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Association of Ventilation System Type with SBS symptoms in Office Workers

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Abstract
This paper provides a review and synthesis of current knowledge about the associations of ventilation system types in office buildings with sick building syndrome symptoms and discusses potential explanations for the associations. Relative to natural ventilation, air conditioning, with or without humidification, was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms. Prevalences were typically higher by approximately 30% to 200% in the air conditioned buildings. In two of three assessments from a single study, symptom prevalences were also significantly higher in air conditioned buildings than in buildings with simple mechanical ventilation and no humidification. In approximately half of assessments, SBS symptom prevalences were significantly higher in buildings with simple mechanical ventilation than in buildings with natural ventilation. Insufficient information was available for conclusions about the potential increased risk of SBS symptoms with humidification. The statistically significant associations of mechanical ventilation and air conditioning with SBS symptoms are much more frequent than expected from chance and also not likely to be a consequence of confounding by several potential personal, job, or building-related confounders. The reasons for the increases in symptom prevalences with mechanical ventilation and particularly with air conditioning remain unclear. Multiple deficiencies in HVAC system design, construction, operation, or maintenance, including some which cause pollutant emissions from HVAC systems, may contribute to the increases in symptom prevalences.

Practical Implications
Because the causes of increases in SBS symptom prevalences in mechanically ventilated buildings are uncertain, the implications for building professionals are also uncertain. The available evidence suggests, but does not prove, that multiple preventative and corrective measures are needed to substantially reduce the SBS symptoms associated with HVAC systems. Commissioning, operational checks, training of operators, and maintenance may be particularly important for reducing the risks of health effects associated with HVAC systems.

Introduction

Purpose of the paper

The primary objectives of this paper were to review and synthesize available literature on the associations of ventilation system types in office buildings with sick building syndrome symptoms and to evaluate potential explanations for the associations.

Background

During the last 20 years, studies in Europe and North America have indicated that non-specific symptoms related to occupancy in office buildings are common among office workers, and that there are large variations among buildings in the prevalence of (i.e., proportion of workers with) these symptoms. These symptoms, generally referred to as sick building syndrome (SBS) symptoms, may include: eye, nose, throat, and skin irritation; nasal congestion (stuffy, blocked nose); nasal excretions (runny nose); cough; wheeze; tight chest; mental fatigue; headache; nausea and dizziness. SBS symptoms dissipate or decrease when the individual is away from the building. The term “SBS” is used primarily when the agents causing the symptoms are unidentified and the symptoms do not indicate a specific known disease.

In many studies, prevalence of sick building syndrome symptoms have been associated with characteristics of buildings and ventilation systems. One of the most important factors affecting indoor air quality is how the building is heated, ventilated and air-conditioned. In many cases, particularly in office buildings, these functions are integrated in one system. In this paper these systems are called HVAC systems (heating, ventilating and air-conditioning systems). Several technical terms used to characterize these systems are explained in the following paragraphs.

In this paper the term ventilation means the supply of outdoor air to a space through the ventilation system, via flow through open doors and windows, and by infiltration through the building envelope. Ventilation brings outdoor air to the occupied zone and removes or dilutes indoor-generated pollutants. Ventilation air can be supplied to rooms through mechanical ventilation systems with fans or through natural forces caused by wind and by temperature differences between indoor and outdoor air.

In general, air conditioning systems may cool, heat and dehumidify or humidify air supplied to rooms as required to maintain acceptable indoor environmental conditions. However, in this paper the term air conditioning refers specifically to the cooling and associated dehumidification of the supply air. The term humidification refers to the intentional addition of water vapor into the air supplied to the building by the HVAC system.

The air supplied to the spaces by HVAC systems (supply air) can be entirely outdoor air or outdoor air mixed with indoor air drawn from the indoor spaces, called return air. Usually HVAC systems have filters to reduce the concentration of particles in the supply air. Typical configurations for HVAC systems are presented in the Figure 1.

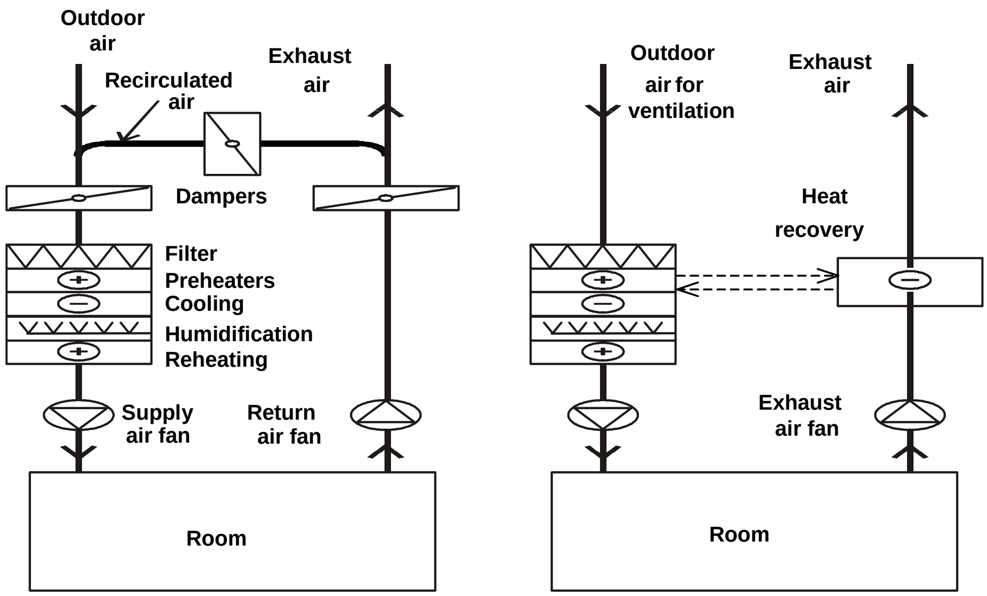

Figure 1. Schematic diagram of the major airflow paths and components of HVAC systems in the U.S. (left) and Europe (right). Typical US systems recirculate part of return air back to the rooms. Typical European systems do not return recirculated air, but the heat content of return air is used to heat or cool the ventilation air.

HVAC systems are intended to supply air that is as clean as practical, which partially replaces and, thus, dilutes the polluted indoor air. However, HVAC systems may contaminate the air supplied to the rooms through the following mechanisms: (1) the HVAC system may be contaminated and, in turn, contaminate the air flowing through it; (2) the HVAC system may draw contaminated air into the building from outdoor sources; (3) HVAC systems that recirculate indoor air (i.e., supply a mixture of return air and outdoor air) may spread throughout the building the contamination generated at specific indoor locations. Potential contamination of HVAC systems include molds and other microbial growth, particularly where liquid water is present or humidities are high, such as on or near components that cool, dehumidify, or humidify air. Other potential sources of contaminants in HVAC systems include deposited dusts, oil residuals from manufacturing, and insulation and sound absorbing materials.

