Symptoms and Microenvironmental Measures in Nonproblem Buildings

Michael J. Hodgson, MD, MPH; John Frohliger, PhD; Edward Permar, Cecilia Tidwell, MSc (Hyg); Neal D. Traven, PhD; Stephen A. Olenchock, PhD; and Michael Karpf, MD

Symptoms commonly defined as the sick building syndrome were studied in a cross-sectional investigation of 147 office workers in five building areas using a linear-analog self-assessment scale questionnaire to define symptoms at a specific point in time. At the same time, the environment in the breathing zone was characterized by measuring thermal parameters (dry-bulb temperature, relative humidity, air speed, and radiant temperature), volatile organic compounds, respirable suspended particulates, noise and light intensity, and carbon dioxide and carbon monoxide levels. Demographic characteristics of the occupants and building characteristics were recorded. Up to 25% of the variance in regression models could be explained for mucous membrane irritation and central nervous system symptoms. These two symptom groups were related to the concentrations of volatile organic compounds, to crowding, to layers of clothing, and to measured levels of lighting intensity. Chest tightness was also related to lighting intensity. Skin complaints were related only to gender. Gender, age, and education failed to demonstrate a consistent relationship with symptom categories. This study suggests that the sick building syndrome may have specific environmental causes, including lighting and volatile organic compounds.

From the Occupational and Environmental Medicine Program, School of Medicine (Dr Hodgson, Dr Karpf), The Physical Plant Department (Mr Permar), and the Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh (Dr Traven); Air Quality Services, Inc (Dr Frohliger, Ms Tidwell); and the Immunology Section, Laboratory Investigations Branch, Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health (Dr Olenchock).

Address correspondence to: Michael J. Hodgson, MD, 190 Lothrop St, Rm 149, Pittsburgh, PA 15261.

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Complaints now termed the "sick building syndrome" (SBS) have been attributed to "tightly" built buildings since the mid-1970s.[1] Symptoms usually considered part of this syndrome include mucous membrane irritation, ie, eye, nose and throat irritation; "neurotoxic" symptoms such as headaches, fatigue, irritability, and difficulty concentrating; odor complaints; skin irritation; and "asthma-like" symptoms, interpreted to include chest tightness, coughing, and wheezing.[2] A wide variety of specific causes has been identified in individual outbreaks, including inadequate temperature and relative humidity control, noise, lighting, vibration, exposure to volatile organic compounds (VOCs), formaldehyde, microorganisms, and environmental tobacco smoke, entrainment of vehicle exhaust or spent air, and office machine gassing.[3] Nevertheless, results of investigations of individual problem buildings cannot be extrapolated to all buildings because the former represent cases of well-defined problems.

The sick building syndrome has been studied in several broad fashions. Large cross-sectional epidemiologic investigations in Europe have variously suggested that ventilation systems[4,5] and gender, crowding, photocopying, and job title[6] were etiologic agents. Population-based telephone interviews have demonstrated decreased subjective productivity and increased upper respiratory infections in buildings with central heating, ventilating, and air-conditioning systems (HVAC).[7,8] Other experimental approaches[9,10] have suggested that ventilation systems, office machines, and environmental tobacco smoke compose approximately 85% of the perceived pollutant load in indoor environments. A specific etiologic hypothesis for the SBS was proposed by Molhave and coworkers,[11] who demonstrated that VOCs may lead to symptoms similar to those of the SBS even at low exposure levels.

Previous field studies of the SBS have inquired about the presence of "usual" symptoms among building occupants. Although several studies[11-13] have used linear analog scales, no simultaneous exposure characterization was undertaken. Because both symptoms and measurements may fluctuate over periods of time less than 8 hours, any relationship between short-term high-level exposures and peak symptoms would be obscured.

We have conducted several field studies to determine the presence of symptoms and their degree at a specific point in time and have used direct reading instrumentation to characterize exposure simultaneously.[14,15] This report presents an extension of that method to five building areas that had not generated enough complaints to lead to a formal indoor air quality investigation, ie, buildings without known problems. We wished to test the hypothesis that specific environmental conditions might be related to the level of complaints, specifically lighting level and respirable suspended particulates. No attempt was made to determine which occupants had expressed dissatisfaction with their environment. Social and organizational aspects of work were not identified. Because of the limitations of survey instrumentation, no specific pollutants, such as pyridine or nicotine, were determined.

