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Volatile Organic Compounds in Ventilating Air in Buildings at Different Sampling Points in the Buildings and their Relationship with the Prevalence of Occupant Symptoms

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Abstract

Total volatile organic compounds (TVOC) are determined in intake, room-supply and room air in 86 office rooms in 29 office buildings in northern Sweden. Measurements of formaldehyde were also made in room air. Building and room characteristics were identified and symptom reports collected from 1087 office workers. Concentrations of TVOC and formaldehyde in room air were low, with mean values of 71 μg/m³ and 31 μg/m³, respectively. The TVOC concentration was generally lower in room air than in supply air or intake air. The "loss" (difference in measured values) of TVOC from supply to room air was associated with raised concentrations of formaldehyde and raised prevalences of occupant symptoms. High TVOC concentrations in room air were associated with reduced prevalences of occupant symptoms.

KEY WORDS:
Ventilation, Sick building syndrome, Epidemiology, TVOC, Formaldehyde.

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Introduction

Pollutants in room air are related to pollutants in the outdoor air and to sources and sinks in the shell of the building, the supply air system and the room. There are few reports on the pollution load from ventilation systems. Berglund and Lindvall (1979) observed in a school building that the supplied ventilation air was sometimes perceived to be more odour-intensive than the room air. In longitudinal studies of a preschool and an office building, Berglund and co-workers (1982a, 1982b) found that the concentration of VOC (volatile organic compounds) and strong odour components increased during passage through the supply air system. Fanger (1988a,1988b) showed that pollution from ventilation systems can have a major influence on the perceived air quality in a room.

Besides inorganic gases, such as CO, CO_2 and NO_2, the focus in non-industrial indoor air chemistry has been on volatile organic substances with boiling points in the range 50 °C to 250 °C, VOC. Mølhave (1990), and Seifert (1990) proposed the use of a mass addition (in μg/m³) of VOC (total volatile organic compounds, TVOC) as an indicator of health effects caused by a multicomponent air exposure to VOC at low concentrations. A major problem in using the mass addition concept is the lack of a convention defining TVOC and its measurements. Seifert suggests defining TVOC as the sum of individual VOC separated and quantified by a gas-chromatographic technique, where the first 10 compounds (ranked by concentration) in each chemical class (alkanes, terpenes, etc.) are summed up. He also proposes some restrictions on the number of single compounds and classes. On the basis of that definition, he suggests a target guideline value of 300 μg/m³ for TVOC. Mølhave proposes an alternative definition (without the need for identification) and suggests a tentative health-related guideline value of 200 μg/m³. In office buildings, typical values of total TVOC are in the range 50-1300 μg/m³ (NKB, 1991), which is 2-10 times higher than typical outdoor levels.

Formaldehyde has been extensively measured in indoor air during the past few decades. Knowledge concerning its occurrence, sources and health effects is substantial as compared with knowledge concerning VOC. WHO (1989) recommends a maximum value of 100 μg/m³ for the general public in non-industrial indoor environments in order to avoid odour and sensory reactions. For specially sensitive groups showing hypersensitivity reactions without immunological signs, WHO recommends a maximum value of 10 μg/m³.

Only few, limited epidemiological studies have been made of the covariation between symptom reports among occupants and chemical load on the indoor air in non-industrial buildings (Skov & Valbjörn, 1987; Norbäck, 1990; Lundin, 1991; Nelson et al., 1991). Moreover, there is still limited knowledge concerning the way in which the complex chemical load of non-industrial indoor air should be characterized so that it is meaningful with respect to health and comfort. The sources and sinks of pollutants in the indoor air are largely unknown, as is their relative importance for the chemical load on the room air to which occupants are exposed. One important building component that can act as either source or sink is the supply air system.

The aims of this investigation were to study changes in TVOC concentration from outdoor air to room air and to study the associations between symptom reports and concentrations of TVOC and formaldehyde in room air.

Materials and Methods

Buildings and Rooms

Air quality measurements were carried out in 29 buildings selected from a large questionnaire study (Stenberg et al., 1993) on almost 6000 office workers and 210 office buildings. The response rate of the original questionnaire was 95.7%. The buildings selected for this study were required to include the two extremes with regard to prevalence of the Sick Building Syndrome (SBS) and to include at least 15 respondents. Fourteen of the buildings had high, and 15 low, prevalences of SBS symptoms. In the selected buildings, 488 men and 599 women completed the questionnaire.

The 29 buildings selected had also been studied in two case referent studies, the one on SBS and the other on skin symptoms among video display terminal (VDT) workers (Sundell et al., 1993). One to four rooms per building were selected randomly for the present investigation, in total 86 rooms. In 84 of these rooms, an extensive climate characterization was performed, and in 77 the occupants responded a second time to a symptom questionnaire. The second questionnaire study and the ventilation measurements coincided in time within a few days. Most of the chemical measurements were made within six months after the second questionnaire study.

A *building* is defined here as a whole building or a uniform part of a building served by one ventilation system. The 29 buildings and 84 rooms were investigated with respect to air flows, air temperature and relative humidity. By inspection, the 84 rooms were characterized as to room size, surface materials, fleece and shelf factors, age of furniture, occupants' smoking habits, cleaning routines and presence of office machinery, such as copiers and laser printers. Measurements and inspections were made during the winter season following the first large questionnaire study (Sundell et al., 1991).

Some characteristics of the buildings and rooms studied are given in Table 1.

Symptom reports

The occupant symptoms asked for in the questionnaire comprised three groups: (1) general symptoms including "fatigue", "feeling heavy-headed", "headache", "nausea/dizziness" and "difficulties in concentrating"; (2) mucous-membrane symptoms including "itching, burning or irritation of the eyes", "irritated, stuffy or runny nose", "hoarse or dry throat" and "cough"; (3) skin symptoms, including "dry facial skin", "flushed facial skin" and "itchy, stinging, tight or burning sensations in facial skin", "scaling, itching scalp or ears" and "hands dry, itching red skin". Responses were to be given in any of three categories: "Yes, often (every week)", "Yes, sometimes" and "No, never" and were required to refer to the respondents' experience of the past three months. Symptoms asked for did not need to be work-related, since some of them were expected to be persistent even during absences from work.

