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Volatile organic compounds and indoor air

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Abstract

TOP

Volatile organic compounds represent one of the two major pollutant categories implicated in the sick-building syndrome. This article reviews measurement and analytic methods, presents a summary of the etiologic considerations, and presents newer, nonregulatory intervention strategies that can be used to prevent complaints resulting from this pollutant category. (J ALLERGY CLIN IMMUNOL 1994;94:296-303.)

Abbreviations used

ASTM	American Society for Testing and Materials
EPA	Environmental Protection Agency
FLEC	Field laboratory emissions cell
SBS	Sick building syndrome
TLV	Threshold limit value
VOC	Volatile organic compound
VVOC	Very volatile organic compound

(Click on a term to search this journal for other articles containing that term.)

Key words: [Occupational health](#), [volatile organic compounds](#), [sick building syndrome](#)

As discussed elsewhere in this supplement, volatile organic compounds (VOCs) and bioaerosols are considered the primary potential etiologic agents in the group of complaints referred to as the sick building syndrome (SBS). This paper will present an overview of classification and measurement of VOCs, a summary of their potential and documented health effects, and a discussion of pollutant levels and standards. VOCs that emanate from molds as secretion products will not be addressed.

Definitions**TOP**

The agents grouped together as VOCs can legitimately be classified in a variety of ways, with each of the classification schemes serving different purposes. These schemes include classification by physical characteristics, that is, molecular weight and boiling point, by chemical species and chemical reactivity, and by their sources. The first approach guides the selection of the available analytic techniques, including sample collection (■ Table I). The second allows the characterization and classification of health effects. The third provides an approach to intervention.

TABLE I. Sampling media for VOCs

Compound	<u>Boiling point (C)</u>		Sorbent
	Begin	End	
VVOC	50	100	Charcoal
VOC	50-100	240-260	Tenax, charcoal

SVOC	240-260	380-400	PUF, XAD2
POM	400		Filters

SVOC, Semivolatile organic compound; POM, particulate organic matter.

The first, traditional classification is based on simple physicochemical characteristics. Very volatile organic compounds (VOCs) generally have a boiling point between 50° and 100° C; VOCs begin to boil from 50° to 100° C and end boiling at 240° and 260° C; semivolatile organic compounds begin boiling at 240° and 260° C and end boiling at 380° to 400° C; and particulate organic matter sublimates above 400° C. The lower the boiling point the higher the volatility and the greater the vapor pressure of the agent. Agents with greater vapor pressure must be collected on sampling media with a greater specific surface.¹ Some investigators believe that the more volatile substances, such as VOCs and VOCs, are likely to cause symptoms on human exposure and are likely to be involved in at least some of the buildings considered “sick”, through odor annoyance and irritation.

A second way of considering the VOCs is to group them by their chemical families independent of their molecular weight and size. Such chemical families include alkanes, aldehydes, alcohols, and acids. A fundamental assumption in toxicology provides legitimacy to this approach in that structure predicts activity. On the other hand, size and volatility are not necessarily taken into account with this approach. Very small agents of a single family with high vapor pressures may then inappropriately be considered less important in a specific circumstance than larger molecular weight agents of the same family with very low vapor pressures, simply because the greater mass per molecule of larger compounds make them appear more important than smaller agents.

Work on irritant thresholds in the general chemical sense (trigeminal nerve) suggests that VOCs and VOCs may have relatively similar thresholds if the concentrations are defined as a function of the ratio of partial vapor pressure to saturated vapor pressure rather than being expressed in a strictly molar fashion.² Eye irritation may follow a similar if not identical pattern. This approach is useful primarily if volatiles are present only in vapor phase and not adsorbed to particulate matter or dispersed as an aerosol.

A third approach to classification is to identify agents by source; this may be most useful for physicians, because this classification scheme leads directly to control. This scheme may require that the same agent be attributed to different sources; for example, trichlorethylene is a component both of perfumes and typewriter correction fluids. Databases exist to allow identification of potential sources, but these are often not very useful in actual practice for problem identification. In addition, it is often easier and cheaper to simply solve a problem than to characterize it well.

