from the adverse effects of exposure to industrial chemicals have been developed over many years. Thresholds Limit Values (TLVs) promulgated by the American Conference of Governmental Industrial Hygienists (ACGIH) constitute one of the most widely used sets of occupational exposures levels (OELs) in the U.S. and elsewhere (ACGIH, 2000 and 2001). TLVs are primarily health based with some consideration given to analytical methods and practical detection limits. The rationale for TLVs is based on human or animal experimental data, industrial case studies, or chemical analogy. The assessments are peer reviewed. The derived time-weighted average (TWA) TLVs are intended to protect workers for an eight-hour workday assuming a typical 40-h workweek. Central nervous system effects,

various noncancer systemic effects, and irritation either separately or in combination with more serious outcomes, serve as the basis for many VOC TLVs.

Several North American governmental 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 a number of toxic air pollutants contained in the EPA's Integrated Risk Information System (U.S. EPA, XXXX). The RfCs are based on reviews and critical assessments of the toxicological and epidemiological literature for both human and other mammalian species. Effects both directly on and peripheral to the respiratory system are considered. Adjustments and uncertainty factors are applied to account for the type of observed endpoint, the exposure duration and inter- and intraspecies differences. The resulting RfCs are concentrations to which it is believed that the human population including sensitive groups can be exposed over a lifetime without deleterious effects. These values are peer reviewed. The Environmental Health Directorate, Health Canada (1996) has developed analogous tolerable concentrations for inhalation for a few VOCs on the Canadian Priority Substances List.

The Agency for Toxic Substances and Disease Registry (ATSDR) has identified a priority list of hazardous industrial substances, including many VOCs, and has developed associated acute, intermediate and chronic health effect guideline levels for oral and inhalation exposure routes. For inhalation exposure, ATSDR determines Minimal Risk Levels (MRLs) utilizing a practice similar to that used by the U.S. EPA for RfCs (ATSDR 2003). An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer effects in sensitive populations over a specified duration of exposure. MRLs are generally based on the most sensitive endpoint of relevance to humans exclusive of very serious effects such as irreparable damage to liver or kidneys or birth defects. Here, we have utilized the lowest inhalation MRLs derived for either the intermediate (>14 to 364 days) or the chronic (365 days and longer) exposure duration as guidelines for chronic toxicity.

OEHHA has developed noncancer chronic Reference Exposure Levels (RELs) for 78 chemicals (Cal-EPA, 2002). OEHHA also follows the same general approach as used by the U.S. EPA in establishing RfCs. Human inhalation exposure data have been emphasized where possible. OEHHA's approaches to time extrapolation and the application of uncertainty factors have differed from those of the U.S. EPA in some cases. These guidelines are intended to protect the general population including sensitive groups from disease for exposure periods of ten years or more.

Scaling of Values

We first endeavored to place the various measures for each considered effect on a comparable scale. For some measures, it was necessary to apply a scaling factor.

The Cometto-Muñiz group OTs were divided by one order of magnitude to adjust for the difference between their 100% recognition criteria and an assumed 50% recognition threshold for the Devos *et al*. values as suggested by Cometto-Muñiz (2000).

Others have estimated sensory irritation effects in humans by application of an uncertainty factor to mouse RD50s. Schaper (1993) demonstrated a linear relationship between the logarithm of RD50s multiplied by 0.03 and the logarithm of the TLVs of 89 chemicals, whose TLVs had been based on irritation as a critical effect. The coefficient (r^2) for the linear least-squares regression was 0.78, and only a few compounds fell outside of the 95% confidence intervals. This relationship gave additional support to Alarie's (1981) original proposal for estimating appropriate TLVs by setting them halfway between 0.1 and 0.01 times the RD50 on a logarithmic scale (*i.e*., 1.5 orders of magnitude).

NPTs occur at elevated concentrations that are approximately equivalent to RD50 concentrations. This low sensitivity is likely attributable to the method of delivery in which one nostril is exposed for only 1-3 seconds. For example, Hansen and Nielsen (1994) state that the nose integrates the trigeminal effect by spatial summation and, therefore, the threshold concentration is expected to be higher if only one nostril is exposed.

Cometto-Muñiz and Cain (1994) showed the relationship between log NPT and log RD50 in ppm for 24, mostly nonreactive VOCs (*i.e.*, alcohols, acetates, ketones, alkylbenzenes and some miscellaneous compounds). Considering all 24 compounds, the best fitting regression line was RD50 = 0.59 NPT + 1.23, r = 0.63. Excluding methyl, ethyl and propyl acetates, which were less potent in humans, improved the regression to RD50 = 0.89 NPT + 0.36, r = 0.85. The strength and near equivalency of the relationship when VOCs with clear interspecies differences were excluded suggests that the same approximate scaling factor can be applied to the RD50s and NPTs for nonreactive compounds when estimating effects for the general population.

As differentiated from a healthy industrial workforce, the general population is presumed to contain sub-populations such as the very young, elderly and those with illnesses (*e.g.*, respiratory disease) that are more chemically sensitive. Governmental agencies and others have attempted to establish inhalation exposure guidelines for the general population by applying uncertainty factors to TLVs and other OELs. As Paustenbach (1997) has noted in his review, this general approach has a number of potential disadvantages, but is backed by a wealth of data accumulated over many years and, at a minimum, serves as a convenient starting point.

Paustenbach (1997) observes that the most popular approach has been to assume the OELs are equivalent to human NOAELs. First an OEL is adjusted for the difference between a 40-h work week and constant 24-h a day exposure by application of Haber's Law. Thus, the TLV is divided by a factor of 168/40 or 4.2. Then, uncertainty factors are applied to account for a difference in sensitivity between the general population and healthy workers and to provide a margin of safety. Paustenbach points out that the size of the overall uncertainty factor should vary with the severity and reversibility of the effect. If the goal is to protect against irritation (or odor), he states that the occupational TLVs will not need much adjustment but gives no specific guidance.