Chemical Measurements

Measurements of air quality were made once in each building during the year following the questionnaire study. The TVOC concentration was determined in

Table 1. Characteristics of examined buildings with low and high prevalences of SBS. Mean and median values, weighted by the number of respondents in the buildings.

Factor	Buildings with			
	Low SBS*-prevalence (15 buildings, 485 respondents)		High SBS*-prevalence (14 buildings, 712 respondents)	
	Mean	Median	Mean	Median
Respondents per building	37	38	79	66
% women	46	50	62	59
% working with video display terminals	42	52	46	36
% current smokers	22	22	26	27
% with "SBS" *	3	4	13	11
% with general symptoms every week	24	25	38	38
% with mucous-membrane symptoms every week	17	17	32	31
% with skin symptoms every week	21	20	31	32
% with at least one symptom every week **	41	41	57	56
Buildings:				
Year of construction	1961	1968	1969	1980
Ventilation running hours	12	11	18	13
% with recirculation of return air	53	–	36	–
% with all-air heating	23	–	10	–
% heated by water radiators	72	–	90	–
Rooms:				
Year of remodelling	1974	1976	1980	1981
% with plastic floors	23	–	18	–
Floor-cleaning frequency /week	3	2	2	2
Outdoor air-flow rate, *l*/s.p	19	13	15	10
Air temperature, °C	22.9	22.8	22.9	22.8
Relative humidity, %	23	22	23	23

* At least one general, one mucous-membrane and one skin symptom every week.
** At least one general or one mucous-membrane or one skin symptom every week.

the outdoor air at the air intake (intake air), at the supply air terminal device of a room (supply air) and in the centre of the room (2 m above the floor, room air). In addition, formaldehyde was determined in the room air. The VOC were trapped on charcoal (glass tubes with two sections, 100 + 50 mg; SKC Inc., lot 120), desorbed with 1.0 m*l* dichloromethane and analysed by gas chromatography (GC) (Andersson et al., 1984). This method allows a long sampling time, proper calibration of the gas chromatograph and selective determination of 2-ethylhexanol in each sample. This compound has been of interest in other investigations as a degradation product of plasticizers (phthalate esters) in floor coverings. The sampling rate was 200 m*l*/min. Formaldehyde was collected by diffuse samplers in two parallel samples and analysed by liquid chromatography (HPLC) (Levin et al., 1988). Samplings of VOC and formaldehyde were performed simultaneously at the three sampling points for at least a five-hour period (between 9 a.m. to 3 p.m.). Six parallel samples of TVOC were collected from the intake air and supply air and two parallel samples from the room air. Samplings were made during the daytime, with the office normally occupied. For GC analysis of TVOC, a Hewlett-Packard Model 5890 gas chromatograph with flame ionization detector was used. The chromatograph was equipped with a 7673A autoinjector, a 3396A integrator, a 9122C diskette station and a fused silica capillary column (50 m, 0.20 μm i.d., 0.33 μm film thickness, Hewlett-Packard, Ultra 2). The temperature of the injector was 150 °C and that of the detector 250 °C. The column temperatures were 40 °C (10 min), followed by a temperature rise of 10 °C/min up to 200 °C (10 min), and a second temperature rise of 10 °C/min up to 250 °C (10 min). Helium, with a flow rate of 0.5 m*l*/min, was used as carrier gas. The samples were injected in the splitless mode.

For HPLC analysis of formaldehyde, a Waters chromatographic system was used, consisting of a M-600 pump, an M-170 autoinjector, an A Chrom Jet integrator, an M-440 UV-detector and a Radial-Pak column (100 × 5 mm i.d., octadecylsilane, 10 μm) in an RCM 100 radial compression module. The mobile phase was 7% of methanol in water with a flow rate of 0.8 m*l*/min.

The organic compounds collected on charcoal, desorbed by dichloromethane and chromatographed on the system used ($> C_7$) are defined as TVOC in this paper. The gas-chromatographic quantification was performed with toluene as an external standard and each compound was quantified before the sum was calculated.

Air temperature and humidity were measured in intake air and in room air. Hot-wire instruments were used.

Data Analysis

Three types of analysis concerning the associations between symptom reports, TVOC and formaldehyde were used:

(1) A comparison between 14 buildings with high, and 15 buildings with low, prevalences of respondents reporting a combination of symptoms comprising at least one general, one mucous-membrane, and one skin symptom each week.

(2) A comparison of rooms with respect to all symptoms reported by the respondents working in each room.

(3) An aggregate analysis of all 29 measured buildings, using questionnaire symptom reports by all the 1087 respondents. In this analysis, buildings are weighted by the number of respondents working in them.

The data were analysed using Epi Info version 3 (Center for Disease Control, Atlanta) and SPSS/PC+ (SPSS Inc., Chicago) statistical packages. In some instances the odds ratio (OR) was calculated. The odds ratio is the ratio of the odds of exposure among the cases to that among the referents.

Results

Chemical Measurements

The distributions of the TVOC concentration in the six parallel samples in intake and supply air were of normal shape. Therefore, the arithmetic mean of these six samples was used.

The mean standard deviation of the six parallel samples taken in the intake and supply air was 15%. This value should be compared with the variation in TVOC concentration in room air in buildings where at least two rooms had been measured: mean SD 35%. The variation between buildings, in mean TVOC concentration in room air, was larger, with SD of 79%.

The concentrations of TVOC in the room air were generally low (Table 2). With two exceptions (740 $\mu g/m^3$ and 220 $\mu g/m^3$) the measured values were below 170 $\mu g/m^3$, with an arithmetic mean of 70 $\mu g/m^3$ and a geometric mean of 45 $\mu g/m^3$. The extreme value, 740 $\mu g/m^3$, related to a drawing room. The comparison of TVOC levels in the supply air and in intake air was made using a t-test.

The TVOC concentrations in the intake air and the supply air were generally higher than the concentration in the room air (Table 2). The concentration of TVOC in the supply air did not differ from that in the intake air in 28 cases. In 37 cases, the amount of TVOC was higher and in 21 cases it was lower in the supply air than in the intake air. The TVOC concentration in the room air was higher than that in the supply air in 12 cases; in 29 cases

Table 2. Measured concentrations in $\mu g/m^3$ of TVOC (intake air, room supply air, room air) and formaldehyde (room air). Data from 86 rooms. Geometric means are adjusted to an outdoor temperature of 0 C: Log(VOCadjusted) = Log(VOC) − b × temperature(intake), where b = 0.025 for TVOC in intake air, 0.018 for supply air and 0.006 for room air. b = 0.008 for formaldehyde.