Methods

Design and Conduct of the Study

The study was conducted as a cross-sectional study in five sites in three buildings to which the investigators had ready access during parts of the months of July and August of 1987. The sites were selected because all were administrative areas involved in research coordination. A sixth area initially selected was vacant during the time of the study because visiting faculty, students, and university faculty were not present during the 6 weeks the study was planned. The protocol was approved by the Institutional Review Board at the University of Pittsburgh, and no consent form was required. The highest ranking person in each area was approached for permission to conduct the study in that area. None of the site supervisors refused. A meeting was then held with all senior members in each office to present the purpose and the design of the study.

At each work station, the purpose of this study and the procedures to protect the confidentiality of responses were explained. Measurements were then performed while the subject was completing the questionnaire. Approximately 20 minutes were required to conduct the measurements at each work station. Subsequently, the equipment was moved to the next work station, the appropriate instruments were cleaned, and explanation was given to the next subject.

Areas were investigated in a 3, 2, 1, 4, 5 sequence. There was no contact between the five areas administratively or through information exchange during the time of the investigation. Renovation was begun in area 1 by the time the investigation had progressed to that area. No attempt was made to record whether renovation was being undertaken in the direct work area of the participating subject.

Questionnaire

Linear analog questionnaires have been previously used in indoor air investigations,[10-14] although the results do not directly provide dissatisfaction rates. This questionnaire collected several kinds of information: 1) demographic data, including age, gender, years of education, years of work at a specific institution and building, and smoking status; 2) the magnitude of 10 complaints, eye, nose, and throat irritation, chest tightness, headaches, difficulty concentrating, irritability, and fatigue; 3) work characteristics, hours per day spent in the building at individual offices and at computer screens; number of workers sharing offices and the percentage of smokers; and 4) personal issues, such as the wearing of contact lenses and glasses, the number of layers of clothing, etc. It also inquired how the workers felt about their air quality at the time of the investigation in relationship to usual and extremely good or bad conditions (Copies of the questionnaire are available from the authors on request.)

Environmental Characteristics

Ten indoor air quality characteristics were measured with direct reading instruments or short-term indicator tubes to obtain levels during the time that workers were actually completing the questionnaire. The instruments and their performance characteristics are presented in Table 1. The Organic Vapor Analyzer was calibrated to butadiene, and results were expressed as parts per million of four-carbon fragments. Measurements were obtained only once at each work station. No attempt was made to validate the performance characteristics of the instruments provided by the manufacturer because exposure levels are known to vary over short periods of time. Samples were measured in the following order: 1) temperature, relative humidity, air speed, and wet bulb globe temperature, 2) noise intensity, 3) light intensity, 4) carbon monoxide and carbon dioxide concentrations, 5) VOCs, and 6) respirable suspended particulates (RSPs).

The percentage of occupants predicted to have dissatisfaction because of draft was calculated from a standard equation.[15] This number predicts the percentage of persons who will be dissatisfied with a given set of thermal conditions of temperature and air speed. The "percent dissatisfaction" was arbitrarily used as a measure of the degree of discomfort that any given person can be expected to suffer under the same environmental conditions. Radiant temperature and humidity ratio (W) were calculated using a standard software program.[16]

The number of smokers in each of the five areas who admitted to current smoking per square foot of floor space was used as a continuous variable, as a surrogate of smoking intensity.

TABLE 1
Instrumentation Used for Indoor Air Quality Study

Parameter	Instrument	Sensitivity	Accuracy Range
Temperature	Battery-operated psychrometer	0.3° C	±0.16° C 0–100° C
Relative humidity	Battery-operated psychrometer	0.3° C	±0.16° C 0–100° C
Noise	Bruel & Kajer sound level meter	0.5 dB (A)	±0.25 dB 25–140 dB (A)
Illumination	Uitron LX-101	1 lux	±2%
Carbon monoxide	Drager detector tube	1 ppm	±3% 0–2000 ppm
Carbon dioxide	Drager detector tube	10 ppm	±3% 1–10000 ppm
Volatile organics	AID model 580 organic vapor analyzer	0.1 ppm	0.1 ppm 0–2000 ppm
Respirable dust	GCA Miniram	0.01 mg/m^3	±0.03 mg/m^3 0.01–100 mg/m^3
Air speed	Kurz series 490 anemometer	10 FPM	±3% 0–2000 FPM
Heat stress	Reuter-Stokes wibget	1° F	±0.16 degree C 0 to 96 degree C