Nielsen *et al*. (1995) reviewed the rationale for setting indoor exposure limits at ~1/40 of the OELs for respiratory effects. They discussed examples of ozone and nitrogen dioxide exposures in rats, which suggested that low-level responses estimated from Haber's Law would

overestimate the real responses. Their review also indicated that the more susceptible individuals might not be that much more sensitive than the general population. Thus, they estimate that 1/40 of the OEL would be a conservative, preliminary indoor-air guideline for respiratory effects. Neilsen *et al*. (1998a) make the point that Haber's Law is not applicable to sensory irritation effects as these are more directly dependent upon concentration than on the product of concentration and time. They carefully evaluated the literature on the sensory and health effects of several compounds in this Review, including formic acid, acetic acid, phenol and butylated hydroxytoluene (Neilsen *et al*. 1998a and b). They set the indoor guideline for sensory irritation at 1 ppm for formic acid, acetic acid and phenol. This value is five to ten times lower than the respective TLVs (*i.e*., less than the general 1/40 guideline).

Based on this information, we have adopted the approach of adjusting the TLVs of compounds with irritancy as the sole or principal effect by a one order of magnitude uncertainty factor (TLV/10) to account for sensitive sub-populations and individuals. By extension, the mouse RD50s were adjusted by a factor of 2.5 orders of magnitude (*i.e*., the 1.5 orders of magnitude factor to equate RD50s with TLVs plus a one order of magnitude uncertainty factor for sensitive groups). The same adjustment factor was applied to NPTs. According to the Alarie *et al*. (2000) scheme for extrapolating RD50s to humans, RD50/100 would not be expected to produce a sensory irritation response and RD50/1000 would not be expected to produce an effect of any kind. Our use of 2.5 orders of magnitude (RD50/316) is the midpoint of this range.

Acceptable noncancer chronic exposure levels can be estimated for the general population from TLVs, which are not based on cancer or irritation as the primary effect. The procedures described by Nielsen *et al*. (1995) and Paustenbach (1997) were utilized. First a factor of 1/40 was applied to approximately account for the difference between a 40-h workweek and a constant 24-h a day exposure and the presumed increased susceptibility of the general public versus industrial workers. 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-live of over eight hours. Thus, the total adjustment is TLV/200.

Calculation of Indoor Hazard Quotients

We next selected best estimates of odor thresholds and protective sensory irritation and noncancer chronic health levels for the general population and compared these levels to the VOC concentrations measured in residences and office buildings. This was accomplished by dividing maximum or estimated 95th percentile concentrations by the selected values to derive indoor effect, or hazard, quotients.

For those VOCs with OT data from both sources, we have assumed the adjusted Cometto-Muñiz *et al*. values are likely to be more reliable because they were determined with consistent contemporary methodologies. Odor quotients were then calculated by dividing the maximum VOC concentrations measured in existing residences, new residences and office buildings by our best estimates of the corresponding odor thresholds.

We have assumed that the human sensory irritation response is best characterized by human measures (NPTs, TLVs, and RELs); that among the human measures NPTs are the most directly applicable; and that acute RELs represent more current and thorough reviews of the literature on human response than TLVs. However, we question the use of Haber's Law in the establishment of the acute RELs based on Neilsen *et al*.'s (1998a) argument. Sensory irritation quotients were calculated as described for OTs; maximum VOC concentrations in new and existing residences and in office buildings were divided by our best estimates of sensory irritation.

We have assumed that chronic REL, RfC and MRL concentrations are better measures of chronic toxicity than the TLV-based measures due to the uncertainty inherent in our application of a universal adjustment factor to TLVs. We gave preference to the OEHHA chronic RELs since they generally are based on assessments of the most current toxicological literature for the largest set of compounds. Our second preference was the lower of the two other measures. Alternately, since the three measures used the same general methodology, the lowest agency value could be selected as the value of interest. An adjusted TLV was selected only if an agency health assessment had not been performed.

To determine hazard quotients for noncancer chronic health risks, we first derived 95th percentile concentrations from the central tendency VOC concentrations summarized in the Review as geometric means (GMs) for existing residences and office buildings. Our rational for selecting 95th percentile concentrations versus central tendency or maximum values is that sustained exposures to relatively high, but not maximum concentration may occur in some indoor environments. Typical geometric standard deviations (GSDs) for distributions of VOC concentrations in residences and office buildings appear to be approximately 2.2 based on several studies that have reported this statistic (Daisey *et al*., 1994; Shields *et al*., 1996; Hodgson *et al*., 2000). Assuming this distribution, a one-tailed Student's *t* value of 1.64 was used to calculate 95th percentile concentrations as:

$$\log_e 95\%\text{ile} = \log_e \text{GM} + 1.64 \log_e \text{GSD} \qquad (1)$$

Hazard quotients for noncancer chronic toxicity were then calculated by dividing the derived 95th percentile concentrations for residences and office buildings by the selected guideline concentrations.

Measured VOCs were classified with respect to the different effects based on their hazard quotients. We consider compounds with quotients in excess of unity to be of primary concern. Quotients within one order of magnitude of unity define the next level of concern. Since this is a screening level assessment based on limited data, we do not ascribe any particular importance to compound ranking within or between the two categories of concern with the exception of a few cases where the quotients are substantially in excess of unity.

Results

Maximum reported VOC concentrations in residences and office buildings were uniformly less than 1 ppm. Thus, we have focused on those compounds with the highest indicated potencies (*i.e*., compounds with effect levels equal to or less than approximately 1 ppm) for the effects under consideration.