	All 29 buildings				15 buildings with low SBS prevalence		14 buildings with high SBS prevalence	
	86 rooms				39 rooms		47 rooms	
	Mean geometric	Mean arithmetic	Min	Max	Mean geometric	Mean arithmetic	Mean geometric	Mean arithmetic
	$\mu g/m^3$							
TVOC								
intake air	50	111	22	530	46	100	54	120
supply air	65	122	7	580	63	107	67	135
room air	45	70	3	740	66	96	33*	49*
supply-intake air	1	11	-340	320	1	7	1	15
room-supply air	-1	-51	-440	658	1	-7	-2*	-85*
HCHO								
room air	26	31	11	59	24	29	27	33

* Indicates a significant difference ($p < 0.001$) between buildings with high versus buildings with low prevalences of SBS (t-test).

Table 3. Correlation coefficients between crude concentrations of TVOC at different sampling points, changes in TVOC concentrations between sampling points, formaldehyde in room air and temperature of intake air. Data from 86 rooms.

	TVOC intake air	TVOC supply air	TVOC room air	HCHO room air	TVOC supply-intake air	TVOC room-supply air	Temp. intake air
TVOC							
intake air	1	0.75*	0.10	0.54*	-0.54*	-0.57*	0.50*
supply air		1	0.15	0.51*	0.14	-0.77*	0.48*
room air			1	0.02	0.03	0.51*	0.03
supply-intake air					1	-0.14	-0.14
room-supply air						1	-0.41*
HCHO							
room air				1	-0.16	-0.41*	0.46*

2-tailed significance, * $p < 0.001$

there was no difference, and in 43 cases the concentration was lower in the room air.

Formaldehyde levels in the room air were relatively low, with a range of 11 $\mu g/m^3$ to 59 $\mu g/m^3$, and an arithmetic mean 31 $\mu g/m^3$. The shape of the distribution is close to normal.

The distributions of TVOC in intake, supply, and room air are all positively skewed (Table 2). The logarithmic values are close to normal distribution and are used in the analysis of differences in mean concentrations between groups of rooms or buildings.

Table 3 shows the correlation coefficients between crude concentrations of TVOC at different sampling points, changes in concentrations between sampling points, formaldehyde in room air and the temperature of intake air. TVOC concentrations in intake and supply air are correlated (Table 3). TVOC in room air is only slightly correlated with TVOC in intake air and with TVOC in supply air. It should be noted that the concentration of formaldehyde (HCHO) is positively associated with the TVOC concentration in intake air (Table 3) but negatively associated with the differences in TVOC between room air and supply air. This means that the more TVOC that are "lost" in the room, the higher the concentration of formaldehyde. The meaning of the expression "lost TVOC" in the room is that the concentration of TVOC is higher in the room supply air than in the room air. Likewise "lost TVOC" in the ventilation system means that the concentration is higher in the intake air than in the room supply air.

Measurements of TVOC were made during different outdoor conditions. There is a strong positive covariation between temperature in intake air and TVOC in intake and supply air, and between temperature in intake air and formaldehyde in room air, but not between the intake temperature and TVOC in room air (Table 3). Accordingly, in the analysis of covariations with symptom reports, concentrations of TVOC and formaldehyde were adjusted for dependence on outdoor temperature. Analyses with arithmetic and crude (not outdoor temperature-adjusted) means were also made. The results of the crude data analysis were close to the results of analysis performed on temperature-adjusted data.

Associations between Pollutant Concentrations and Building Factors

Table 4 shows mean values of temperature-adjusted logarithmic concentrations of TVOC, "lost" TVOC and formaldehyde as functions of selected building and room characteristics (84 rooms). In a crude analysis there are essential covariations between a number of building and room characteristics and air-quality variables. It is notable that the "newer" the building ("virtual age", i.e. age with respect to the number of years since the building was constructed or remodelled), the more TVOC tend to be "lost" in the ventilation system, i.e. the TVOC concentration in intake air was higher than in the room supply air. Almost the opposite trend appears to occur with regard to TVOC "lost" in the room.

Since there are large covariations between different building and room characteristics, it is difficult to identify "real" associations as opposed to associations via confounders in a bivariate analysis. Associations were therefore tested for crude as well as adjusted data with multiple linear regression techniques. Only associations coherent in the different analyses are presented here.

Apart from its strong association with outdoor temperature, *TVOC* in *intake air* was also significantly and positively associated with the number of floors in the building, the "virtual age" of the build-

Table 4. Logarithmic concentrations of TVOC, adjusted for the covariation with the outdoor temperature, and changes in TVOC from intake to room air and formaldehyde in 84 rooms against selected characteristics of the room and the sex of respondents working there.

			TVOC intake air	TVOC supply-intake air	TVOC room-supply air	TVOC room air	Form-aldehyde room air
		n	Log μg/m³, adjusted				
Floor:	Plastic	18	1.6	.15	.00	1.7	1.4
	Linoleum	40	1.8	.09	-.20	1.7	1.4
	Textile	15	1.5	.16	-.22	1.5	1.4
Recirculation	Yes	36	1.8	.09	-.12	1.8	1.5
of air	No	47	1.6	.14	-.19	1.6	1.4
Outdoor air	< 13.6	39	1.8	.09	-.12	1.7	1.5
flow, *l*/s.p	≥ 13.6	40	1.6	.14	-.21	1.6	1.4
"Virtual" age	≤ 1965	4	1.5	.23	-.02	1.8	1.5
of building*	66-76	38	1.7	.18	-.18	1.7	1.4
	77-86	36	1.8	.07	-.19	1.6	1.5
	≥ 1987	6	1.5	-.07	.07	1.5	1.4
Floor cleaning	≥ 2	59	1.7	.09	-.20	1.6	1.4
frequency/week	> 2	25	1.6	.19	-.05	1.8	1.4
Air temperature	≤ 22.8	44	1.7	.12	-.08	1.7	1.4
°C	> 22.8	40	1.7	.12	-.25	1.6	1.4
Air relative	≤ 22.9	42	1.6	.19	-.22	1.6	1.4
humidity %	> 22.9	42	1.8	.05	-.09	1.7	1.5
Women		17	1.7	.09	-.15	1.6	1.4
Men		67	1.7	.23	-.19	1.7	1.4

* The "virtual age" is the year of construction or remodelling.

ing, and the presence of a garage. Together, these associations explain 30-40% (R^2 0.3-0.4) of the variation in TVOC levels in intake air.