* FPM, feet per minute

Because of additional information[4] that dust might contribute substantially to complaints, we collected 20 representative bulk dust samples from the sites approximately 3 months later. Endotoxin analyses were performed using a Limulus amebocyte lysate assay. Each filter was extracted separately in 10 mL of sterile nonpyrogenic water (Travenol Laboratories, Inc, Deerfield, IL) by rocking at room temperature for 60 minutes. The extracts were decanted into sterile plastic tubes and centrifuged for 10 minutes at 1000*g*. The supernatant fluids were assayed in duplicate for the presence of Gram-negative bacterial endotoxins by means of the chromogenic modification of the Limulus amebocyte lysate test (QCL-1000; Whitaker Bioproducts, Walkersville, MD).

Statistical Analyses

Data were analyzed using the Statistical Packages for the Social Sciences for Microcomputers (SPSS/PC 2.0). The maximum number of complete records available for each comparison of interest was used. Differences were accepted as statistically significant when the associated *P* value was less than 0.05. Where *P* values fell between 0.10 and 0.05, the differences were considered suggestive of an effect and more closely scrutinized.

Data were plotted. Where they were log-normally distributed (all measures, including symptoms, except draft and radiant temperature), appropriate transformations were undertaken for analysis. Where the results of a measurement fell below the limit of detection, the lower limit of detection was used as the actual measured number. Radiant temperature was distributed bimodally, so that an indicator variable for high *v* normal radiant temperature was included. An indicator variable was also used for the presence or absence of perimeter units.

For data analysis, symptoms were grouped into several variables by adding the logarithms of the individual symptom scores. For purposes of this investigation, the symptoms were grouped to 1) mucous membrane symptoms, ie, eye, nose, and throat irritation; 2) central nervous system symptoms, ie, headaches, nausea, irritability, difficulty concentrating, and fatigue; 3) skin irritation; 4) chest tightness; and 5) the SBS as defined by Finnegan,[4] ie, headaches, fatigue, and mucous membrane symptoms. Indicator variables were calculated for age (older or younger than 35 years), computer work (more or less than 1 hour per day), and wearing contacts (yes *v* no). Education (completed high school, completed college, or entered graduate school) and crowding (alone in an office, up to three workers; four to seven workers; eight or more workers) were used as ordinal variables.

The data were initially examined through grouped analyses using analyses of variance (AOV) or *t* tests for continuously distributed variables and χ^2 tests for noncontinuously distributed variables. All analyses were undertaken first for demographic variables, then symptoms, and then measured environmental data. For analyses of variance, main effects were either gender and smoking status, together with an interaction term, or the five-building area (without an interaction term). The method of least significant differences was used to adjust for multiple comparisons within all analyses of variance. No attempt was made to adjust significance levels for multiple comparisons in the overall study.

The zero-order relationships among demographic, symptom, and environmental characteristics were examined using simple correlation.

Finally, multivariable regression models using backward-stepping techniques were developed using the five symptoms categories as dependent variables and environmental and demographic data as predictor variables. Four dummy variables were used to control for the effect of building site. Because of concern for overparameterization, three different approaches were used, a sequential, a hierarchical, and a simultaneous method. In the sequential approach, four sets of models were developed. First, personal data, including age, education, gender, smoking status, layers of clothing (clo units), and contact lens wearing were examined. The second set of models characterized office environments, including the percentage of smokers in the building, hours spent at computers (more or less than 1, hours spent at the desk, the number of persons sharing the office, and the presence of perimeter units. Subsequently, the contribution of measured air quality characteristics alone was examined. The fourth set was developed using all variables that had contributed to any of the first three sets of models at a probability level of 0.1. The hierarchical approach also involved examining the three groups of variables individually, but whenever a variable had contributed significantly to one of the models, it was included in the subsequent models. For both approaches, there were at least 10 records for each independent variable, a reasonably conservative approach to modeling. In the third approach, despite the risk of overparameterization, a group of models was developed entering all possible variables of interest at the same time. For this set of models, only five records per independent variable were present. Because the coefficients were virtually the same, only the last group of coefficients is presented.