Odor Thresholds

Odor thresholds were obtained from Devos *et al*. for 67 VOCs and from the Cometto-Muñiz group for 25 VOCs in the Review. The Devos *et al*. values and the adjusted Cometto-Muñiz *et al*. values are listed and compared in Table 1 for the most odorous VOCs in the Review. This list is dominated by oxygenated compounds (principally carboxylic acids, alcohols, aldehydes, and ketones) and aromatic hydrocarbons including chlorinated aromatics. OTs are available from both sources for 16 compounds in the Review. These values are compared on a logarithmic scale in Figure 1. Substantial differences are apparent. The adjusted Cometto-Muñiz *et al*. OTs for acetic acid, hexanoic acid, and formic acid (not plotted, off scale) are more than one order of magnitude lower than the Devos *et al*. values, while the adjusted Cometto-Muñiz *et al*. OTs for ethylbenzene, p-cymene, butanal and hexanal are more than one order of magnitude higher.

Our selected OT values of interest are given in the right-hand column of Table 1. These values indicate that the most odorous compounds (*i.e*., OTs <10 ppb) from the Review are 1-octanol; the aldehydes 3-methylbutanal, hexanal, heptanal, octanal, and nonanal; acetic acid; and hexanoic acid. The next decade of odorous compounds (OTs approximately100 ppb, or less) includes phenol, propionaldehyde, benzaldehyde, naphthalene, dichlorobenzenes and carbon disulfide.

Sensory Irritation Levels

Forty-three of the VOCs in the Review have reported RD50 values, and 20 have reported NPT values. Of the 13 VOCs in the Review with both RD50s and NPTs, ten have values, which are within approximately one order of magnitude of each other. The three exceptions are ethyl acetate, butanal and pentanal, which are indicated to be less potent in humans. Twenty-six of the VOCs in the Review have occupational TWA TLVs for which irritation is given as the sole critical effect or as the primary basis for establishment of the TLV (ACGIH, 2000 and 2001). OEHHA acute RELs with sensory irritation as the effect also are available for 13 VOCs in the Review.

The adjusted RD50, NPT and TLV concentrations and the acute RELs are listed and compared in Table 2 for the 14 most potent sensory irritants in the Review. Oxygenated compounds and chlorinated aromatic hydrocarbons are the only represented chemical categories. Seven of the VOCs have irritation values derived from more than one source. With the exception of acrolein, the multiple values for individual compounds are within one order of magnitude or less of each other. The values selected based on our criteria and their sources are given on the right side of Table 2. These indicate that acrolein is, by far, the most potent irritant among the compounds identified by the Review.

For the two most potent reactive compounds, acrolein and formaldehyde, the irritation levels are lower than their odor thresholds, which is expected. It also is expected that irritation levels should be higher than odor thresholds for most nonreactive compounds based on the work of the Cometto-Muñiz group, which has shown odor to be protective of irritation for a number of different classes of VOCs. This is true for the large majority of the compounds listed in Table 2. However, for two nonreactive compounds with sensory irritation measures below 1 ppb (2-ethyl-1-hexanol and 2-furaldehyde), the selected irritation levels are somewhat lower than their odor thresholds. This inconsistency points to possible uncertainty in one or both measures.

Noncancer Chronic Toxicity Levels

TLVs adjusted to estimate acceptable noncancer chronic exposure levels are available for 38 VOCs in the Review. ATSDR intermediate or chronic inhalation MRLs (23 VOCs), EPA RfCs (19 VOCs) and OEHHA chronic RELs (27 VOCs) are available for a number of compounds. Adjusted TLVs and chronic RELs for 20 VOCs are compared on a logarithmic scale in Figure 2. The values agree within approximately one order of magnitude except for acrolein (not shown, off scale), naphthalene and tetrachloroethene, which have distinctly lower chronic RELs.

Table 3 lists and compares chronic toxicity levels for the 35 most potent VOCs in the Review. Aromatic hydrocarbons and halogenated compounds are well represented on this list. Acrolein is indicated to be the most potent compound. Other compounds with low chronic

toxicity levels (*i.e.*, <10 ppb) include, formaldehyde, acetaldehyde, 1,3-butadiene, naphthalene, 1,2,4-trichorobenzene, bromomethane, carbon tetrachloride, tetrachloroethene and acrylonitrile.

Hazard Quotients

The Review summarized maximum concentrations of VOCs measured in existing and new residences and in office buildings. Table 4 lists the maximum concentrations and calculated odor quotients by building type for the 38 compounds whose selected OTs are 1 ppm or less. For a number of the VOCs, their reported maximum concentrations do not approach levels of concern with respect to odor. VOCs with odor quotients exceeding one, indicating under some realistic circumstances that building occupants will perceive their presence through olfaction, are 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 in the next decade (*i.e*., quotients between 0.1 and 1) are 1-butanol, formaldehyde, acetaldehyde, propionaldehyde, 3-methylbutanal, m/p-xylene, naphthalene, and 1,4-dichlorobenzene. Due to limited building data, a quotient was not determined for the highly odorous compound, 1-octanol.

Only 11 VOCs whose maximum concentrations in residences and office buildings were summarized by the Review are considered to be relatively potent sensory irritants. The maximum concentrations of these compounds are listed by building type along with their respective sensory irritation quotients in Table 5. Due to its very low sensory irritation value, acrolein has the singularly highest quotient in residences. Formaldehyde and acetic acid with quotients near or in excess of unity also are indicated to be of relatively high concern with respect to sensory discomfort in residences.

Derived 95th percentile concentrations of VOCs measured in existing residences and office buildings and their corresponding chronic toxicity hazard quotients are listed in Table 6 by building type for the 28 compounds whose chronic toxicity guidelines are 1 ppm or less. VOCs with hazard quotients of approximately one or more are formaldehyde, acetaldehyde and

acrolein, for which only residential data are available. Of these, acrolein has the singularly highest hazard quotient. VOCs with hazard quotients within one order of magnitude below unity are the aromatic hydrocarbons, benzene, toluene and naphthalene and the chlorinated solvent tetrachloroethene.