Measurement

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Exposure assessment and quantitative measurement are the domain of industrial hygiene. They involve selection of a purpose, a sampling strategy, and an analytic method. Each of these three must be undertaken thoughtfully and is the subject of wide-ranging discussing and controversy.

Purpose

Industrial hygienists define sampling strategies as the collection of field data for specific purposes. A traditional approach in most compliance investigations is “worst case” sampling, a method to assure that the most severe exposure conditions have been identified. Data collected for those purposes will differ from data collected for “representative” or “mean” exposure levels within groups.

Sampling strategy

Depending on the purpose of the investigation, different sampling strategies must be used. Buildings and their internal environments change over time because many pollutants are generated intermittently. Therefore the timing of sampling may need to vary. If worst case conditions are to be replicated, one may choose to sample after heating, ventilation, and air-conditioning systems have been inoperable for some time. As ventilation systems cycle off, pollutant levels may accumulate and are sometimes adsorbed to sources that serve as secondary sinks. These sinks may reemit the agents later. Second, some activities may occur only at certain times. For example, off-gassing from recently dry-cleaned clothing, operation of a laser printer, perfume, or use of typewriter correction fluid may all lead to substantial changes in the concentrations of VOCs. Third, attempts to identify “average” or representative exposure levels may require longer term sampling intervals, that is, over days and weeks. On the other hand, attempts to characterize relatively brief peak exposures may require the use of direct reading instrumentation or the collection of sample results in 10 to 15 minute sampling intervals. The sample variability will define the ideal time interval.

Finally, exposure assessment may be undertaken to quantify source strengths. This may occur in chamber studies in the laboratory or with use of a newly developed technique for field work, the Field Laboratory Emissions Cell (FLEC).³ In any case, it goes well beyond the capabilities of most field investigators. The FLEC technique may serve as the basis of defining ventilation requirements for buildings in the future and represents an exciting new development in conceptual approaches to pollutant control.

VOC sample collection strategies

There are four basic forms of sampling for VOCs: the use of screening devices, the active or passive collection of substrate on sorbent samplers, and the use of previously evacuated canisters. Each of the methods has inherent fundamental weaknesses, although they are admittedly the basis of our knowledge of dose-response relationships for VOCs.

The three screening devices include flame ionization detection, photoionization detection, and photoacoustic detection. All three are direct reading instruments with essentially instantaneous readings. They cannot determine the concentrations of specific compounds but can only indicate a response to either specific infrared wavelengths, emitted or absorbed light, or amount of released energy. All three screening devices are usually sensitive to multiple different agents at the same time and have a variable ability to identify them. These devices can therefore be used to identify changes in the concentration of relatively constant mixtures or of single agents. They are often useful in identifying local sources of VOCs but are generally not useful in interbuilding comparisons of VOC concentrations. Although the National Institute for Occupational Safety and Health convened a workshop on comparison of the methods in 1990, no formal publications are available.

There are substantial differences in the estimated exposure levels at the same actual exposure of mixed solvents among the different techniques.

Active samplers use pumps to draw air at a defined flow rate through a sorbent collecting tube. These sorbents may consist of a single sorbent, such as charcoal, or of several different compounds to take advantage of the varying specific surface for each compound.⁴ For example, charcoal may not collect highly volatile agents such as VVOCs. In fact, some work suggests that higher specific activities of the medium, that is, surface area per gram of collection medium, predict greater ability to collect analyte.¹ A review of active sampling techniques (Kennedy ER, Gagnon YT. Unpublished National Institute for Occupational Safety and Health draft document, 1990) and discussions by others⁵ suggest that work still needs to be done to fully understand the relationships and differences among the various techniques.

Knöppel⁶ summarized the accuracy and validity of passive sampling for VOCs in indoor environments with use of personal dosimeters. His review suggested that the accuracy of sampling collection and analysis using a short-diffusion tube with an orifice relatively unaffected by turbulent flow was in the same range (15% to 20%) as that for active sampling techniques.