A high *TVOC* concentration in *supply air* was significantly associated (R^2 0.6-0.7) with a high TVOC concentration in intake air as well as with ventilation characteristics, such as heat exchangers, a high degree of recirculation of air, a high outdoor air-flow rate, and an early year of construction or remodelling (old according to "virtual age"). The difference between TVOC concentrations in supply air and intake air was significantly (R^2 0.3-0.5) associated with TVOC in intake air as well as with heating and ventilation factors and the "virtual" age of the building. Thus, a large *"loss" of TVOC in the supply air system* was associated with rooms space-heated by radiators (as opposed to all-air heating), a late year of construction or remodelling, and ventilation systems with no heat exchangers.

The difference between TVOC concentration in supply and that in room air was significantly (R^2 0.4-0.6) associated with TVOC in supply air and the type of heating installation. Thus, a large *"loss" of TVOC in room air* was associated with space heating by radiators. There was also a tendency (not significant in all analyses) towards an association between "lost" TVOC in room air, a low floor-cleaning frequency and a high outdoor air-flow rate.

A high *TVOC* concentration in *room air* was significantly (R^2 0.4-0.6) associated with a high TVOC concentration in the supply air, all-air heating systems, a high floor cleaning frequency, and a low outdoor air-flow rate.

A high *formaldehyde* concentration in *room air* was significantly (R^2 0.5-0.6) associated with a low outdoor air-flow rate, "lost" TVOC in room air, ventilation systems with no heat exchanger, and a late year of construction of the building (factual age).

Associations between Symptom Reports and Concentrations of TVOC, Formaldehyde and "Lost" TVOC: Comparison between Buildings with Low and High Prevalences of SBS.

Buildings with a high prevalence of SBS (n = 14) had significantly lower TVOC concentrations in room air and a greater "loss" of TVOC from intake to room air than buildings with a low prevalence of SBS (n = 15) (Table 2). The odds ratio (OR) of being a high-prevalence building, was substantially elevated in buildings where TVOC were "lost" from intake to room air in comparison with buildings where TVOC were "added", as can be seen in the fourfold table below.

TVOC difference room-intake air	Prevalence of SBS		OR	95% CI
	high	low		
"Lost" TVOC (-)	12	2	39	3.6-730
"Added" TVOC (+)	2	13	1	

Analysis of Symptom Reports versus Formaldehyde and TVOC Concentrations in 86 Rooms

In an analysis with variables dichotomized (by the median value), the covariance between symptoms, symptom groups and air-quality variables was tested.

In a bivariate analysis, formaldehyde levels above the median value of 31 μg/m³ acted as a significant risk indicator of mucous-membrane symptoms "each week" (OR 3.1, 95%CI 1.14-8.7), of skin symptoms "each week" (OR 7.1, 95%CI 2.1-25.3), and of "at least one symptom each week" (OR 4.6, 95%CI 1.07-22.7) and tended to act as a risk indicator of general symptoms "each week" (OR 1.6, 95%CI 0.62-4.4) and of "at least one general, one mucous-membrane and one skin symptom each week" (OR 2.0, 95%CI 0.62-6.4).

"Loss" of TVOC from intake air to room air tended to be associated, though not significantly, with all types of symptom groups: mucous-membrane symptoms (OR 2.1, 95%CI 0.74- 6.2), skin symptoms (OR 2.8, 95%CI 0.99-8.2), and "at least one symptom each week" (OR 4.1, 95%CI 0.96-19.8), general symptoms (OR 1.3, 95%CI 0.45-3.5) and "at least one general, one mucous-membrane and one skin symptom each week", (OR 2.8, 95%CI 0.79-9.8). Such symptoms as "fatigue", "feeling heavy-headed", "hoarse or dry throat" and "facial dry skin" were most frequently associated with "loss" of TVOC.

The associations presented above are only marginally changed in an analysis stratified for gender. A logistic analysis was also used to test the associations with age, gender, smoking habits, personal

Table 5. Correlation coefficients between reported symptom prevalence and concentration of TVOC and formaldehyde (logarithmic values, adjusted for outdoor temperature). Data from 29 buildings with 599 women and 488 men. Prevalence data are weighted by the number of respondents in each building.

Symptom "at least once each week"	Prevalence %		TVOC intake air	TVOC supply air	TVOC room air	TVOC room-intake air	Formaldehyde room air
	mean	range	Correlation coefficients				
General symptoms							
≥ 1	30	14-55	.4#	.1#	-.4#	-.7#	.4
Fatigue	24	5-55	.3#	ns	-.4#	-.6#	.3
Feeling heavy-headed	13	0-36	.2	ns	-.4#	-.5#	.1
Headache	12	0-27	.2	ns	-.3	-.4	.2
Nausea/dizziness	2	0-13	.1	ns	-.3	-.4#	.2
Difficulties in concentrating	3	0-13	.2	.3	ns	-.1#	.2
Mucous-membrane symptoms							
≥ 1	25	7-64	.1	ns	-.4#	-.4#	.2#
Itching, burning, or irritating eyes	14	2-41	ns	ns	-.4#	-.4#	.1
Irritated, stuffy or runny nose	10	0-44	.2	.2	-.1	-.3	.3#
Hoarse or dry throat	8	0-27	.2	.2	-.3	-.5#	.2#
Cough	3	0-14	.2	ns	ns	-.3	ns
Skin symptoms							
≥ 1	28	10-64	ns	-.2	-.5#	-.4	ns
Dry facial skin	18	2-46	.2	-.2	-.4#	-.4	.1
Flushed facial skin	6	0-20	ns	ns	-.3#	-.3#	.2
Itchy, stinging, tight or burning sensation in facial skin	6	0-27	.2	-.2	-.2#	-.4	ns
Scaling, itching scalp or ears	11	0-27	ns	-.1	-.5#	-.2#	ns
Hands dry, itching red skin	7	0-32	ns	-.1	-.4#	-.3	.2
At least one general, or mucous-membrane or skin symptom	50	29-73	.2	ns	-.6#	-.6#	.3
At least one general,one mucous-membrane and one skin symptom	9	0-50	ns	ns	-.3#	-.2	.2

All correlation coefficients have a 2-tailed significance with $p < 0.001$. # indicates that there is a correlation ($p < 0.001$) separately for both men and women.