Discussion

Limitations of Methodology

The methodology presented here is imperfect due to the shortcomings of the data on which it is based. The limitations of the indoor VOC database are broadly outlined in the introduction. Additionally, a number of compounds known or suspected to occur in indoor air have not been reported in the literature, and potentially important compounds with respect to comfort and health have not been measured because of the inadequacies of conventional methods. Many potentially important health effects associated with VOC inhalation exposures are not included in the analysis. We purposefully did not attempt to assess cancer or reproductive toxicity. Other serious irreversible effects and less threatening reversible effects have been omitted in part due to the lack of readily accessible risk data relevant to exposures in the indoor environment. Among these concerns are lower respiratory effects, allergies, hypersensitivity reactions, and subtle neurological effects such as headache, drowsiness and memory loss. Even for the effects being considered, the amount and robustness of the comfort and health data are limited. We have relied, in part, on occupational studies both directly through the use of TLVs and indirectly though the use of agency health hazard assessments, which attempt to use human data whenever possible. Such data most often are obtained from occupational studies. Many of these studies may be imperfect bases for the establishment of indoor air guidelines. For example, occupational exposures often occur at exceptionally high concentrations that are inadequately characterized, and frequently dose-response relationships have not been determined. Studies of other mammalian species, which form the basis of other health hazard assessments involve the application of large policy-mandated uncertainty factors to account for unmeasured effects (*e.g.*,

extrapolation to humans from animals, failure to identify a NOAEL, and accommodation of sensitive populations) that may equal or exceed three orders of magnitude.

Odor

The complexity of the olfactory system makes it impossible to entirely substitute instrumental measurements for human judgement. Consequently, the cause of odor problems in buildings often cannot be deduced analytically. For example, a number of VOCs such as alcohols, unsaturated aldehydes, carboxylic acids and amines may not be detected with sufficient sensitivity or may be missed entirely by standard techniques (Wolkoff, 2003). Thus, the calculation of odor quotients based on reported VOC concentrations is a valuable, but very incomplete assessment of potential odor impacts in buildings. The assessment does show that most measured VOCs are unlikely to be perceived by olfaction. Among the measured VOCs with the lowest OTs, there is more probability of detection in residences than in offices. In new residences particularly, the concentrations of acetic acid, hexanoic acid and higher molecular weight aldehydes have exceeded OTs. These aldehydes, and probably the carboxylic acids, are emitted by a variety of composite wood materials that are used in substantial quantities to construct and finish the interiors of houses (Hodgson *et al.*, 2000). These materials also may emit unsaturated aldehydes and other oxidized species with even lower OTs. Among non-oxygenated compounds, less volatile aromatic hydrocarbons and chlorinated aromatic compounds such as naphthalene and 1,4-dichlorobenzene are the most likely to approach OTs.

Sensory Irritation

Of the small number of relatively potent, measured VOCs, only acrolein, which is emitted by tobacco and wood smoke, was shown to substantially exceed its irritation level indoors. Daily average indoor concentrations of HAPs including acrolein were estimated for houses where smoking occurs using typical values for number of smokers, cigarette consumption rate, house ventilation rate and house volume (Nazaroff and Singer, Submitted). This exercise predicted an indoor acrolein concentration of 0.8 ppb, an order of magnitude above the irritation level. Only

one study in the Review (Sheldon *et al*., 1992) reported acrolein concentrations by a method judged to be reliable (Hodgson and Levin, 2003). A number of the residences in the study had significant smoking (*i.e*., more than 20 cigarettes per day), but the data were not presented or analyzed as a function of smoking. The median concentration was 1.8 ppb, and the maximum value was 13 ppb (presumably from a smoking residence). Formaldehyde and acetic acid were the two other measured VOCs that approached or exceeded irritation levels, and only in residences.

The effect of mixtures of reactive aldehydes such as acrolein and formaldehyde has been shown in rats to be consistent with competition for a common trigeminal nerve receptor such that that the response was increased, but less than additive, relative to the individual compounds (*i.e.*, competitive agonism) (Cassee *et al*., 1996). Competitive agonism was also shown for a mixture of acrolein and formaldehyde in mice (Kane and Alarie, 1978). The receptor binding site is believed to be a thiol group (Nielsen, 1991). Alarie *et al*. (1998a and b) used physiochemical descriptors to separate non-reactive from reactive compounds and to estimate the potency of non-reactive compounds. For non-reactive chemicals, it is assumed that the mechanism for stimulation occurs via physical interaction rather than chemical binding with the receptor protein (Nielsen and Alarie, 1982). Furthermore, it often is assumed that at low concentration the potency of non-reactive chemicals in a mixture is approximately described by simple additivity and that there is a threshold below which irritation is unlikely (Alarie *et al*., 1996). However, this assumption rarely has been tested. One such study of the additive effects of mixtures showed that the mixtures increased their stimulus agonism with the increasing number of components and the increasing lipophilicity of these components suggesting that the effects of mixtures may not be so easily predicted (Cometto-Muñiz *et al*., 1997).

The irritant potency of mixtures of non-reactive VOCs (*i.e.*, compounds acting by a common mechanism) has been estimated using a hazard index, which is the sum of the hazard quotients of the individual compounds. The potencies of 22 compounds comprising a 25-mg m^{-3} mixture of VOCs evaluated for sensory irritation in human exposure studies were predicted using

physiochemical variables (Alarie *et al*., 1996). These estimated RD50s were adjusted downward by a factor of 1,333 through multiplication by a 0.03 scaling factor to approximate TLV levels and division by 40 to achieve protection for the general population. The calculated hazard index was in the range of 7-9, depending upon the method used to estimate the RD50s, indicating likely sensory irritation with the two predominant compounds (butyl acetate and p-xylene) contributing 50% of the effect.