In the 1980's, five studies performed in the United Kingdom (Burge et al. 1987, Finnegan and Pickering 1987, Harrison et al. 1987, Hedge 1984, Robertson 1989) and one performed in Denmark (Skov et al. 1987) compared the prevalence of the SBS symptoms in occupants of buildings with different HVAC systems. The results were inconsistent. Mendell and Smith (1990) contacted authors of these studies, gathered standardized information across studies on HVAC system characteristics, and then reanalyzed and summarized of the studies. They re-categorized the buildings by HVAC system type (in some cases differently from the original papers) using the following five categories: natural ventilation, simple mechanical ventilation, air-conditioning without humidification, air-conditioning with steam humidification, and air-conditioning with water-based humidification. Prevalences of symptoms were statistically-significantly higher in air-conditioned buildings than in buildings with natural ventilation, with odds ratios (ORs) of 1.3 - 5.1 for individual central nervous system symptoms, and 1.4 – 4.8, for upper respiratory and mucous membrane symptoms. For lower respiratory and skin symptoms, the association with air conditioning was not as consistent and fewer studies provided data. Air-conditioning systems with steam humidification did not seem to be associated with higher prevalences of symptoms than systems without humidification; however, air conditioning systems with liquid-water-based humidification were associated with an increased prevalence of some symptoms compared to systems without humidification. Simple mechanical systems, i.e. systems with mechanical supply and exhaust but no air conditioning, were not consistently associated with a higher prevalence of symptoms than natural ventilation. Mendell and Smith (1990) caution readers about generalizations from the reanalysis because the studies were performed only in the United Kingdom and Denmark, and other countries have different climates and different building and HVAC system designs and operational procedures. Additionally, each of the reviewed studies had limitations due to potential bias and uncontrolled confounding.

HVAC system type cannot directly influence health symptoms; however, it may be a surrogate for one or more exposures that affect symptom prevalences. Based on the literature and our engineering experience, Table 1 summarizes the suspected risk factors for poor indoor environmental quality associated with HVAC types and features.

Table 1. Suspected risk factors of HVAC types and building features.

HVAC System Type	Risks
Natural ventilation with operable windows	No particle removal via filtration; poor indoor temperature and control; noise from outdoors; inability to control the pressure difference across the building envelope and exclude pollutant infiltration or penetration of moisture into structure; low ventilation rates during some weather conditions; possible low ventilation rates in some portions of the occupied space
Systems with ducts and fans but no cooling or humidification (simple mechanical ventilation)	HVAC components may be dirty when installed or become dirty and release pollutants and odors; poor control of indoor temperature due to absence of cooling; low humidity in winter in cold climates; high humidity during periods of humid weather; noise generated by forced air flow and fans; draft caused by forced air flows.
Systems with ducts, fans and cooling coils (air conditioning systems)	Additional risk factors from cooling coils: very high relative humidity or condensed moisture (e.g. in cooling coils and drain pans) and potential microbial growth; biocides used to treat wet surfaces such as drain pans and sometimes applied to nearby insulation.
Systems with ducts fans, cooling coils and humidifiers of various types	Additional risk from humidifiers: microbial growth in humidifiers; transport of water droplets downstream of humidifiers causing wetting of surfaces; leakage and overflow of humidifier water; condensation from high-humidity air; biocides in humidifiers; chemical water treatments in steam generators.
Systems with recirculation of return air (recirculation may occur in all mechanical HVAC systems)	Additional risks* from recirculation: indoor-generated pollutants are spread throughout the section of building served by the air handling system; typically higher indoor air velocities increase risk of draft and HVAC noise; supply ducts and filters of HVAC system may become contaminated by recirculated indoor-generated pollutants.
Sealed or openable windows (windows may be sealed or openable with all types of mechanical HVAC systems)	Additional risk with sealed windows: no control of the environment if HVAC systems fails; psychological effect of isolation from outdoors. Additional risk with openable windows: more exposure to outdoor noise and pollutants.
Decentralized systems (cooling and heating coils located throughout building, rather than just in mechanical rooms)	Additional risk of decentralization: potentially poorer maintenance because components are more numerous or less accessible. Potentially more equipment failures due to larger number of components.

*However, recirculation facilitates removal of indoor-generated pollutants using air cleaners, e.g. particle filters, and may also decrease concentrations of pollutants near pollutant sources.

Studies of the associations of ventilation system types or features with health and perception outcomes have primarily been performed in buildings several years after construction, and risk factors could differ in new buildings. Most studies have been cross-sectional, with data on health (or perception) outcomes, ventilation system characteristics, and other relevant factors collected in multiple buildings and these data analyzed statistically to determine the strength and uncertainty in the associations of health outcomes with the type of HVAC system. A weakness of this study design is that many factors other than ventilation system type vary among the buildings and may influence the health outcomes, confounding the association of HVAC system type with the health outcome. The better cross-sectional studies control for many potential confounding factors in the study design or data analyses. Unfortunately, some studies have controlled for few or no confounding factors in statistical analyses. Another inherent weakness of cross-sectional studies is that occupants with substantial adverse health effects from exposures in a building may more frequently be absent or quit working in the building. For these reasons, cross sectional studies can find statistical associations but, without other supporting findings, such studies cannot confirm causal relationships.

Table 2 lists some of the factors that are potential confounders because they vary among buildings or with time and have commonly been associated with SBS symptoms (Mendell 1993, Menzies and Bourbeau 1997, Seppanen et al. 1999). To create actual confounding bias in a study, however, a factor must be associated both with the health effect and the risk factor (e.g., HVAC type) being studied.

Table 2. Potential confounding factors.

Personal Characteristics	Work Related Factors	Building-Related Factors	Indoor Environmental Factors
Gender Atopy (allergic disposition) History of asthma Smoking history Job type Medical treatment (especially for asthma and atopy)	Job stress or satisfaction Use of carbonless copy paper Use of or proximity to photocopy machines Use of video display terminals	Ventilation rates Quantity of carpet or textile surfaces Sealed windows Building age Depth of the building bays	Air temperature Air humidity Environmental tobacco smoke Dusty surfaces

Approach

General approach

Our overall approach was to identify relevant papers for review, to set criteria for studies to be included, to analyze the available information from studies meeting the inclusion criteria and process the results into a common format, and finally to draw conclusions. We then used the findings from these field studies and from other field and laboratory studies to assess the evidence supporting or refuting hypothesized explanations for the associations of HVAC types with symptoms.