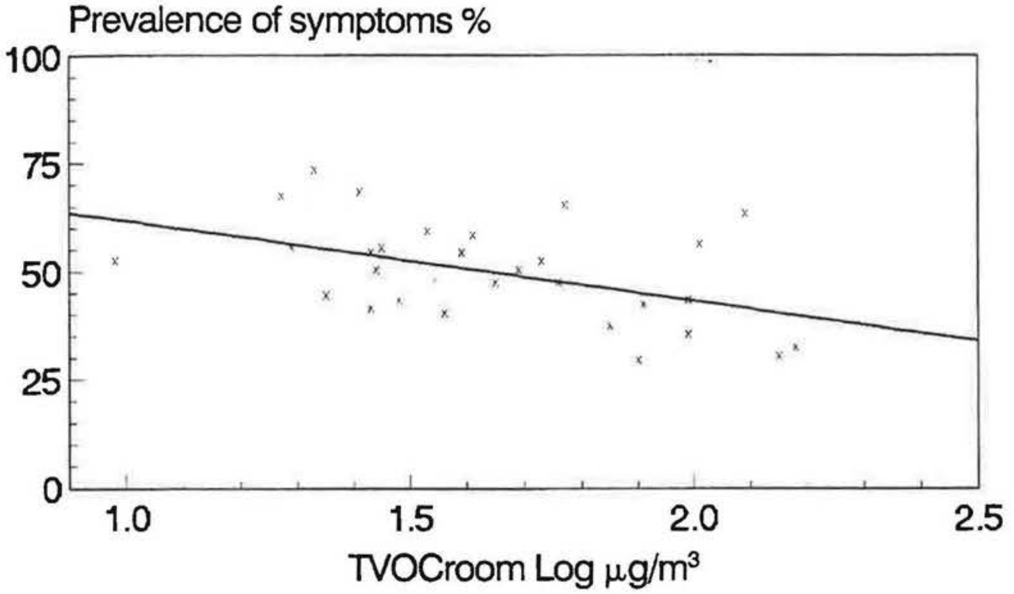

Fig. 1 Prevalence of symptoms (at least one symptom each week) against adjusted Log concentrations of TVOC in room air (TVOCr). 29 buildings, 1087 respondents. Correlation coeff.: -0.56 $p < 0.0001$.

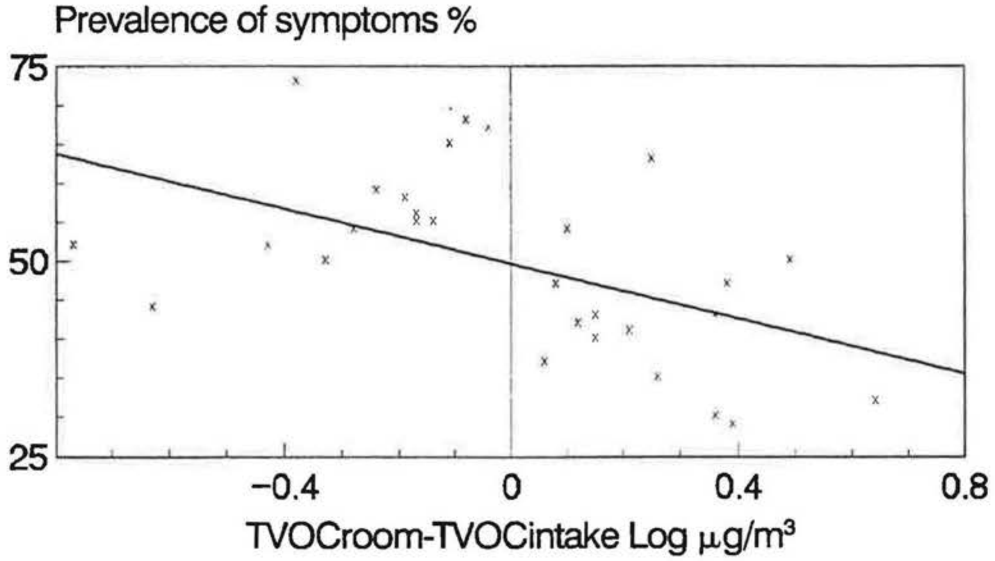

Fig. 2 Prevalence of symptoms (at least one symptom each week) against the difference in adjusted Log concentrations of TVOC in room air and intake air. 29 buildings, 1087 respondents. Correlation coeff.: -0.60 $p < 0.0001$.

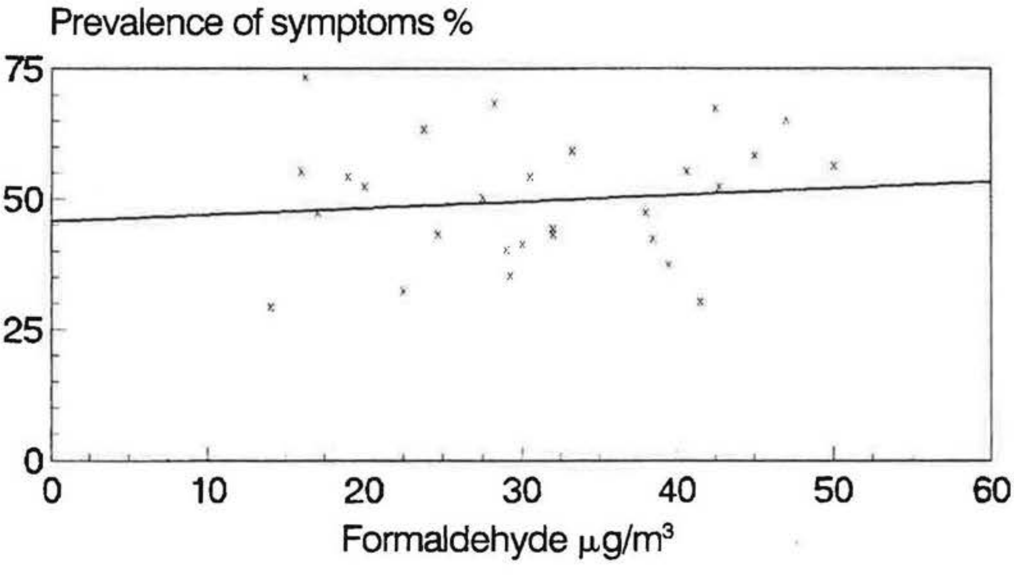

Fig. 3 Prevalence of symptoms (at least one symptom each week) against the concentration of formaldehyde in room air. 29 buildings, 1087 respondents. Correlation coeff.: 0.28 $p < 0.0001$.

sensitivity (asthma), and an index for psychosocial load at work as forced into variables. The directions of the associations are then unchanged, but generally slightly weakened.