VOC concentrations in buildings rarely approach such high levels and yet irritant symptoms are a common complaint among occupants. Several VOC exposure metrics were developed and tested for their ability to predict self-reported irritant symptoms among ~500 workers in 12 California office buildings (Ten Brinke *et al.*, 1998). One metric was the sum of irritancy-weighted individual compounds with RD50 as the measure of irritancy and toluene as the reference compound. This metric was not effective in predicting irritancy symptoms in a logistic regression model, suggesting that simple addition of the effects for mixtures of non-reactive VOCs may not account for irritant symptoms in office buildings. A new metric was developed using principal component analysis of VOCs selected of their irritancy and associations with known sources. The metric variously accounts for irritant potencies, the highly correlated nature of indoor VOC mixtures and the probable presence of highly potent, but unmeasured VOCs. Eye, skin and irritated mucus membrane symptoms were successfully predicted by the metric. This result is consistent with a hypothesis, proposed by others, that irritant symptoms are related to oxidation processes in indoor air involving ozone and possibly nitrogen oxides that produce potent irritants not detected by standard methods (Wolkoff *et al.*, 1997).

Noncancer Chronic Toxicity

Our limited analysis of noncancer chronic toxicity did not include the identification of the toxicological endpoint or the type of study and the uncertainty factors applied by agencies to make their derivations. Careful consideration of the underlying toxicological data may modify the comparisons among acceptable exposure levels and adjusted TLVs and influence the

selection of concentrations of interest. However, the simple comparison and classification suggest there are only a relatively small number of commonly measured VOCs that, when considered singly, may be of concern with respect to serious irreversible health effects not associated with cancer.

Since humans clearly are exposed daily to complex mixtures of VOCs and other air pollutants in both their residences and other indoor environments, a cumulative risk assessment should be considered. The common approach for assessing the risks of exposures to mixtures is to assume dose additivity for chemicals producing a concurrent exposure and acting through a common mechanism of toxicity. The hazard index method (*i.e.*, summation of the hazard quotients for the individual compounds) that uses agency-determined reference exposures levels as the denominators has been criticized because these reference exposures levels are not true measures of potency (Wilkinson *et al*., 2000). Other methods have been proposed, but a clear consensus about how to proceed has yet to be developed (*ibid*.).

Conclusions

We have presented a methodology for classifying the relative importance of individual VOCs that commonly occur in indoor air with respect to odor, sensory irritation and noncancer chronic toxicity. Although both the concentration distribution and the health effects data upon which this methodology is based are imperfect, only a small number of the more than 100 reported VOCs were shown to exceed levels that might be of concern with respect to the comfort and health endpoints considered. A more rigorous ranking of importance among these identified compounds will require assessments of the populations and number of individuals that are routinely exposed. At this early assessment stage, we recommend that future studies to characterize VOC concentrations and exposures in buildings focus their resources on measurements of those compounds that are 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 physiochemical

properties (*e.g.*, potential sensory irritants such as reactive aldehydes and carboxylic acids) should be included in monitoring studies. For a very few compounds, such as acrolein and formaldehyde, the evidence based on sensory irritation and chronic toxicity is sufficient to warrant efforts to reduce and otherwise control the sources of these compounds in buildings.

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Table 1. Odor thresholds (OTs) for VOCs measured in residences and office buildings. Values reported by Cometto-Muñiz *et al*. are adjusted downward by one order of magnitude to estimate 50% OT detection. Only compounds with selected OTs less than or equal to 1000 ppb are shown. Selected OTs of interest that are less than 10 ppb are indicated in bold text.

		Odor Threshold (ppb)		
Compound	Chem. Class[a]	Devos *et al*.[b]	Cometto-Muñiz[c]/10	Value of Interest[d]
1-Butanol	Alc	490	200	200
Phenol	Alc	110		110
2-Ethyl-1-hexanol	Alc	240		240
1-Octanol	Alc	5.8	0.7	**0.7**
2-Butoxyethanol	Gly	340		340
4-Methyl-2-pentanone	Ket	540		540
Cyclohexanone	Ket	710		710
1-Phenylethanone	Ket	360		360
Formaldehyde	Ald	870		870
Acetaldehyde	Ald	190		190
Propionaldehyde	Ald	27		27
Acrolein	Ald	170		170
Butanal	Ald	8.9	320	320
3-Methylbutanal	Ald	2.2		**2.2**
Pentanal	Ald	6.0	500	500
Hexanal	Ald	14	7.9	**7.9**
Heptanal	Ald	4.8	3.2	**3.2**
2-Furaldehyde	Ald	780		780
Octanal	Ald	1.4	0.4	**0.4**
Benzaldehyde	Ald	42		42
Nonanal	Ald	2.2		**2.2**
Butyl acetate	Estr	200	240	240
Formic acid	Acid	28000	790	790
Acetic acid	Acid	140	1.0	**1.0**
Hexanoic acid	Acid	13	0.5	**0.5**
n-Decane	Alka	740		740
β-Pinene	Terp		1000	1000
d-Limonene	Terp	440	790	790
p-Cymene	Terp	2.1	130	130
m/p-Xylene	Arom	320		320
o-Xylene	Arom	850		850
Styrene	Arom	140		140
Isopropylbenzene	Arom	24	100	100
Propylbenzene	Arom		320	320
1,3,5-Trimethylbenzene	Arom	230		230
1,2,4-Trimethylbenzene	Arom	160		160

Table 1. Continued.

Compound	Chem. Class[a]	Odor Threshold (ppb) Devos *et al*.[b]	Cometto-Muñiz[c]/10	Value of Interest[d]
Naphthalene	Arom	15		15
1,4-Dichlorobenzene	ClAro	48		48
1,2-Dichlorobenzene	ClAro	72		72
Carbon disulfide	Misc	96		96
Pyridine	Misc	85	130	130

a. Alc = alcohol, Gly = glycol ether, Ket = ketone, Ald = aldehyde, Estr = ester, Acid = carboxylic acid, Alka = alkane hydrocarbon (HC), Terp = terpene HC, Arom = aromatic HC, ClAro = chlorinated aromatic HC, Misc = miscellaneous chemical classes
b. Values from Devos *et al*. (1990) are assumed to represent 50% odor detection
c. Values reported between 1990 and 1998 by Cometto-Muñiz *et al*. (see text) and summarized by Cometto-Muñiz (2001) are divided by 10 to estimate 50% OT detection
d. If available, values reported by Cometto-Muñiz *et al*. and adjusted for 50% detection are selected as OTs of interest

Table 2. Sensory irritation thresholds (ITs) for VOCs measured in residences and office buildings. Mouse RD50 values and human nasal pungency thresholds (NPTs) are adjusted downward by 1.5 orders of magnitude (see text). Threshold Limit Values (TLVs) with irritation as the primary effect are adjusted downward by one order of magnitude to account for more sensitive populations. Only compounds with selected ITs less than or equal to 1000 ppb are shown.