Classification of HVAC Systems

Based on the potential risks described in the introduction and on the available data, this paper uses a slightly different HVAC type classification from Mendell and Smith (1990). Our classification is presented in Table 3.

Table 3. Classification of buildings by type of HVAC systems

I Natural ventilation via leakage paths and intentional openings (e.g., windows) with or without a passive ventilation stack present to help drive the air flow.
II Mechanical exhaust ventilation
III Simple mechanical ventilation with both mechanical supply and exhaust, with no air conditioning
    III A Without humidification
    III B With humidification
IV Air conditioning with both mechanical supply and exhaust, without humidification
V Air conditioning with humidification
    V A Air conditioning with steam humidification
    V B Air conditioning with evaporative humidification
    V C Air conditioning with spray humidification

Three categories of humidification are used because they have different potential mechanisms for producing air contaminants. In *steam humidification*, the temperature of steam is high enough to kill micro-organisms in the water but there is also a potential risk in condensation of moisture on surfaces downstream the humidifier. Additives to the water in steam generation systems are another possible pollutant source. In *evaporative humidification*, the water is evaporated from wetted extended surfaces such as wetted fibrous matts. Volatile contaminants in the water are released to the air but microbial particles and other solid pollutants generally remain in the water within the humidifier. In *spray humidification*, water is sprayed into the air as small droplets either by pressure or ultrasonic devices, and both gaseous and particulate (e.g., microbiological) contaminants may be released into the airstream. With spray humidification there is also a potential risk that water droplets will not fully evaporate and will wet surfaces downstream of the humidifier. Water reservoirs of both evaporative and spray humidification systems may become contaminated by microbial growth.

All buildings with mechanical cooling were simply categorized as air conditioned. No distinction was made between various types of air conditioning systems, such as multi zone, variable air volume, reheat or dual-duct systems as this detailed information was not systematically available across studies.

<u>Study inclusion criteria</u>

This review included only studies of office buildings, although some information is available from schools, residences, etc. Most of the studies have used SBS symptoms as the outcome, and we excluded other outcomes from the review. We also excluded studies that did not perform a statistical test to determine if there were statistically-significant differences in symptoms between occupants of buildings with different HVAC types.

The power of a cross-sectional study increases with the number of study buildings or study spaces with different HVAC systems, and also with the number of occupants included in the study. Increased power reduces effects of random error, but does not reduce systematic bias. For this review, we excluded from consideration any cross-sectional study with less than two buildings in any included HVAC-type category. We also excluded studies primarily containing complaint buildings, because we suspected that the widespread concerns about health in complaint buildings could decrease the validity of self-reported symptoms.

Some published experimental studies involved movement of subjects from building to building or with replacement of HVAC systems, with analyses of the changes in symptom prevalences within subjects. Some potential confounding is eliminated by within-subject analyses; for example by personal and job-related factors, which are unchanged during the experiment. However, there is still a possibility of confounding by many parameters which may have varied among the experimental periods, such as building characteristics, indoor temperature, outdoor conditions or job stress. We considered these sources of potential bias so significant that we excluded from our review any studies with movement of the study population between buildings or with replacement of HVAC systems. Another weakness of these studies is that occupants' awareness of the HVAC and environmental changes may have influenced their symptom reporting on questionnaires.

All studies that fulfilled the criteria described above were included in our review whether or not statistically significant associations were reported.

Processing of the study data

In the review, we used the information reported in the papers; however, some of the desired study information was not provided unambiguously. We have used our judgment to make interpretations, and there may be some errors in our interpretations. Classification of humidifiers was based on available information; however, information on type of humidication system was often very limited. Some of the studies did not report whether the HVAC system recirculated a portion of return air, and in some cases a group of buildings classified by HVAC system had buildings with and some without recirculation. In one study, two buildings with mechanical exhaust ventilation were included in the group of naturally ventilated buildings. Information on window type was not always available; however, in most European office buildings windows are openable and in most large North American office buildings windows are sealed.

Relative risks and odds ratios

Studies generally reported the strength of associations as relative risks or odds ratios, often adjusted for confounding factors. The relative risk (RR) is the prevalence of the outcome in the group with the risk factor of interest (P_1) divided by the prevalence of the outcome in the reference group (P_0), i.e. RR =P_1 /P_0. The odds ratio (OR) is defined by the equation

$$OR = [P_1/(1-P_1)]/[P_0/(1-P_0)] \qquad (1)$$

When P_1 and P_0 are both less than ~0.2 and the OR is less than approximately 2.5, which is the case for many of the studies, the OR and relative risk are quite similar numerically. As P_1 and P_0 increase above ~0.2, the odds ratio becomes progressively higher than the relative risk. When OR and P_0 are known, the relative risk may be calculated as follows (Zhang et al. 1998)

$$RR = OR / [(1-P_0) +(P_0 \times OR)] \qquad (2)$$

If the OR has been adjusted for confounding factors, equation 2 is nor exact; however, the estimated RR is still generally close to the true RR (Zhang et al. 1998).

Some studies did not report relative risks or odds ratios, but reported the prevalences of recorded symptoms in each population and indicated if there was a statistically-significant difference in prevalence. When possible, we calculated the relative risks, which were not adjusted for confounders, from reported prevalences. In addition, we used equation 2 to estimate values of RR from the values of OR and P_0 provided in some studies.

Results

Characterization of studies

Twelve studies from six countries in Europe and the USA (Table 4) were included in the review. The studies included 467 total buildings with approximately 24,000 subjects. All studies included both men and women; however, some analyzed results for men and women separately.

Table 4. Summary of studies by country and number of buildings

Country	Number of studies	Number of buildings
Denmark	1	74
Finland	1	41
Germany	1	14
Holland	2	80
Sweden	1	160
United Kingdom	5	86
United States	1	12
Total	12	467

Some studies have been reported in more than one paper. Although only some studies used rigorously representative sets of study buildings, none of the studies focused on complaint buildings. The results represent the influence of HVAC systems on sick building syndrome symptoms in typical non-problem office buildings.

Tables 5 and 6 summarize the major features and findings of studies included in this review. A study may have performed multiple analyses (called assessments) between different groups of HVAC types or analyzed different subsets of study data (e.g., a low ventilation rate group may have been compared with both a medium and a high ventilation rate group). Each assessment is presented on an individual row in Table 5 or 6. In these tables, we have used the reanalysis of five studies by Mendell and Smith (1990), rather than data from the original papers, because these reanalyses are based on HVAC type categories consistent with those in this paper.