An alternative is the collection of air in stainless steel evacuated canisters that can be filled over minutes or weeks through a control valve. The canister must then be taken to a laboratory and the contents analyzed with use of gas chromatographic/mass spectrophotometric techniques. The samples themselves may change over time as reactive species in the air interact with one another, as has been demonstrated for indoor air in general.⁷ Passive sampling has the advantage of simplicity, reduced expense, and ready availability when compared with other methods.

Analytic method

Samples may be desorbed from their collection medium with a solvent or the more efficient and sensitive thermal desorption. The gases are then passed through a gas chromatograph or other separation instrument and chemically analyzed. An alternative is the collection in specific sampling media that allow characterization of only that one agent. Such sampling methods are necessary for most reactive species and are listed in standard reference books.

Choice of the analytic method greatly influences the outcome, and expected concentrations of the agents in question will also define the limits of analytic sensitivity of the method. For example, it may not be possible to collect enough material in a short period of time to allow measurement with use of sorbent-based samplers. In that case, only a more indirect method, such as the use of screening devices, is possible. Analytic methods include flame ionization, mass spectrometry, and specific chemical techniques.

Potential outcomes of interest

Headaches, fatigue, difficulty concentrating, and irritability are integral components of the SBS. This combination of symptoms is also seen after exposure to VOCs in the occupational setting, where adverse effects of this group of substances have been recognized for more than 140 years. Several conferences in 1985 provided classification systems to the spectrum of disorders.⁸ The mildest form is simply the presence of the above symptoms. A more severe form consists of symptoms together with evidence of neuropsychologic dysfunction on standardized tests. A third form consists of dementia according to standard classifications. Several different mechanisms have been postulated.

Neuropsychologic testing follows one of two broad strategies. The first compares relative functioning of various domains attributable to different parts of the brain, the Luria-Nebraska approach. It focuses on intra-individual abnormalities rather than on comparing performance on specific domains with normative data and allows easier following of the same person over time on repeat testing. It is not commonly used in the United States; readers are referred to standard textbooks for a broader discussion. The second approach uses standardized batteries such as the Halstead-Reitan test battery or the Wechsler Adult Intelligence Scale-Revised Version. Collected performance data are then compared with normative data acquired elsewhere. Several test batteries have been used in occupational studies, among them the Baker-Letz battery and the Pittsburgh Occupational Exposures Test battery.

Two basic tenets of toxicology apply only partially, at least in their simplified form, to solvent neurotoxicity: the predictability of dose-response relationships and the homogeneous susceptibility of populations to neurotoxins. A well-documented example of the limitations of the first is the influence of alcohol on both the direct and indirect toxicity resulting from modification of styrene and toluence metabolism. Therefore the characteristic dose-response relationship is complicated by an additional agent. The genetic susceptibility to anticholinesterase agents is an example of the second point, the lack of homogeneous susceptibility of populations to the toxic effects of a given substance. This was originally recognized in anesthesia and led to the introduction of a screening test before the use of succinylcholine for muscle relaxation. These issues will be discussed further under the topic standard setting.

Complaints of headaches, fatigue, irritability, and difficulties concentrating are widespread among office workers without clear evidence of neuropsychologic dysfunction. This is discussed further elsewhere in this supplement. Case reports,⁹ uncontrolled field studies,¹⁰ and theoretic discussions¹¹ have addressed this syndrome in the context of indoor environments.

Sensitization

Small reactive chemicals, including some such as trimellitic anhydride and isocyanates found in the indoor air, may function as haptens and lead to sensitization. There is reasonable evidence, both from animal models and from human studies, that overexposure is at least one cause of sensitization. The presence of specific antibodies by themselves always serves as an indicator of exposure, not as a measure of sensitization. "Reactions" to agents are attributed to an allergy only in the presence of convincing physiologic abnormalities related to an exposure coupled with specific immunologic reactivity. Despite anecdotal reports and case series concerning trimellitic anhydride and toluene diisocyanate, there is no convincing evidence that complaints of the SBS are related to these agents. Reports have generally not contained control groups or provided justification for normal values. In addition, simple presence of antibodies is not considered evidence for causal

relationships of disease.