		Concentration (ppb)					
Compound	Chem. Class[a]	RD50/ 316	NPT/ 316	TLV/ 10	Acute REL[b]	Value of Interest[c]	Basis
2-Ethyl-1-hexanol	Alc	140				140	RD50
1-Octanol	Alc	150	310			310	NPT
Butylated hydroxytoluene	Alc			22		22	TLV
1,4-Dioxane	Ethr				830	830	REL
1-Phenylethanone	Ket	320		1000		1000	TLV
Formaldehyde	Ald	13		30[d]	77	77	REL
Acrolein	Ald	6.6		10[d]	0.08	0.08	REL
2-Furaldehyde	Ald	910		200		200	TLV
Diethyl phthalate	Estr			55		55	TLV
Formic acid	Acid		1000	500		1000	NPT
Acetic acid	Acid	1200	130	1000		130	NPT
1,4-Dichlorobenzene	ClAro	570				570	RD50
1,2-Dichlorobenzene	ClAro	570				570	RD50
1,2,4-Trichlorobenzene	ClAro			500		500	TLV

a. Defined in Table 1
b. Cal-EPA (1999) acute Reference Exposure Level
c. Selection order for IT values of interest: 1) acute REL, 2) adjusted NPT, 3) adjusted TLV, and 4) adjusted mouse RD50
d. TLV is ceiling value

Table 3. Agency determined and estimated acceptable non-cancer, chronic exposure levels for VOCs measured in residences and office buildings. Threshold Limit Values (TLVs) for which primary effect is not cancer or irritation only are adjusted downward by a factor of 200 (see text). Only compounds with selected chronic exposure levels less than or equal to 1000 ppb are shown. Selected values of interest less than 10 ppb are indicated in bold text.

		Concentration (ppb)					
Compound	Chem. Class[a]	TLV/ 200	ATSDR MRL[b]	EPA RfC[c]	Chronic REL[d]	Value of Interest[e]	Basis
1-Butanol	Alc	100				100	TLV
Phenol	Alc	25			52	52	REL
1,4-Dioxane	Ethr	100			830	830	REL
Ethylene glycol	Gly				160	160	REL
2-Butoxyethanol	Gly	100	200, C	270		200	MRL
2-Butanone	Ket	1000		340		340	RfC
4-Methyl-2-pentanone	Ket	250		720		720	RfC
Cyclohexanone	Ket	120				120	TLV
Formaldehyde	Ald	1.5	8, C		2.4	**2.4**	REL
Acetaldehyde	Ald			5.0	5.0	**5.0**	REL
Acrolein	Ald	0.50	0.009, I	0.01	0.03	**0.03**	REL
n-Nonane	Alka	1000				1000	TLV
1,3-Butadiene	Alke			0.9	9.0	**9.0**	REL
Benzene	Arom		4, I	9.4	19	19	REL
Toluene	Arom	250	80, C	110	80	80	REL
Ethylbenzene	Arom	500	1000, I	230	460	460	REL
Xylenes (combined)	Arom		100, C	23	160	160	REL
Styrene	Arom	100	60, C	240	210	210	REL
Isopropylbenzene	Arom	250		81		81	RfC
1,3,5-Trimethylbenzene	Arom	120				120	TLV
1,2,4-Trimethylbenzene	Arom	120				120	TLV
1,2,3-Trimethylbenzene	Arom	120				120	TLV
Naphthalene	Arom	50	2, C	0.6	1.7	**1.7**	REL
Chlorobenzene	ClAro	50			220	220	REL
1,4-Dichlorobenzene	ClAro	50	100, C	130	130	130	REL
1,2-Dichlorobenzene	ClAro	120				120	TLV
Vinyl chloride	Halo		30, I	39		30	MRL
Bromomethane	Halo	5.0	5, C	1.3	1.3	**1.3**	REL
Dichloromethane	Halo	250	300, C		120	120	REL
Chloroform	Halo	50	20, C		61	61	REL
1,1,1-Trichloroethane	Halo	1800	700, I		180	180	REL
Carbon tetrachloride	Halo	25	50, I		6.4	**6.4**	REL
1,2-Dichloroethane	Halo	50	600, I		99	99	REL

Table 3. Continued.

Compound	Chem. Class[a]	Concentration (ppb) TLV/ 200	ATSDR MRL[b]	EPA RfC[c]	Chronic REL[d]	Value of Interest[e]	Basis
Trichloroethene	Halo	250	100, I		110	110	REL
Tetrachloroethene	Halo	120	40, C		5.2	**5.2**	REL
Carbon disulfide	Misc	50	300, C	220	260	260	REL
Acrylonitrile	Misc			0.9	2.3	**2.3**	REL
Pyridine	Misc	25				25	TLV

a. Defined in Table 1
b. ASTDR (2003) Minimal Risk Level for inhalation exposures of intermediate (I, >14-364 days) or chronic (C, 365 days and longer) duration
c. U.S. EPA (XXXX) Inhalation Reference Concentration
d. Cal-EPA (2002) noncancer chronic Reference Exposure Level
e. Selection order for chronic exposure levels of interest: 1) REL, 2) lowest RfC or MRL, and 3) adjusted TLV

Table 4. Maximum VOC concentrations measured in existing residences, new residences and office buildings, and odor quotients (OQs) calculated for each compound as maximum concentration divided by selected odor threshold of interest from Table 1. OQs exceeding or within one order of magnitude of unity are indicated in bold text.