A factor that may affect the outcome is the design and use of windows. In the U.S. studies (Mendell et al. 1996) and some European studies (Burge et al. 1987, Hedge 1984, Finnegan and Pickering 1987, Zweers et al. 1992), some or many buildings had sealed windows. In Nordic buildings (Jaakkola and Miettinen 1995, Sundell et al. 1994 windows are predominately openable, although possibly not opened during the study.

Because these studies benefit from a large study population, based on our experience they have been performed primarily in medium to large office buildings. Thus, the results of this review may not apply to the many existing small office buildings, e.g., with < 30 occupants.

The degree to which studies controlled for confounding factors varied considerably. Tables 5 and 6 indicate if studies controlled for one or more personal (P), work (W), or building (B) factor other than HVAC type. Six of 12 studies and 19 of 29 assessments controlled for some confounding via the statistical model used to analyze the data[1].

[1] This uses the reanalyses of several studies by Mendell and Smith (1990) which did not control for confounding but provided a clearer categorization of HVAC system type than the original studies.

Exposure to environmental tobacco smoke is a potential confounding factor that was usually not controlled in the studies reviewed. Smoking was allowed in some buildings. For the characterization in Tables 5 and 6, a building was considered a non-smoking building if smoking was allowed only in designated areas. Many of the studies did not report whether smoking was allowed or restricted.

Ventilation rates, which are associated with symptom prevalences (Seppanen et al. 1999), may have varied between types of HVAC systems and confounded results, but the ventilation rate was only measured in a few studies. No studies controlled for ventilation rates in the analysis.

Prevalences of SBS symptoms were usually assessed with self-administered questionnaires, and occasionally via interviews. Most studies included many different symptoms, and some included only a few; some performed analyses using individual symptoms, and some with symptom groups. An integrated symptom summation score was used in one study (Hawkins and Wang 1991).

Most of the studies were performed in moderate climates during the winter months, when people stay indoors the highest percentage of time, and windows are most often closed. Two studies were performed in cold climates (Jaakkola and Miettinen 1995, Sundell et al. 1994). No studies were performed in hot humid climates where a higher ventilation rate can lead to increased indoor humidities.

Association of HVAC system types with SBS symptoms

Table 5 presents the assessments comparing symptoms among occupants of air conditioned buildings with those in naturally-ventilated or simple-mechanically-ventilated buildings. Table 6 presents the assessments comparing symptoms associated with simple mechanical ventilation to symptoms associated with natural ventilation. Tables 5 and 6 provide the following data: a) the number of symptoms or symptom groups in the analyses; b) the number of symptoms that were statistically significantly associated with HVAC system type; and c) when available, the range of relative risks or odds ratios for statistically-significant associations. Additionally, the presence or absence of statistically-significant associations of HVAC system types with outcomes is illustrated graphically within the tables using an adaptation of the format of Mendell (1993). HVAC system types are indicated by circles located in the appropriate columns. When the type of humidification was uncertain or included multiple types, the circle was replaced with a horizontal bar extending across the applicable columns. Within these tables, shading of a circle or horizontal bar (relative to no shading), indicates that the study found a statistically-significant increase in prevalence of one or more symptoms among occupants with that HVAC system type relative to buildings with the reference-type of HVAC. Unshaded circles at both ends of a connecting line indicate that the subjects served by different types of HVAC systems did not have significantly different symptom prevalences. The numbers adjacent to the circles denote the number of buildings in the assessment with that type of HVAC system.

Referring to Table 5, 16 of 17 assessments found a statistically significant increase in the prevalence of symptoms with air conditioning relative to natural ventilation. Two of three assessments found a statistically significant increase in the prevalence of symptoms with air conditioning relative to simple mechanical ventilation without air conditioning. Air conditioning was associated with significant increases in symptom prevalences with or without humidification. The studies provided minimal information to assess the hypothesized increase in risks with various types of humidification. In 12 of 20 assessments, air conditioning was associated with a significant increase in the prevalence of a majority of the symptoms or symptom groups. Most of the relative risks or odds ratios were between 1.3 and 3.0, indicating roughly up to 30% to 200% increases in symptom prevalences in the air conditioned buildings.

Table 5. Comparison of SBS symptom prevalences with and without air conditioning.

Reference		Study Characteristics				Building Characteristics				Ventilation System Type								Results		
											Mechanical Without AC			Air Conditioning						
First Author	Year	Symptoms (S) in the analysis ^	No of Subjects in Study	Controlled confounders#	No of respondents in comparison	No of buildings in Study	Sealed or openable windows*	Smoking	Recirculation *	Natural Ventilation	Mechanical exhaust	Simple mechanical, no humidification	Simple mechanical with humidification	No Humidification	Steam Hum.**	Evaporative Hum.	Spray Hum.	Number of Symptoms with signicantly higher prevalences in assessment	Range of risk ratio or (odds ratio) for outcomes	Remarks
Jaakkola	95	14 S	2678	P,W,B	868	41	O		Y/N	7				9				2 of 14 S	1.5-2.6^^ (1.6-2.6)	
Mendell	96	7 S	880	P,W	710	12	S	N	Y	3				6				6 of 7 S	1.6-5.4^^ (1.9-6.0)	a
Burge Mendell	87 90	10 S			1459		S/O			11				10				10 of 10 S	(1.3-2.1)	
Harrison Mendell	87 90	6 S			1044		S		Y/N	8				6				6 of 6 S	(1.7-2.9)	
Zweers	92	5 gr. of S	7043	P,W,B	2806	61	S/O	Y		21								5 gr. of S	1.5-1.7^^ (1.6-1.7)	b
Jaakkola	95	14 S	2678	P,W,B	335	41	O		Y	7					2			3 of 14 S	(1.9-2.5)	
Burge Mendell	87 90	10 S			863		S/O			11					4			8 of 10 S	(1.3-2.1)	
Zweers	92	5 gr. of S	7043	P,W,B	3573	61	S/O	Y		21								5 gr. of S	1.3-1.9^^ (1.4-2.2)	b
Jaakkola	95	14 S	2678	P,W,B	559	41	O		Y/N	7						3		3 of 14 S	(2.0-2.7)	
Teeuw	94	8 S	1355		927	19	S/O		Y/N	7						7		5 of 8 S	1.4-2	c
Burge Mendell	87 90	10 S			1991		S/O			11							15	10 of 10 S	(1.4-2.2)	
Finnegan Mendell	87 90	11 S			787	8	S	Y	Y/N	3							3	6 of 11 S	(2.5-4.8)	
Harrison Mendell	87 90	6 S			2080		S		Y/N	8							13	5 of 6 S	(2.1-3.2)	
Hedge Mendell	84 90	2 S			1214	4				2							2	2 of 2 S	(2.7-3.0)	
Zweers	92	5 gr. of S	7043	P,W,B	3846	61	S/O	Y		21								5 gr. of S	1.5-2.1^^ (1.7-2.2)	b
Brasche	99	7 gr. of S	1403	P,W		14												3 of 7 S	(1.4-1.4)	
Hawkins	91	S Score	722	P	255	13		N	Y	6							6			
Jaakkola	95	14 S	2678	P,W,B	1828	41	O		Y/N			18		9				2 of 14 S	(1.3-1.7)	
Jaakkola	95	14 S	2678	P,W,B	1295	41	O		Y/N			18			2			1 of 14 S	(1.8-1.8)	
Jaakkola	95	14 S	2678	P,W,B	1519	41	O		Y/N			18				3				