Aggregate Analysis of Symptom Reports versus Formaldehyde and TVOC Concentrations

Aggregate analysis was made of the mean concentrations of TVOC and formaldehyde and changes of TVOC concentration from intake to room air for the 29 buildings versus the prevalence of reported symptoms, weighted by the number of respondents in the buildings (in total 1087 persons). In the analysis adjusted for the covariance with the intake air temperature, logarithmic concentrations of TVOC and formaldehyde were used.

The results of a bivariate analysis of the covariation between symptoms and air-quality variables are given in Table 5. Most symptoms and groups of symptoms show a negative covariance with concentration of TVOC in room air, while the covariance with TVOC concentration in intake air is positive but not very strong. "Lost" TVOC from intake to room air is especially correlated with general symptoms, such as "fatigue" and "feeling heavy-headed". Formaldehyde is positively, but not very strongly, correlated with various symptoms. TVOC concentration in supply air does not seem to be a strong risk indicator of SBS symptoms. Figures 1, 2, and 3 show plots of the prevalence of symptoms (at least one symptom each week) against the mean concentration of TVOC in room air, "lost" TVOC from intake to room air, and formaldehyde in room air, respectively.

The associations above were tested in a multiple regression analysis with symptoms as dependent variables, and age, smoking habits, personal sensitivity (gender, asthma) and an index regarding the psychosocial load at work as independent variables. The associations between chemical factors and symptoms then remain generally unchanged, i.e. the associations are seemingly not due to common confounders.

Discussion

Methodological Aspects

Reliability of symptom reports. The questionnaire used for characterization of buildings with regard to occupant reports on health and comfort has been used on a large scale in the Nordic countries since 1986. As reported by Andersson et al. (1988), the test-retest reliability of the questionnaire was tested on a group of 27 office workers who answered the same questions two weeks apart. For symptom questions the percentage discordance varied in the range 0-26% (mean 12%). Andersson et al. also validated the questions against the results of a physician's interview with 23 respondents. The specificity was reported to be generally high as was the sensitivity to all questions except regarding dermal symptoms (around 50%).

In the present study the same questionnaire on symptoms was used twice, with an interval of three to six months; a first time, as a screening instrument on almost 6000 respondents, and a second time, on a subsample of more than 500 persons in 160 buildings. The test-retest reliability for single symptoms was generally fair, kappa-values mean 0.45, range 0.31 – 0.59; and for symptom groups, mean 0.50, range 0.45-0.54. Kappa-values greater than 0.75 indicate generally excellent agreement, between 0.40 and 0.75 fair to good agreement, and below 0.40 poor agreement (Fleiss, 1981). Reported symptoms such as "nausea/dizziness", "cough" and "feeling heavy-headed" had kappa-values below 0.40, while "itching, burning or irritating eyes", "dry facial skin" and "scaling, itching scalp or ears" had values above 0.50. Thus, respondents tended to some extent to change their symptom reporting.

In the 86 rooms where chemical measurements were made, 77 persons answered the questionnaire twice. Of 22 persons who, in the first questionnaire, reported at least one general, one mucous-membrane and one skin symptom every week ("full case"), only 13 remained as "full" cases in the second questionnaire. Instead, there were seven new "full" cases, making a total of 20. However, in general, "new" cases replaced the primary cases in the same buildings: in the first questionnaire there were four "full" cases in the low-prevalence buildings and 18 in the high-prevalence buildings, and in the second questionnaire there were 5 and 15 "full" cases, respectively. The odds ratio, of being a "full" case when working in a high prevalence building as compared with working in a low-prevalence building, was 7.3 (95%CI 1.9-30) judged by the first questionnaire and 4.1 (95%CI 1.2-15) judged by the second questionnaire. Analyses regarding single symptoms or groups of symptoms give the same picture. Although the intraindividual consistency seems low, the intragroup consistency seems high, i.e. the mean response of a large group of occupants seems fairly stable even though the individuals of the group may have changed. The associations shown between VOC and symptom reports are generally the same, being only slightly strengthened if the replies to the second questionnaire are used.

Representativeness of the building sample. In comparison with other studies of the association between VOC and symptom reports of the SBS type (Skov et al., 1987; Norbäck, 1990; Lundin, 1991; Nelson et al., 1991), this study involves a large number of buildings, representative integrated measurements of TVOC on a working day, and parallel measurements of intake, supply and room air. The buildings investigated were those with the highest and lowest prevalences of SBS, selected from a typical population of office buildings in northern Sweden (Sundell et al.,1993). Buildings and rooms represent a broad range with regard to symptom prevalences from the "healthiest" to the "sickest".

Reliability of chemical measurements. The TVOC concentrations in room air vary considerably over the day (Skov et al., 1987; Berglund et al., 1990). Accordingly, an integrated measure of TVOC levels over more than five hours was preferred in the present study, being intended to be representative of a working day. Furthermore, the variation in VOC over days, weeks and months in single buildings may vary considerably. However, typically, the rank order of buildings, or parts of a building, as regards TVOC levels generally remains unaffected (Seifert et al., 1989; Shields and Weschler, 1992). Thus, in this study, it is believed that the chemical measurements are comparable on a group basis although the measurement period lasted almost a year. Moreover, in an attempt to increase the comparability of measurements made at different times of the year, the measured TVOC and formaldehyde values in most data analyses were adjusted for the covariation with the outdoor temperature. The temperature adjustment does not qualitatively change the covariations shown between air pollutants, building variables and symptom reports.

There are no standards for measuring VOC and there is no interlaboratory calibration procedure for checking the performance of a measurement method for VOC. Thus, it is not even possible to compare the levels of TVOC found in this study with levels reported by others. However, within the framework of the present study, comparisons between sampling sites are justified. The same methods were used throughout the investigation and all sampling and analyses were performed in a non-systematic time order.