Asthma and other allergic diseases, from contact urticaria to hypersensitivity pneumonitis, have been attributed to indoor pollutants.^{[12](#)}, ^{[13](#)} When such diseases are encountered in building occupants, standard approaches to disease characterization and attribution are undertaken, including documentation of physiologic changes related to an exposure and characterization of the exposure. Most allergic reactions have occurred because of bioaerosols and will not be addressed in this summary. Rare cases of carbonless copy paper or laser printer–associated disease have been described.

Mucous membrane irritation

Eye, nose, and throat irritation are integral components of the SBS. The first two are mediated by the common chemical sense and the trigeminal nerve, and the latter is mediated by the glossopharyngeus nerve. Complaints of eye irritation from allergies are indistinguishable from those of irritation simply on the basis of a clinical description. This is discussed further elsewhere in this supplement. In addition, elevated or decreased relative humidity, draftiness, and inadequate lighting or glare may lead to overlapping complaints.

Evidence for Voc as a Cause of the Sbs

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As with most syndromes, the SBS clearly has several different causes. In specific “outbreaks,” one or more causes are usually identifiable. Many of the documented problems have been attributed to VOCs in indoor air, although exposures are generally two to three orders of magnitude below permissible exposure levels and threshold limit values (TLVs). What then is the theoretic basis of the assumption that VOCs are at least one cause of the SBS?

Animal evidence

There is a well known American Society for Testing and Materials (ASTM) method for the estimation of sensory irritancy of airborne chemicals.^{[14](#)} This method uses mice exposed to irritants in a standardized fashion and allows measurement of slowing of respiration as an indicator of trigeminal stimulation. It has been used to evaluate specific agents commonly encountered in indoor environments, such as carbonless copy paper, floor material, and carpeting,^{[15](#)} ^{[18](#)} and served to evaluate series of similar chemicals to characterize structure-activity relationships.^{[19](#)} It has also been used for the characterization of agents associated with specific outbreaks of building occupant complaints.^{[20](#)} The results of this type of testing have shown that emissions from such agents lead to irritation in rodents.

Controlled human exposures

Humans have been exposed to VOCs in limited controlled studies. First, three studies that used a specific mixture of VOCs have been reported. Mølhave created a mixture of 22 different VOCs

commonly encountered in indoor environments. In a first study he and his coauthors²¹ exposed 150 subjects who claimed substantial discomfort and illness in offices to the above mixture in a blinded fashion at 0, 5, and 25 mg/m³.³ Symptom increases and a decrease in measures of attention were documented at the 5 and 25 mg exposure concentrations. Otto et al.²² at the Environmental Protection Agency (EPA) attempted to reproduce the study but chose to use a substantially small number of healthy young men. Only symptom increases were noted. Finally, Kjaergard et al.²³ repeated the study and demonstrated similar effects to those described by Mølhave.

Other authors have attempted to expose persons to individual agents, for example, aldehydes and alcohols, and obtained information on odor and irritant thresholds.²⁴ This approach has allowed the determination of odor and irritant thresholds and has outlined ways of predicting interactions between specific agents. The authors have begun the systematic study of complex mixtures in an attempt to clarify the interactions of chemical species, numbers of compounds, and specific concentrations.

In any case, two groups of experimental human studies suggest that human reactions occur predictably at exposures two orders of magnitude below permissible exposure levels.

Field studies

Experimental studies must rely on specific subjects, and their results can be generalized only to similar persons. Nevertheless, they allow tests of hypotheses. Field studies, on the other hand, identify factors that are important in the real world and compare and contrast them. Importantly, the results may again only be extrapolated to the same kind of investigation. Therefore results from investigations of specific problems may not be generalizable; results from nonproblem buildings may not be generalizable to “sick” buildings.

Three series of field studies have suggested that SBS symptoms are related to VOCs. Berglund et al.²⁵ investigated a recognized “sick” library and a control building. They identified a narrower range of VOCs in the sick building than in the control building. That group of authors has subsequently used a similar technique in other investigations and suggested that the presence of fewer agents is one important aspect of the problem. Norback et al.^{26 27} presented data from two investigations that used area sampling and suggested that, in a longitudinal approach, symptoms were primarily attributable to low molecular weight compounds, that is, undecane and lower (less than 12 carbon atoms). Finally, Hodgson et al.^{28 29} have presented two studies suggesting that VOCs were at least one contributor, in addition to noise, lighting, and work stress, to the SBS.