^gr = groups #P = personal factors, W = work factors, B = building factors *In mechanically-ventilated buildings **Hum = Humidification
^^From Equation 2

Remarks a) Problem building term in statistical model, also reported in Fisk, et al, 1993

b) Two of naturally-ventilated buildings had mechanical exhaust

c) Relative risk estimated from prevalences assuming that each building type has same number of workers

d) Same study as reported in Burge et al 1987

Key: (open circle – open circle; open circle – open bar) No statistically significant difference in symptoms; (open circle – filled circle; open circle – filled bar) Statistically significant difference in symptoms

The results of the nine assessments that did not involve air conditioned buildings are provided in Table 6. In four of seven assessments[2] that compared simple mechanical ventilation[3] to natural

[2] In one of these studies, the mechanical ventilation systems humidified the air.

ventilation, prevalences of one or more symptoms were statistically-significantly higher with simple mechanical ventilation. When prevalences were significantly higher with simple mechanical ventilation, the odds ratios or relative risks ranged from 1.4 to 2.3, with one outlier of 6.0. One of these seven assessments had the opposite finding (significantly more symptoms with natural ventilation) and two had no statistically-significant findings. In two other assessments in Table 6, prevalences of symptoms with mechanical exhaust ventilation did not differ significantly from prevalences with natural or simple mechanical ventilation.

Considering only the seven studies (out of nine total) within Table 6 that controlled for confounding eliminates the one study with increased symptoms in naturally ventilated buildings and eliminates one of the studies without a significant association. As a consequence, in four of the five remaining assessments that compared simple mechanical ventilation to natural ventilation, prevalences of one or more symptoms were statistically-significantly higher with simple mechanical ventilation.

Table 6. Comparisons of symptom prevalences among buildings without air conditioning.

Reference		Study Characteristics				Building Characteristics				Ventilation System Type				Results		
First Author	Year	Symptoms (S) in the analysis^	No of Subjects in Study	Controlled confounders#	No of respondents in comparison	No of Buildings in Study	Sealed (S) or openable windows (O) in mechanically ventilated buildings	Smoking	Recirculation*	Natural Ventilation	Mechanical exhaust	Simple mechanical, no humidification	Simple mechanical, with humidification	Symptoms with signicantly higher prevalences in assessment	Range of risk ratio or (odds ratio) for outcomes	Remarks
Jaakkola	95	14 S	2678	P,W,B	456	41	O		N	7 ○	○ 2					
Skov Mendell	87 90	3 S			2596				Y/N	6 ○		▭ 7				
Jaakkola	95	14 S	2678	P,W,B	1460	42	O		Y/N	7 ○		● 18		1 of 14 S	2.2 (2.3)	
Mendell	96	7 S	880	P,W	300	12	O	N	Y	3 ○		● 3		4 of 7 S	1.5-5.4^^ (1.8-6.0)	
Burge Mendell	87 90	10 S			1386		S/O			11 ●		○ 7		3 of 10 S	(0.7-0.8)	
Sundell	94	3 gr. of S	2649	P,W,B	778	160	S/O			○		○				
Zweers	92	5 gr. of S	7043	P,W,B	3009	61	S/O	Y		21 ○		●		2 gr. of S	1.3-1.5^^ (1.4-1.6)	a
Sundell	94	3 gr. of S	2649	P,W,B	788	160					○	○				b
Zweers	92	5 gr. of S	7043	P,W,B	2879	61	S/O	Y		21 ○			●	4 gr. of S	1.4-2.1^^ (1.5-2.2)	

^gr = groups #P = personal factos, W = work factors, B = building factors *In mechanically-ventilated buildings **Hum = Humidification ^^From Equation 2

Remarks a) Two of naturally-ventilated buildings had mechanical exhaust

b) Results are for men, only 30 subjects with mechanical exhaust. Similar results for women. Buildings were simple mechanical ventilation had heat exchangers for energy recovery.

Key: ○—○ / ○—▭ No statistically significant difference in symptom prevalences; ○—● / ○—▬ Statistically significant difference in symptom prevalences

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[3] One of these studies used a group of buildings with simple mechanical ventilation or mechanical exhaust ventilation.

The results portrayed in Tables 5 and 6 provide minimal information on the potential additional risks of humidification. Hedge et al. (1989) compared symptom prevalences among three sets of air-conditioned buildings: buildings without humidification, buildings with steam humidification, and buildings with evaporative humidification. The prevalences of five of ten symptoms differed significantly among the three HVAC types; suggesting that humidification type may affect symptom prevalences. For eight of ten symptoms, prevalences were highest with evaporative humidification. The results reported in Table 6 of Zweers et al. (1992), comparing symptom prevalences with simple mechanical ventilation (independently with and without humidification) to symptom prevalences with natural ventilation, also suggest that humidification may be associated with higher prevalences of two out of five symptom groups.

Discussion

Overall findings

The results in Table 5 indicate a nearly consistent (16 of 17 assessments) statistically-significant increase in symptom prevalences in air conditioned buildings, with or without humidification, relative to symptom prevalences in naturally-ventilated buildings. In addition, within two of three assessments, symptom prevalences were significantly-higher in air conditioned buildings than in buildings with simple mechanical ventilation. When symptom prevalences are significantly higher in air conditioned buildings, the increase in prevalence is typically between roughly 30% and 200%. Much less information (Table 6) is available on the risk of mechanical ventilation without air conditioning, relative to natural ventilation. Although the findings are less consistent than with air conditioning, the association of higher symptom prevalences with simple mechanical ventilation in about 50% of studies is unlikely to be the result of chance. Insufficient information is available to assess the risks or benefits of either mechanical exhaust ventilation or steam humidification. The available data suggest that evaporative humidification may be associated with an increased risk of symptoms, but these data are insufficient for conclusions.