Associations between TVOC Concentrations and Symptom Reports

TVOC concentrations reported in different studies are difficult to compare. But it should, at least, be possible to compare the size of concentration ranges as well as associations between concentrations and symptom reports. Skov et al. (1987) measured and analysed TVOC in 14 buildings with both Tenax and charcoal sorbent tubes. They found concentrations of TVOC between 430 $\mu g/m^3$ to 2630 $\mu g/m^3$, i.e. an order of magnitude higher than in the present study. They found no significant association between TVOC levels in room air and occupant symptoms. In a study of three office buildings (Nelson et al., 1991) no consistent covariation between TVOC levels and symptom reports was found, but a significant negative covariation with nasal and cough symptoms was found among men. In contrast, Norbäck et al.(1990a) found a significant positive association between TVOC concentrations (range 50 -1380 $\mu g/m^3$) and mean number of symptoms in a study of 11 buildings. In another study of six schools, they found an association between symptoms lasting more than 4 years and TVOC concentration (range 70-180 $\mu g/m^3$), but not for the incidence of new symptoms (Norbäck et al., 1990b). In a longitudinal study of a library building, Berglund et al.(1989) and Lundin (1991) reported an association between symptom reports and TVOC concentration in room air (range 51-362 $\mu g/m^3$). In the present study, the room air concentration of TVOC was relatively low (range 3-740 $\mu g/m^3$) and associations were found between TVOC concentrations and symptom reports. However, these relationships are all negative.

Associations between Formaldehyde, "Lost" TVOC and Symptom Reports

The results of the present study are intriguing as they suggest that typically high TVOC concentrations in room air are not a positive risk factor of occupant symptoms. Instead, "lost" TVOC and, to a lesser degree, formaldehyde act as risk indicators. In general, all the various analyses made show similar results. Important confounding factors, such as sex or work characteristics, were tested through stratification, multiple regression and logistic regression and were not found to change the general results.

Possible confounding by technical variables was tested and not found to be important. The results obtained from the different types of analysis on different subpopulations all point in the same direction. Thus, it is not likely that the results are chance findings or due to confounding, at least not by known confounders. The formaldehyde levels measured are all below the WHO guideline value for the general population but above the value recommended for specially sensitive groups (WHO, 1989). The levels are comparable to the levels ($>30\ \mu g/m^3$) at which Quackenboss and co-workers (1989) reported a significant relationship between formaldehyde exposure in homes and variability in peak expiratory flow in children.

The correlation between "lost" TVOC and a slightly elevated concentration of formaldehyde may be explained by a covariation in outdoor air between TVOC and formaldehyde, in that TVOC may be "lost" in the ventilation system but not formaldehyde. This possibility is not supported by a multiple regression analysis with formaldehyde concentration in room air as the dependent variable, and with technical variables, TVOC in intake air, and "lost" TVOC in room air as independent variables. In such an analysis there is a significant covariation between formaldehyde in room air and "lost" TVOC but not between formaldehyde and TVOC in intake air. In a study of reentrainment of air pollutants, conducted in the same region, formaldehyde was measured in intake air as well as in supply and exhaust air (Andersson et al. 1993). Typically the concentration of formaldehyde in intake air was an order of magnitude lower than in room-exhaust air, pointing at dominating indoor sources for formaldehyde. Unfortunately formaldehyde was not measured in intake air in the present study.

The associations between symptom reports, "lost" TVOC and formaldehyde, respectively, may be real associations or associations via some unknown confounding factor(s). Few other studies support the view that small fluctuations of formaldehyde around 25 μg/m3 or reduced concentrations of TVOC are associated with symptoms (Nelson et al., 1991; Quackenboss et al., 1989). It is more likely that "lost" TVOC are either changed into biologically more potent matter or into matter that is not trapped or analysed by the method used in this study, or both.

A crucial question is, What might be the fate of the "lost" TVOC? Up to now, interest in VOC has been directed towards source strength, dilution, dispersion, sorption and deposition but not transformations (Berglund et al. 1982a; Otson & Fellin, 1992). Weschler and co-workers (1992a, 1992b) have reported the formation of free radicals and aldehydes through indoor chemistry involving reactions between VOC, ozone and nitrogen dioxide. They found that, even at moderate ozone concentrations (55-86 $\mu g/m^3$; 28-44 ppb), essential chemical changes take place. For example, selected VOC were reduced to as little as up to one-tenth of their pre-ozone levels, and at the same time, formaldehyde levels were increased as much as three times. In a report of a controlled chamber study, Wolkoff et al.(1992) suggests that the high formaldehyde concentration found in a simulated office environment may be due to ozonolysis of VOC. Our results support the findings of Weschler et al. (1992a, 1992b) and Wolkoff et al. (1992) since we found an association between "lost" TVOC and formaldehyde also in a field study.

The surprising covariation shown in the present study between symptom reports and TVOC demonstrates that there may not be a single monotonous dose-response relationship, at least not at low levels of exposure. The transformation of TVOC and single organic compounds in indoor air should be more extensively studied as well as their interaction with the physical and chemical microenvironments.

Transformation products of TVOC are suspected of being a partial cause of occupant building-related symptoms.

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References

Andersson, B., Andersson, K. and Nilsson, C.-A. (1984) "Mass spectrometric identification of 2-ethylhexanol in indoor air: Recovery studies by charcoal sampling and gas chromatographic analysis at the microgram per cubic meter level", *Journal of Chromatography*, **291**, 257-263.

Andersson, B., Andersson, K. and Sundell, J. and Zingmark, P.-A. (1993) "Mass transfer of contaminants in rotary enthalpy exchangers", *Indoor Air*, **3** (2), 143-148.

Andersson, K., Fagerlund, I., Bodin, L. and Ydreborg, B. (1988) "Questionnaire as an instrument when evaluating indoor climate". In: Berglund, B., Lindvall, T. (eds), *Healthy Buildings '88*, Stockholm, Swedish Council for Building Research, Vol. 3, pp. 139-145.

Berglund, B., Berglund, U., Johansson, I. and Lindvall, T. (1982a)

"The influence of ventilation on indoor-outdoor air contaminants in an office building", *Environment International*, **8**, 395-399.