		Maximum Conc. (ppb)			Odor Quotient		
Compound	Chem. Class*	Exist. Res.	New Res.	Office Build.	Exist. Res.	New Res.	Office Build.
1-Butanol	Alc		21	5.0		**0.11**	0.03
Phenol	Alc		5.8	2.5		0.05	0.02
2-Ethyl-1-hexanol	Alc			9.0			0.04
2-Butoxyethanol	Gly		12	14		0.04	0.04
4-Methyl-2-pentanone	Ket			6.8			0.01
1-Phenylethanone	Ket			2.8			0.01
Formaldehyde	Ald	180	62		**0.21**	0.07	
Acetaldehyde	Ald	16	43		0.08	**0.23**	
Propionaldehyde	Ald	5.6	19		**0.21**	**0.70**	
Acrolein	Ald	13			0.08		
Butanal	Ald	2.4	2.0		0.01	0.01	
3-Methylbutanal	Ald	1.2			**0.55**		
Pentanal	Ald	2.0	9.8	1.3		0.02	
Hexanal	Ald		36	2.4		**4.6**	**0.30**
Heptanal	Ald		4.9			**1.5**	
2-Furaldehyde	Ald	1.5					
Octanal	Ald		7.2			**18**	
Benzaldehyde	Ald	1.3	3.7	1.5	0.03	0.09	0.04
Nonanal	Ald		7.6	1.4		**3.5**	**0.64**
Butyl acetate	Estr		14	3.9		0.06	0.02
Formic acid	Acid	19			0.02		
Acetic acid	Acid	81	280		**81**	**280**	
Hexanoic acid	Acid		5.5			**11**	
n-Decane	Alka	13	22	5.8	0.02	0.03	0.01
β-Pinene	Terp		26			0.03	
d-Limonene	Terp		12	12		0.02	0.02
m/p-Xylene	Arom	67	11	10	**0.21**	0.03	0.03
o-Xylene	Arom	14	4.4	3.5	0.02	0.01	0.01
Styrene	Arom	5.5	7.8	12	0.04	0.06	0.09
Isopropylbenzene	Arom	1.2			0.01		
Propylbenzene	Arom	3.5			0.01		
1,3,5-Trimethylbenzene	Arom	6.5		1.1	0.03		0.01
1,2,4-Trimethylbenzene	Arom			2.9			0.02
Naphthalene	Arom	0.95		1.9	0.06		**0.13**

Table 4. Continued.

Compound	Chem. Class*	Maximum Conc. (ppb) Exist. Res.	New Res.	Office Build.	Odor Hazard Quotient Exist. Res.	New Res.	Office Build.
1,4-Dichlorobenzene	ClAro	26		7.0	**0.54**		**0.15**
1,2-Dichlorobenzene	ClAro	0.09	0.54	2.2		0.01	0.03
Carbon disulfide	Misc			5.8			0.06
Pyridine	Misc	2.0			0.02		

*Defined in Table 1

Table 5. Maximum VOC concentrations measured in existing residences, new residences and office buildings, and sensory irritation quotients (SIQs) calculated for each compound as maximum concentration divided by selected irritation threshold of interest from Table 2. SIQs exceeding or within one order of magnitude of unity are indicated in bold text.

		Maximum Conc. (ppb)			Sensory Irritation Quotient		
Compound	Chem. Class*	Exist. Res.	New Res.	Office Build.	Exist. Res.	New Res.	Office Build.
2-Ethyl-1-hexanol	Alc			9.0			0.06
1,4-Dioxane	Ethr	39			0.05		
1-Phenylethanone	Ket			2.8			0.03
Formaldehyde	Ald	180	62		**2.3**	**0.81**	
Acrolein	Ald	13			**160**		
2-Furaldehyde	Ald	1.5			0.01		
Formic acid	Acid	19			0.02		
Acetic acid	Acid	81	280		**0.62**	**2.2**	
1,4-Dichlorobenzene	ClAro	26		7.0	0.05		0.01
1,2-Dichlorobenzene	ClAro	0.09	0.54	2.2	<0.01	<0.01	<0.01
1,2,4-Trichlorobenzene	ClAro			0.16			<0.01

*Defined in Table 1

Table 6. Central tendency VOC concentrations measured in existing residences and office buildings, derived 95th percentile concentrations (see text), and non-cancer chronic toxicity quotients (CTQs) calculated for each compounds as 95th percentile concentration divided by selected chronic exposure levels from Table 3. CTQs exceeding or within one order of magnitude of unity are indicated in bold text.

		Concentration (ppb)				Chronic Toxicity Quotient	
		Central Tendency		Derived 95%ile			
Compound	Chem. Class*	Exist. Res.	Office Build.	Exist. Res.	Office Build.	Exist. Res.	Office Build.
2-Butoxyethanol	Gly		0.65	3.6			0.02
1,4-Dioxane	Ethr	0.03		0.11		<0.01	
Formaldehyde	Ald	17		61		**26**	
Acetaldehyde	Ald	3.0		11		**2.2**	
Acrolein	Ald	1.8		6.5		**217**	
n-Nonane	Alka	0.25	0.36	0.90	1.3	<0.01	<0.01
1,3-Butadiene	Alke	0.23		0.83		0.09	
Benzene	Arom	0.90	1.0	3.2	3.6	**0.17**	**0.19**
Toluene	Arom	3.3	2.1	12	7.6	**0.15**	0.09
Ethylbenzene	Arom	0.53	0.48	1.9	1.7	<0.01	<0.01
m/p-Xylene	Arom	1.3	1.4	4.7	5.1	0.03	0.03
o-Xylene	Arom	0.51	0.66	1.8	2.4	0.01	0.01
Styrene	Arom	0.23	0.40	0.83	1.4	<0.01	<0.01
Isopropylbenzene	Arom	0.07		0.25		<0.01	
1,3,5-Trimethylbenzene	Arom	0.25	0.38	0.90	1.4	0.01	0.01
1,2,4-Trimethylbenzene	Arom	0.79	0.88	2.9	3.2	0.02	0.03
1,2,3-Trimethylbenzene	Arom	0.20	0.29	0.72	1.0	0.01	0.01
Naphthalene	Arom	0.09		0.32		**0.19**	
1,4-Dichlorobenzene	ClAro	0.09	0.03	0.32	0.11	<0.01	<0.01
Vinyl chloride	Halo	0.01		0.04		<0.01	
Dichloromethane	Halo	1.4	0.40	5.1	1.4	0.04	0.01
Chloroform	Halo	0.22		0.79		0.01	
1,1,1-Trichloroethane	Halo	0.35	1.6	1.3	5.8	0.01	0.03
Carbon tetrachloride	Halo	0.09		0.32		0.05	
1,2-Dichloroethane	Halo	0.01		0.04		<0.01	
Trichloroethene	Halo	0.07	1.8	0.25	6.5	<0.01	0.06
Tetrachloroethene	Halo	0.14	0.47	0.51	1.7	**0.10**	**0.33**
Pyridine	Misc	0.17		0.61		0.02	