Air conditioning with or without sealed windows is associated with increased symptoms. Insufficient data were available to determine whether the relationships between HVAC system type and sick building symptoms were affected by air recirculation, climate, or smoking restrictions.

Improvements Relative to the Previous Review

This review overcomes some of the limitations in a previous review (Mendell and Smith 1990). Our review contains a substantially larger number of studies from a wider geographical area, although a large proportion of studies are still from northern Europe. Studies in the previous review (Mendell and Smith 1990) were performed in two countries; we have included in our review studies from seven countries; however, most of these studies are still from northern Europe. In contrast to the previous review, our review included only assessments that have at least two buildings with each HVAC type; consequently, chance findings are less likely to affect the results of this new review. Finally, the reanalyses by Mendell and Smith (1990) did not assess control for confounding, while the majority of the studies in this new review controlled for more than one class of confounders.

Chance Association

With the typical criteria for statistical significance ($p < 0.05$), in about one out of twenty instances, there will be a statistically significant association caused by chance. Thus, the following question arises: are the significant associations identified in these studies likely to be just chance associations? For several reasons, these findings appear not to be mere chance associations. First, only two assessments found significant increases in symptoms with natural ventilation although chance negative associations are as probable as chance positive associations. Second, in every study with a reported significant association, the number of significant associations relative to the number of statistical tests performed exceeded that expected from chance. In 12 of 20 assessments, air conditioning was associated with a significant increase in the prevalence of a majority of the symptoms or symptom groups.

Confounding

A majority of the studies reviewed controlled for several potential personal, work, or building-related confounding factors that are not a direct consequence of HVAC system type. Nevertheless, none of the studies have controlled for all of the potential confounders identified in Table 2. However, confounding by factors that are not directly affected by HVAC type seems to be an unlikely explanation for the overall results of this review. The personal and work-related confounders listed in Table 2 and environmental tobacco smoke are not likely to be associated in a consistent manner with HVAC system type. Other potential confounders from Table 2 that are not obviously affected by HVAC type are: quantity of carpet or textile surfaces; sealed windows, building age; depth of the building bays; and dusty surfaces. In contrast, ventilation rates, indoor temperatures, and indoor humidities are intentionally modified by many HVAC systems. The potential overall confounding by each of these factors, except for ventilation rate, is discussed in the subsequent paragraphs. The review of the hypothesized explanations of our findings, provided later in this paper, includes a discussion of ventilation rates.

- *Carpets and textile surfaces* have been associated with SBS symptoms and may be more common in newer buildings that may more often have mechanical ventilation and air conditioning. However, such confounding seems an unlikely explanation for the overall findings because: 1) control in three studies (Jaakkola and Miettinen 1995, Mendell et al. 1996, Zweers et al. 1992) for carpets and other “fleecy” surfaces did not eliminate the associations of symptoms with ventilation type, and 2) the association of fleecy surfaces with HVAC system type, if it exists, is probably weak. Also, the associations of symptoms with fleecy surfaces have not been as strong or consistent as the associations of symptoms with HVAC types.

- *Building age* may be associated with both HVAC system type and with risk factors for SBS symptoms. The age of buildings may be related to the types and strengths of indoor pollutant sources. Newer buildings may be more likely to have mechanical ventilation and air conditioning (Sundell et al. 1994) and buildings that are very new may have more or stronger sources of volatile organic compounds emitted by building materials. However, within a few years after initial building construction the emissions of VOCs from the building’s initial construction materials will usually be smaller than emissions from occupants, consumer products, equipment, and products used for ongoing building refurbishment and maintenance (A.T. Hodgson, Lawrence Berkeley National Laboratory, Personal communication). Additionally, the evidence of associations of HVAC types with symptoms is much stronger and more consistent than the evidence of an association of indoor VOC concentrations with SBS symptoms (Ten Brinke et al. 1998; Apte et al. 1999; Mendell 1993). Thus, a high level of confounding due to an association of indoor VOC sources with building age seems unlikely. Building age could also be a source of confounding because older buildings are less often air conditioned but more likely to have microbiological contamination on indoor surfaces or in HVAC systems. If true, and this microbiological contamination causes symptoms, the associated confounding would tend to obscure the associations of air conditioning with symptoms.

- *Depth of the building bays*, i.e., average distance of workstations from exterior walls, may be associated with HVAC system type. Ventilation in naturally ventilated buildings is dependent on widows and leakage through the building envelope. Naturally ventilated buildings tend to be narrower than mechanically ventilated buildings. Air conditioned buildings are more flexible with respect to building shape and can have work spaces without any windows located a considerable distance from exterior walls. Distance of the workstation from a window has been associated with prevalence of symptoms (Fisk et al. 1993) and could be a potential confounder. However, most of the studies reviewed were performed in Europe and many European countries avoid windowless working rooms. Thus, in Europe, the depth of building bays is not highly dependent on HVAC type. Consequently, our overall results are not likely a result of confounding by the depth of building bays.

- *Dusty surfaces* have been associated with higher prevalences of symptoms (Valbjorn and Skov 1987, Gyntelberg et al. 1994). There is no evidence that indoor sources of dust differ in a consistent manner with HVAC type. The dust accumulation on surfaces will depend to some degree on concentration of particles in indoor air. Air filtration, which occurs only in mechanically ventilated buildings, can be highly effective in lowering indoor particle concentrations particularly when air is recirculated, as it is in many buildings with air conditioning. Thus, on average, we would expect more dusty surfaces in naturally ventilated buildings. Therefore, confounding by dusty surfaces may have tended to obscure or weaken the findings of this review.

- *Increased air temperatures* have been associated with more SBS symptoms and with worsened perceptions of indoor air quality (Mendell 1993, Fang et al. 1998). Typically, air conditioned office buildings have better control of indoor temperatures than naturally ventilated buildings, and, in particular, elevated temperatures are much less common with air conditioning. Therefore, confounding from higher temperatures in naturally ventilated buildings may have tended to obscure or weaken the associations of air conditioning with increased symptoms.

- *Air humidities* that are particularly low have been associated with increased skin and mucous membrane symptoms in a few studies (e.g., Wyon 1992, Reinikainen et al. 1992) These very low humidities are more likely to be associated with non-humidified buildings located in cold climates. Based on this review, air conditioning combined with humidification was consistently associated with an increase in symptom prevalences. The low humidities expected in naturally ventilated buildings might have tended to obscure or weaken the observed associations of air conditioning plus humidification with symptoms. In field-studies, higher humidities have not been consistently or strongly associated with increased SBS symptoms (Mendell 1993).