Berglund, B., Johansson, I. and Lindvall, T. (1982b) "A longitudinal study of air contaminants in a newly built preschool", *Environment International*, **8**, 111-115.

Berglund, B., Johansson, I., Lindvall, T. and Lundin, L. (1989) "Air quality and symptoms in a sick library building with a return-air ventilation system". In: Kulic, E., Todorovic, B., Novak, P. (eds) *CLIMA 2000*, Amersfoort, REEHVA, Vol. III: Air Conditioning Components and Systems, pp. 13-18.

Berglund, B., Johansson, I., Lindvall, T. and Lundin, L. (1990) "A longitudinal study of airborne chemical compounds in a sick library building". In: Walkinshaw, D. (ed), *Proceedings of Indoor Air '90*, Ottawa, International Conference on Indoor Air Quality and Climate, Vol. 2, pp. 672-682.

Berglund, B. and Lindvall, T. (1979). "Olfactory evaluation of indoor air quality". In: Fanger, P.O. and Valbjörn, O. (eds), *Indoor Climate*, Copenhagen, Danish Building Research Institute, pp. 141-157.

Fanger, P.O. (1988a) "Introduction of the olf and decipol units to quantify air pollution perceived by humans indoors and outdoors", *Energy and Buildings*, **12**, 1-6.

Fanger, P.O. (1988b) "A comfort equation for indoor air quality and ventilation". In: Berglund, B. and Lindvall, T. (eds), *Healthy Buildings '88*, Stockholm, Swedish Council for Building Research, Vol. 1, D19: 1988, pp. 39-51.

Fleiss, J.L. (1981) *Statistical Methods for Rates and Proportions*, New York, John Wiley & Sons, Second edition, p. 218.

Levin, J.-O., Lindahl, R. and Andersson, K. (1988) "High performance liquid-chromatographic determination of formaldehyde in indoor air in the ppb to ppm range using diffusive sampling and hydrazone formation", *Environmental Technology Letters*, **9**, 1423-1430.

Lundin, L. (1991) *On Building Related Causes of the Sick Building Syndrome*, Stockholm, Almqvist & Wiksell.

Molhave, L. (1990) "Volatile organic compounds, indoor air quality and health". In: Walkinshaw, D. (ed), *Proceedings of Indoor Air '90*, Ottawa, International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 15-33.

Nelson, C.J., Clayton, C.A., Wallace, L.A., Highsmith, V. R., Kollander, M., Bascom, R. and Leaderer, B.P. (1991) "EPA's Indoor air quality and work environment survey: Relationships of employees' self reported symptoms with direct indoor air quality measurements". In: *IAQ 91, Healthy Buildings*, Atlanta, ASHRAE, pp. 22-32.

Norbäck, D. (1990) *Environmental Exposures and Personal Factors Related to the Sick Building Syndrome*, Uppsala, Acta Universitatis Upsaliensis.

Norbäck, D., Michel, I. and Widström, J. (1990a) "Indoor air quality and personal factors related to the sick building syndrome", *Scandinavian Journal of Work, Environment and Health*, **16**, 121-128.

Norbäck, D., Torgen, M. and Edling, C. (1990b) "Volatile organic compounds, respirable dust, and personal factors related to prevalence and incidence of the sick building syndrome in primary schools", *British Journal of Industrial Medicine*, **47**, 733-741.

NKB, Nordic Committee on Building Regulations (1991) *Indoor Climate – Air Quality*, Helsinki, Nordic Committee on Building Regulations, NKB Publication No 61E.

Otson, R. and Fellin, P. (1992) "Volatile organics in the indoor environment: Sources and occurrence". In: Nriagu, J.O. (ed), *Gaseous Pollutants: Characterization and Cycling*, New York, John Wiley & Sons, pp. 335-401.

Quackenboss, J.J., Lebowitz, M.D., Michaud, J. and P., Bronniman, D. (1989) "Formaldehyde exposure and acute health effects study", *Environment International*, **15**, 169-179.

Seifert, B. (1990) "Regulating indoor air". In: Walkinshaw, D. (ed), *Proceedings of Indoor Air '90*, Ottawa, International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 35-49.

Seifert, B., Mailahn, W., Schulz, C. and Ullrich, D. (1989) "Seasonal variation of concentrations of volatile organic compounds in selected German houses", *Environment International*, **15**, 397-408.

Shields, H.C. and Weschler, C.J. (1992) "Volatile organic compounds measured at a telephone switching center from 5/30/85-12/6/88: A detailed case study", *Journal of the Air and Waste Managment Association*, **42**, 792-804.

Skov, P., Valbjörn, O. and the Danish Indoor Study Group (DISG) (1987), "The sick building syndrome in the office environment: The Danish town hall study", *Environment International*, **13**, 339-349.

Stenberg, B., Hansson Mild, K., Sandström, M., Sundell, J. and Wall, S. (1993) "A prevalence study of the sick building syndrome (SBS) and facial skin symptoms in office workers", *Indoor Air*, **3** (2), 71-81.

Sundell, J., Lindvall, T. and Stenberg, B. (1991) "Influence of type of ventilation and outdoor airflow rate on the prevalence of SBS symptoms". In: *IAQ 91, Healthy Buildings*, Atlanta, ASHRAE, 85-89.

Sundell, J., Lindvall, T. and Stenberg, B. (1993) "SBS and facial skin symptoms in office workers in relation to building and room characteristics. Two case-referent studies". *Indoor Air*, submitted.

Weschler, C.J., Brauer, M. and Koutrakis, P. (1992a) "Indoor ozone and nitrogen dioxide: A potential pathway to the generation of nitrate radicals, dinitrogen pentaoxide, and nitric acid indoors", *Environmental Science and Technology*, **26**, 179-184.

Weschler, C.J., Hodgson, A.T. and Wooley, J.D. (1992b) "Indoor chemistry: Ozone, volatile organic compounds, and carpets", *Environmental Science and Technology* (in press).

Wolkoff, P., Johnsen, C.R., Franck, C., Wilhardt, P. and Albrechtsen, O. (1992) "A study of human reactions to office machines in a climatic chamber", *Journal of Exposure Analysis and Environmental Epidemiology*, Suppl.1, 71-96.

World Health Organization (1989) *Formaldehyde*, Geneva, World Health Organization (Environmental Health Criteria 89).