Results

All five building areas had central HVAC systems. Environmental characteristics were significantly different among the five areas with the exception of the lighting intensity. They were all in the range frequently seen in offices. Of great interest was that radiant temperature was distributed bimodally, with a lower peak around 19°C and a higher peak around 39°C.

Table 2 presents the correlation matrix for environmental parameters. There was a positive, zero-order correlation between VOCs and CO_2, a negative one between VOC and draft, and a positive relationship between VOCs and relative humidity and radiant temperature on the one hand, and VOCs and CO on the other. As temperature and humidity ratio increased, and draft decreased, the concentration of RSPs also increased. Nevertheless, no direct relationship between RSPs and CO_2 was seen. There was a positive association between noise and draft, implying that as ventilation systems were more effective, the noise levels increased. Light intensity and noise levels were negatively correlated.

Zero-order correlations were calculated among five symptom variables and 10 environmental characteristics. Associations of interest were noted between chest tightness and RSPs ($r = 0.13$, $P = 0.085$) and VOCs ($r = 0.13$, $P = 0.083$) and between radiant temperature and mucous membrane irritation ($r = 0.17$, $P = 0.04$). Symptoms were significantly associated with the smoking density among the five building areas.

Only weak zero-order correlations were noted between symptoms and environmental measures individually. Eye ($r = 0.14$, $P < 0.09$) and nose ($r = 0.20$; $P < 0.02$) irritation were correlated with radiant temperature, as were summary variables containing these two. Eye irritation was also weakly correlated with relative humidity ($r = 0.14$; $P < 0.08$). Difficulty concentrating ($r = 0.20$; $P < 0.02$) and chest tightness ($r = 0.15$; $P < 0.07$) were related to the concentrations of carbon dioxide.

Table 3 summarizes demographic characteristics among the five areas. Most variables were not randomly distributed because there were substantial differences

TABLE 2
Correlation Matrix of Environmental Measures

	Temperature	W	Draft	Globe	CO_2	CO	RSP	VOC	Light
Temperature*									
W†	.452‡								
Draft§	.067	.048							
Globe‖	.165	−.159¶	.229#						
CO_2**	−.192††	−.057	−.074	−.273‡					
CO‡‡	−.077	−.038	−.053	.078	.418‡				
RSP§§	.180††	.165††	−.179††	−.143¶	−.155	.074			
VOC‖‖	0.142	−.357‡	−.144¶	−.210††	.182††	.254#	.249#		
Light¶¶	−.109	.035	−.057	−.104	.016	−.060	−.012	.125	
Noise##	.096	−.056	.240#	.314‡	−.106	.104	−.019	.000	−.158¶

* Temperature: Logarithm of dry bulb temperature.
† W: Humidity ratio.
‡ $P < 0.001$.
§ Draft: as calculated by Fanger and Christensen (Perception of draught in ventilated spaces. *Ergonomics*. 1986;29:215–235.)
‖ Globe: Radiant temperature.
¶ $P < 0.1$.
# $P < 0.01$.
** CO_2: Logarithm of the carbon dioxide concentration.
†† $P < 0.05$.
‡‡ CO: Logarithm of the carbon monoxide concentration.
§§ RSP: Logarithm of the respirable suspended particulates.
‖‖ VOC: Logarithm of the concentration of volatile organic compounds.
¶¶ Light: Logarithm of light intensity.
Noise: Logarithm of noise intensity.