*Defined in Table 1

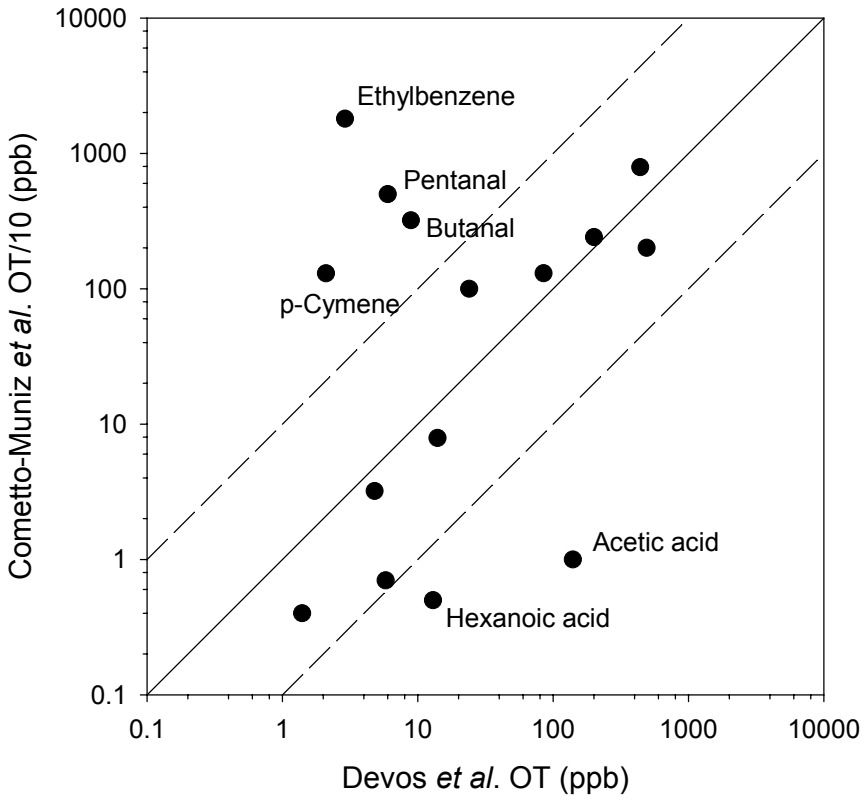

Figure 1. Comparison of odor thresholds (OTs) reported by Cometto-Muñiz *et al*. and adjusted to estimate 50% OT detection with standardized OTs from Devos *et al*. (1990).

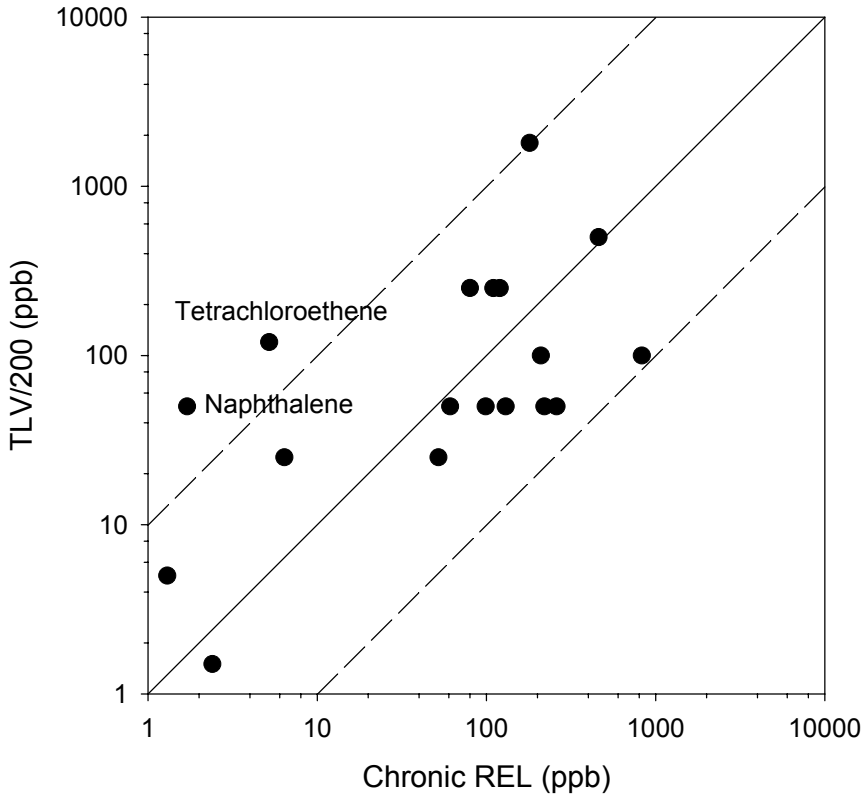

Figure 2. Comparison of ACGIH Threshold Limit Values (TLVs) for which primary effect is not cancer or irritation only and adjusted to accommodate continuous exposure of the general population with Cal-EPA noncancer chronic Reference Exposure Levels (RELs).