These results should not be interpreted to mean that the SBS has only one cause. On the contrary, thousands of investigations have demonstrated that multiple problems exist in most buildings about which there are complaints. There is as yet little documentation that intervention into one or the other of these problems actually provides a solution. Nevertheless, there is reasonable evidence that VOCs, even at the concentrations encountered in offices, contribute to the problem.

Are TLVs appropriate for indoor spaces?

During the past 10 years, many indoor investigations were carried out using a “traditional” industrial hygiene approach, that is, potential causes were identified, the appropriate environmental air samples were collected, and a report was generated. The vast majority of such investigations concluded that there was no problem because “all measured levels were below applicable standards.” Breyse³⁰ has described the background of the development of TLV since the 1930s, their appropriate use, and why they should not be used in indoor environments. In brief, TLVs were developed for use in industrial environments, where usually only one or two agents are present. Second, they were generally set to prevent disease and disability but not discomfort or irritation. The kind of work traditional “blue collar” workers performed was thought to require less “close” attention to detail. They were therefore expected to work in the presence of mucous membrane irritation. Third, even TLVs were not expected to protect everyone, just most persons. Even then, most occupational literature was developed with use of Caucasian men as subjects. The applicability of such work to other populations, such as women, remains to be documented. Finally, preexisting disease and susceptibilities are not considered, such as atopy, allergies, and asthma. In any case, the conclusion of the American Conference of Governmental Industrial Hygienists presentation was that TLVs are not applicable to the indoor air.

Rafferty and Light³¹ and the Indoor Environmental Quality Committee of the American Industrial Hygiene Association³² present a different industrial hygiene approach to indoor investigations, again without relying on published standards. Three alternatives have been suggested. First, comparisons internally of problem and nonproblem areas may identify true culprits. Second, use of building performance standards and diagnostics may identify problems even when quantitative exposure assessment fails to identify “pertinent” elevations. Finally, biologic monitoring, either with the ASTM mouse method or with humans (n-of-one clinical trials) show an alternative.

European guidelines and other standards

The World Health Organization published air quality guidelines for Europe in 1987. The levels are often substantially below those accepted as valid “thresholds” of “environmental criteria” in the United States. Even those standards assume or imply that a single defined level will “protect.” In fact, populations often contain persons with differing levels of susceptibility. In addition, the assumption of dose-response may indicate that low levels of exposure will cause rare but measurable effects, such as is documented for formaldehyde even at levels recommended in the World Health Organization guidelines. In fact, the new ventilation guidelines for Europe attempt to present a different view of ventilation and comfort. Implicit is the idea that more ventilation reduces exposures and discomfort, in analogy to the well-known radiation health concept of ALARA, “as low as reasonably achievable.”

Two subsequent recommendations have been made on VOCs. Seifert suggests a level of 250 µg/m³ as an acceptable level; higher exposures can be assumed to cause problems. Mølhave suggests a level of 300 µg/m³, with no more than 20% coming from any individual exposure.

Control strategies to limit human exposure to VOCs in indoor air fall into two categories: source control and ventilation. The latter is addressed elsewhere in this supplement. Source control, considered much more effective, is accomplished by elimination, substitution, isolation, and encapsulation.^{33 34}

Emission factors

A first major aspect of source control is the development of standardized methods for quantifying VOC emissions from indoor sources. A standard guide by the ASTM³⁵ sets forth basic principles of such testing and provides guidance for the development of material and product-specific methods. Such methods are under development for carpets, carpet adhesives, and carpet cushions; particleboard and other “boards;” and paints and architectural coatings. These methods allow the comparison of different products between and among classes. They allow a “yardstick” by which manufacturers can improve their product, architects and engineers can specify low-emitting materials, and regulators can determine the importance of VOC contributions from various indoor sources. Most of these methods are conducted in small “environmental” chambers less than 200 L in volume and made of glass or stainless steel with controllable ventilation rate, temperature, humidity, and air movement. Some tests are also conducted in large, room-sized, similarly constructed “environmental chambers.” Most recently the FLEC was developed for field investigations in Europe.³⁶ A variety of other office products have been characterized, including office machines such as photocopiers and laser printers.