<u>Bias</u>

A bias common to most or all studies seems improbable as an explanation of our overall findings. There is no reason to expect that the building selection process caused a relevant bias, since the investigators did not know the prevalence of symptoms prior to building selection. Building occupants' knowledge that they were in sealed air-conditioned buildings could have biased their responses due to their expectations, as discussed subsequently. Finally, we have no reason to expect that researchers intentionally or unintentionally caused a bias during their data analyses. Publication bias remains a possibility, since significant associations are more likely to be published in journals and conference proceedings than reports of no association.

Potential explanations of findings

Within studies, the prevalences of symptoms vary considerably among buildings with the same HVAC system type (Aizlewood et al. 1996, Burge et al. 1987, Finnegan et al.1984, Mendell et al. 1996). This variability suggests that type of HVAC system is only a surrogate for potential exposures or conditions that increase the risk of health symptoms. Various aspects of HVAC system design, construction, operation, or maintenance may affect the indoor exposures or environmental conditions that influence symptom prevalences.

Based on the literature and our professional judgment, we developed six hypotheses to explain the associations of higher symptom prevalences with HVAC system types, particularly with air conditioning. In the following paragraphs, we discuss each hypothesis in the light of scientific evidence from both field studies and laboratory measurements. Very few epidemiological studies provide data directly relevant to these hypotheses.

Our first hypothesis is that pollutants are emitted by HVAC components, ductwork, or surface contamination transferred with supply air to the occupied spaces where they elicit symptoms. The pollutants may be volatile organic compounds (VOCs) and semi-volatile organic compounds, particles, or fibers. Some of these pollutants may be bioaerosols and gaseous metabolic products resulting from microbiological growth within HVAC systems, particularly on surfaces that are wetted or exposed to very humid air. Some pollutants may be produced in HVAC systems by oxidation reactions (Sundell et al.1993).

Measurements of VOC emissions from typical materials used in HVAC system are sparse. In studies by Morrison and Hodgson (1996) and Morrison et al. (1998), the HVAC materials with higher VOC emission rates per unit surface area, such as interior duct insulation (duct liner), neoprene gaskets, elastomeric duct connectors and sealants did not appear to be major VOC sources because of the limited quantities of these materials in most HVAC systems. The very high surface area materials in HVAC systems, such as sheet metal, had relatively low emission rates of VOCs.

Sensory evaluations of the pollution generated by various components are more abundant. The European Project on Air Pollution Sources in Buildings (Bjorkroth et al. 1997a,b, Clausen and Fernandes (1997) confirmed earlier measurements (Bluyssen 1990, Pejtersen 1996a and 1996b, Torkki and Seppanen 1996) indicating that almost all HVAC system components are sources of sensory pollution; i.e., reduce peoples' sensory evaluation or rating of the air quality. The review by Seppanen (1998) suggests that air filters and coils are among the stronger sources of sensory pollutants in new HVAC systems. Measurements of chemical pollutant concentrations combined with simultaneous sensory ratings indicate that common measurement methods for VOCs may not detect all of the important odorous compounds (Bjorkroth et al. 1997a,b). The sensory emissions of pollutants from HVAC filters and ducts may increase after use when they become coated with particles (Bjorkroth et al. 1997a,b). Seppanen (1998) found that cleaning a 30-year-old duct improved the sensory quality of the exiting air.

Microbiological contamination of HVAC systems has been reported in many case studies and investigated in a few multi-building research efforts (e.g., Battermann and Burge, 1995; Bencko et al. 1993; Martiny et al. 1994; Morey 1988, Morey 1994; Morey and Williams 1991; Shaughnessy et al. 1998, ISIAQ 1996, Pasanen 1998). Sites of reported microbiological contamination include the outside air louvers, the mixing box where outside air mixes with recirculated air, filters, cooling coils, cooling coil drain pans, humidifiers, and the surfaces of ducts. Wetted surfaces, such as humidifiers, drain pans, water traps, sumps, cooling coils, and duct liner (the porous insulating and sound adsorbing material used inside some HVAC systems) may be particularly prone to contamination (ISIAQ 1996, Pasanen 1998, Morey and Williams 1991). Byrd (1996) found microbial growth in one third of cooling coils of large buildings and two thirds of small buildings, even in the dry climate of California. Supporting the evidence of microbiological contamination from field studies are laboratory-based studies that have demonstrated that fungi can grow on various HVAC materials under a wide range of temperatures and humidites, but particularly when the relative humidities are high (e.g., > 80%). [e.g., Martikainen et al. 1990, Foarde et. al. 1996]

The previous discussion shows clearly that HVAC systems can be sources of pollutants and become contaminated microbiologically, but these studies do not confirm that the pollutants emitted actually cause the symptoms associated with mechanical HVAC. There is very limited relevant information. Sensory ratings of air by unadapted individuals were not significantly associated with SBS symptom prevalences in a large European study (Bluyssen et al. 1996), implying that the sensory emissions from HVAC may not be the cause of SBS symptoms. However, Sieber et al. (1996) found that indicators of poorer HVAC cleanliness – suggesting pollutant emissions -- were significantly[4] related to elevated prevalences of multiple respiratory symptoms. The relative risks, adjusted only for age and gender, were 3.1 for debris in the outside air intake, 1.6 for residue/dirt in cooling-coil drain pans, 3.0 for poor or no drainage from drain pans, and 2.1 for dirty ductwork.

In summary, considerable evidence is available to support this hypothesis, but the evidence is not sufficient for conclusions.

Our second hypothesis is that mechanical systems sometimes draw pollutants in from outdoor pollutant sources located close to air intakes and distribute these pollutants into the occupied spaces of buildings, and that these pollutants increase SBS symptoms. These pollutants may include combustion products from vehicle exhaust, combustion products released from combustion exhaust stacks, organic pollutants from sanitary vents, trash dumpsters, etc., allergens from nearby vegetation, and bioaerosols from microbiological contamination located near the outside air intake (e.g., on the roof top). Although case studies have suggested that entrainment of outdoor pollutants into HVAC systems is associated with complaints (Morey and Shattuck 1989, Angell and Daisey 1997, Wallingford and Carpenter 1986), there is very limited information on the frequency and extent of this phenomena and on its relationship to SBS symptoms. This hypothesis is supported by the results of a study of 80 US office buildings with health complaints , as reported by Sieber et al. (1996). After controlling for age and gender, they found an increased prevalence of multiple lower respiratory symptoms significantly[5] associated with standing water, exhaust vents, sanitary vents, vehicle traffic, and trash dumpsters located within 7.6 m (25 ft) of the outside air intake.