TABLE 3
Description of Occupants: Demographic Characteristics and Symptom Levels

	Area 1	Area 2	Area 3	Area 4	Area 5	χ^2 (Probability)
Gender						16.48
Male	12	25	5	2	4	.008
Female	36	20	17	7	9	
Smoking						NS*
Current	16	18	9	2	5	
Never/ex	36	32	14	7	8	
						F Ratio† (Probability)
Age, y, mean (SD)	39.3 (9.8)	32.9 (8.1)	36.9 (13.0)	43.1 (7.7)	37.3 (11.5)	3.57 (.008)
Education, y, mean (SD)	17.3 (3.7)	15.0 (2.0)	14.9 (2.8)	15.7 (2.8)	14.5 (2.3)	4.74 (.001)
Symptom levels‡						
Central nervous system	4.7 (1.6)	5.4 (1.9)	3.8 (1.9)	4.6 (2.1)	5.5 (2.7)	2.49 (.046)
Mucous membrane irritation‖	2.9 (1.6)	3.5 (1.4)	2.0 (1.2)	2.2 (1.8)	3.0 (1.8)	4.75 (.001)
Chest tightness	.78 (.62)	.75 (.53)	.48 (.39)	.49 (.41)	.53 (.63)	1.92 (.110)
Skin irritation	.70 (.62)	.76 (.60)	.48 (.44)	.61 (.64)	.83 (.72)	1.06 (.376)
Sick building syndrome¶	7.6 (3.9)	9.0 (2.8)	5.8 (2.8)	6.8 (3.6)	8.5 (4.4)	3.76 (.006)

* NS, not significant.
† The range for the least significant difference procedure for significant differences between the individual area for symptom levels was 2.80.
‡ Sum of the logarithms of individual symptoms belonging to that group. Values are means and standard deviations.
§ Central nervous system symptoms: sum of headache, irritability, fatigue, difficulty concentrating, and nausea.
‖ Mucous membrane irritation: eye, nose, and throat irritation.
¶ Sick-building syndrome: headaches, fatigue, and mucous membrane irritation.

in age, educational status, and gender distribution of occupants among the five areas. On the other hand, smoking habits were not significantly different. Therefore, differences in results attributed to area effects may actually be subject to the influence of age, education, and gender. Table 3 also presents the same symptom scores for the five areas. Areas 1, 2, and 5 generally had higher levels of complaints than did areas 3 and 4. An analysis of variance demonstrated significant differences for central nervous system symptoms, mucous membrane symptoms, and the SBS, but not for chest or skin symptoms among those five areas. Two-way and three-way analyses of variance using gender and smoking status as additional main effects, with interaction terms, did not show them to be independent contributors to the level of complaints for any of the five sets of symptoms. Analyses of variance for various symptom groups and environmental measures showed no differences between women and men or between smokers and nonsmokers in age, education, or time spent at desks or computers.

Several specific hypothesis were examined using *t* tests. Differences of note were that women had attended school, on average, fewer years than men (15.2 *v* 16.8 years; $P = 0.035$) and worked fewer hours at computers (1.6 *v* 2.4 hours; $P = 0.08$). Women were not significantly younger than men. They were exposed to statistically significantly higher mean levels of VOC (.86 *v* .38 ppm; $P = 0.003$) and RSP (62 *v* 44 $\mu g/m^3$, $P = 0.042$) than men. Also, smokers spent, on average, fewer hours at their desks than nonsmokers (3.4 *v* 4.5 hours; $P = 0.005$), had higher levels of CO in the breathing zone (5.0 *v* 4.2 ppm; $P = 0.04$), and were exposed to draftier conditions by standard prediction calculations (13.6% *v* 13.1% dissatisfied; $P = 0.069$).

Finally, multivariable regression models were developed. Age, education, and gender were not clearly related to symptom groupings (Table 4). Measured levels of VOC and of lighting intensity were stable and consistent predictors of symptoms. The smoking density variable failed to contribute significantly to the final models.

Discussion

The results in this cross-sectional study suggest that indoor air quality symptoms may result from specific pollutants presented in the office rather than from "inadequate ventilation." The method described here may provide both the technique to identify specific causes and, more importantly, may provide a framework in which to validate dose-response relationships in indoor environment.

TABLE 4
Regression Models for Four Symptom Categories*

	Symptom Category			
	Central Nervous System	Eye, Nose, and Throat Irritation	Sick Building Syndrome	Chest Tightness
r^2	.20	.27	.26	.12
P	<.0001	<.0001	<.0001	<.01
Smoking		−.15†		.15†
Sex		.16†		
No. of workers sharing work space	.24‡	.18§	.24‡	
Layers of clothing	−.17§	−.19§	−.20§	
Hours spent at desk	−.17§	−.25‡	−.20§	
VOC	.27‡	.28‡	.30‡	.22§
Light intensity	.19§	.19§	.19§	.23‡

* Numbers represent beta coefficients.
† P value equivalent < .10.
‡ P value equivalent < .01.
§ P value equivalent < .05.