Sources fall into three general categories based on the rate at which their emissions decay after they are first introduced into the building. Slow decay sources include carpets, ceiling tile, particleboard, and other solid, “dry” materials. Although there may be an initial emissions “burst” in the first few hours, the rates decline slowly and remain strong months and even years after installation. Fast decay sources include paints, adhesives, floor and furniture waxes, and spray products. These are introduced as “wet” sources and dry, that is, emit most of the liquid content, within minutes, hours, or days. Even so, such products may continue to release VOCs for months or years. Constant sources are introduced to emit as part of their use, including room air fresheners and deodorants, insect repellants, and moth crystals.³³

Emissions from indoor sources are reported as “emission factors,” with units in mass per surface area unit per time. Multiplication of this factor by the product quantity provides an emission rate. Factors for flooring, ceilings, wall coverings, and paints are expressed as a mass per surface per hour, in $\text{mg}/\text{m}^2 \cdot \text{hour}$, ranging from single- to six-digit $\text{mg}/\text{m}^2 \cdot \text{hour}$.³⁷ Some products are reported in mass per unit per hour, such as chairs or office work stations, laser printers, photocopiers, and fax machines.

Ventilation and VOC emissions

The ventilation standard of the American Society of Heating, Refrigerating, and Air-Conditioning

Engineers (ASHRAE) is based primarily on expected human emissions, such as body odor. It mandates a minimum ventilation rate of 15 cubic feet of outside air per occupant per minute. The ASHRAE standard does not directly address the increased ventilation requirements from product emissions, although it does suggest that such ventilation may be inadequate in the presence of strong indoor sources. In the presence of less than adequate ventilation (less than 15 cubic feet of outside air/occupants), even weak indoor sources can lead to substantial airborne concentration. In the presence of strong sources, ventilation rates must be raised to avoid potentially harmful exposures. During the initial drying stages of paints and other wet products that emits ten and hundreds of thousands of mg/m²*hour, extremely high ventilation is required. Even with high ventilation rates, these emissions may result in exposures that exceed limits set by the Occupational Safety and Health Administration.

Manufacturers' response to emissions testing

Federal and state legislation concerning indoor air and office buildings in the late 1980s led the EPA to a nonregulatory approach to products. In 1990 a 2-year "carpet policy dialogue" began between the EPA, manufacturers, and interested public and private organizations. The process resulted in the development of a standardized carpet test method.³⁸ That method now forms the basis for periodic testing of carpet products under a quality control program organized by the Carpet and Rug Institute, a trade association. Standards were established for emissions of specific VOCs, and carpets meeting the standards receive the Carpet and Rug Institute's "green tag," intended to assure consumers of the product's quality. Subsequent programs are to be established by adhesives and cushions manufacturers. A similar effort is conducted by a carpet trade association in the Federal Republic of Germany.

The Swedish Flooring and Trade Association has developed a standard test for determining VOC emissions, using the FLEC. More than 80 products have been tested, providing the rates for materials aged 4 and 26 weeks after unwrapping the newly produced material.³⁹

The recognition of materials characteristics and their influence on indoor environmental acceptability has generated manufacturers responses in a time frame in which regulatory approaches alone have failed. This approach is also under consideration for incorporation into the new ventilation standard, 62-89R (ventilation for acceptable indoor air quality) by ASHRAE.

Conclusion

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VOCs are at least one major contributor to complaints related to indoor environments as documented by both animal and human chamber and field studies. Measurement of VOCs is technically difficult and expensive. "Standards" are theoretically available but practically of little use except as general guidelines. General dilution ventilation is a relatively inefficient way of addressing their effects. A much more useful approach is to minimize exposure through the selection of low-emitting products and local source control.

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