A first methodologic question to be answered is whether this technique of symptom quantification and exposure assessment is valid or useful. It has been used by others in the past[12,13] and by this group of investigators.[14,15] Linear analog scales cannot be "validated" in the true sense because symptoms vary over short periods of time. Therefore, attempts at replicating symptoms on the basis of the questionnaire are impossible. Nevertheless, such scales are analogous to the frequently used clinical approach of asking patients to describe the severity of chest pain or other discomfort. Other studies of the SBS have used very differently structured questionnaires, addressing "usual" symptoms, and area sampling for pollutants has generally involved averaging levels over eight hour periods. Because both pollutant levels and symptoms vary substantially over short periods of time, techniques used in those investigations have been unable to identify causal relationships. A second difficulty associated with identification of dose-response relationships through sampling is that personal exposures are generally higher than area exposures. Certainly in an office setting, where workers perform certain tasks that generate exposures (dust or VOCs), area samples will underestimate exposure. In any case, the technique presented here has implicated certain exposures. The validity of that implication can be demonstrated only through replication of this study.

A second methodologic problem is the substantial interrelationship among various environmental measures. Using regression modeling to develop dose-response relationships leaves the issue of co-linearity between predictor variables unsettled. A much larger data set may be necessary to examine the relative contribution of a variety of exposures.

The relationships suggested here are plausible and have been described in the past. First, Molhave and coworkers[11] and Otto[16] have demonstrated symptoms of the SBS at low levels of VOCs. This study then confirms, in a cross-sectional field study, only what has been predicted from isolated chamber experiments. Second, the relationship between lighting intensity and symptoms has been described.[15,17] In one of these studies, the authors conducted a quasi-experimental study of offices changing ventilation rates and lighting. Both influenced the level of symptoms. Again, this study then merely confirms what has been predicted from previous studies. A legitimate question is whether the measurement instruments used here were appropriate. Although photoionization detectors are relatively insensitive, this would lead to a consistent and random measurement error in a study of this type and not to the introduction of bias toward a specific hypothesis. Therefore, any possible dose-response relationship would be obscured rather than reinforced.

In regression models, gender was not consistently associated with increased levels of symptoms after controlling for the level of VOC exposure. This is in distinction to field studies[6,7] in which women had approximately 50% elevation of symptoms over men. No prior studies have examined the relationship of personal exposures with symptoms. Because women had substantially higher VOC levels, and VOC levels were a primary exposure predictor of complaints, gender may be related to complaints only because women have higher VOC exposures. Their higher exposures may be from office characteristics, such as the use of laser printers, typewriter correction fluids, and photoduplication machines, or may be related to personal characteristics, such as wearing makeup. This deserves further study in the future. We also noted that ventilation efficiency, as measured by CO_2 levels, was unrelated to complaints. Although this may seem surprising at first glance, it is consistent with published studies.[10,11] Because CO_2 is produced primarily by humans, but approximately 85% of pollution load in office buildings is not of human origin and therefore unrelated to CO_2 levels, ventilation such as recommended in the ventilation rate procedure under the standard 62-89 of the American Society of Heating, Refrigerating and Air-conditioning Engineers[18] designed to address human pollutants may be inadequate to dilute nonhuman pollutants.

This study was not designed to address the effects of smoking because sampling for nicotine, pyridine, furfuryl, and cotinine would require much more sensitive instrumentation. There was a weak relationship between the density of smokers and the levels of symptoms across the five buildings, although there was confounding with the crowding variable. Because the irritant and malodorous properties of tobacco smoke are unrelated to carbon monoxide or respirable particulate levels as measured here, we are unable to comment on the importance of smoking in this data set, although such a relationship has been seen elsewhere.[19]

This study suggests that the SBS may have several different causes, each of which may require different remediation strategies. Because the study was conducted in a small number of buildings, during one time of the year, without extensive organizational characterization of the office, the study must be replicated before further conclusions are drawn. Nevertheless, it does suggest a method for relating exposures to symptoms and may provide a framework in which health affects may be examined more rigorously.

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