Entry of pollutants into buildings from nearby sources could occur in buildings with all types of ventilation systems, including buildings with natural ventilation. The particle filters typically present in mechanical ventilation systems should reduce the indoor concentrations of some of these outdoor particulate pollutants, while filters are not used with natural ventilation. It seems

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[4] 95% confidence interval excluded unity, except for residue/dirt in drain pans that that a 95% confidence interval of 1.0 to 2.8

[5] 95% confidence intervals excluded unity or the lower bound of the 95% confidence interval was 1.0

unlikely that this hypothesized risk for SBS symptoms is more common in naturally ventilated buildings. Consequently, mechanically-ventilated buildings do not appear to be more likely to expose occupants to pollutants from nearby outdoor sources than naturally ventilated buildings; therefore, this hypothesis is unlikely to the primary explanation for the findings of this review.

Our third hypothesis is that mechanically ventilated buildings, particularly those with air conditioning, tend to have lower ventilation rates than naturally ventilated buildings, leading to higher indoor concentrations of indoor-generated pollutants that cause symptoms. These low ventilation rates may occur throughout the building or within specific zones or rooms. A review by Seppanen et al. (1999) found that lower ventilation rates, particularly below 10 L s^{-1} per person (a typical code requirement), are usually associated with increased SBS symptoms. Such low ventilation rates in mechanically ventilated office buildings are common. Engdahl (1998) reported results from the Swedish mandatory ventilation inspection program indicating that ventilation rates were below the code values in 48 % of office buildings with mechanical ventilation and in 25% of the mechanical ventilation systems with heat recovery. Very few data are available on ventilation rates in naturally-ventilated buildings; however, the available data suggest that ventilation rates tend to be lower in naturally ventilated (Burge et al. 1990, Sundell et al. 1994) than in mechanically-ventilated office buildings. This may be particularly true in Nordic countries which tend to have more airtight building envelopes. Consequently, the available information, while limited, tends to refute this hypothesis.

Our fourth hypothesis is that recirculation of return air causes pollutants released from concentrated indoor sources and return-air ductwork to spread throughout buildings, increasing the number of occupants exposed and increasing their health symptoms. In U.S. buildings, up to 90 % of the air supplied to occupied spaces is recirculated air. Recirculation is less common in Europe and, when employed, typically less than 50 % of the air supplied to occupied spaces is recirculated air.

In this review, we could not determine whether recirculation increased the probability of finding significant associations between HVAC types and symptoms. Many studies provided no information on recirculation or included groups of buildings with and without recirculation.

Jaakkola and Miettinen (1995) found higher prevalences of typical sick building symptoms in mechanically ventilated office buildings with air recirculation than in mechanically ventilated buildings without recirculation. The adjusted odds ratios were statistically significant for nasal discharge (OR=1.6) and allergic reaction (OR=1.3), however, the effects of recirculation may have been confounded by ventilation rates which are expected to be lower in European buildings with recirculation compared to without recirculation. The results of the cross sectional study by Sundell et al. (1994) suggested that air recirculation may diminish SBS symptoms in buildings with outside air ventilation rates below 13.6 L s^{-1} per person and increase symptom prevalences in buildings with higher ventilation rates; however, most of the associations were not statistically significant.

Although air recirculation may widely distribute indoor pollutants, it will also reduce indoor concentrations of pollutants near the concentrated sources. Additionally, recirculation combined with air filtration – the norm – will reduce indoor particle concentrations relative to no recirculation combined with filtration of only the incoming outside air. Thus, recirculation has theoretical benefits as well as risks.

In summary, the evidence in support of this hypothesis is quite limited.

Our fifth hypothesis is that sealed windows lead to increased reporting of SBS symptoms through a psychological mechanism. Workers believe that sealed buildings are unhealthy based on press reports, etc.; consequently they may believe their building causes health effects and report more building-related health effects on questionnaires. Workers may also be unhappy because they are unable to control their environment and feel isolated from outdoor air, and consequently report more symptoms.

In support of this hypothesis, Zweers et al. (1992) found that presence of openable windows was associated with significantly fewer skin, temperature and noise complaints. However, many of the studies finding air conditioning and mechanical ventilation to be associated with symptoms have been performed in sets of buildings that have openable windows in some or all of the buildings (see Tables 5 and 6).

In summary, concerns about sealed windows cannot explain the overall findings of this review.

Our sixth hypothesis is that the presence of air conditioning may lead to increased reporting of SBS symptoms through a psychological mechanism. Office workers' knowledge of the results of previous research finding an association of air conditioning with symptoms could lead to health concerns among workers in air-conditioned buildings and associated increased reporting of symptoms on questionnaires. We are not aware of any specific evidence in support of this hypothesis; however, there is only limited evidence for refuting the hypothesis. The very first findings of an association of air conditioning with symptoms could not be explained by this hypothesis. Also, in the U.S., the public seems to be relatively comfortable with air conditioning because it is very common in homes. The single U.S. study in our review (Mendell et. al 1996) provides some evidence contrary to this hypothesis. In this study, buildings with air conditioning and those with simple mechanical ventilation had similar increases in symptom prevalences, relative to naturally-ventilated buildings. In summary, there is limited evidence regarding the validity of this hypothesis.

<u>Building process and risk factors in HVAC systems</u>

Errors in each stage in the building process can lead to serious problems with indoor climate. Some potential HVAC problems related to indoor air quality and climate, based on the authors' knowledge and judgment, are presented in Table 7. HVAC problems are often multifactorial and related to equipment, design, operation or maintenance. As an example, standing water in the drain pan under the cooling coil may cause microbial growth in the HVAC system. The standing water may be caused by improper construction of the drain pan, improper installation of the drain pan, inadequate drainage due to poor maintenance, or improper design with respect to the dimensioning of the drains.

Based on the prior discussion, it is unlikely that a single factor is responsible for the relatively consistent association of SBS symptoms with mechanical HVAC systems, particularly with air conditioning. Consequently, the available evidence suggests that multiple preventive and corrective measures are needed to substantially reduce the increases in SBS symptoms associated with HVAC. A major difference between HVAC and structural elements of buildings is that HVAC systems are generally very complex and dynamic, while structural elements are mostly static and generally less complex. Consequently, operational checks, training of operators, and maintenance are particularly important for HVAC systems. Procedures for the HVAC commissioning process have been published in the USA (ASHRAE 1996, PECI 1998) and Europe (EN 2000). If these procedures were followed, it is possible that many of the elementary problems could be avoided. We also believe that many IEQ problems are also caused by inferior maintenance of HVAC systems. Poor maintenance may be a consequence of inadequate training of HVAC personnel, the constant desire to cut costs, and ignorance about the importance of maintenance and commissioning. An effort to improve the knowledge and

Table 7. Examples of potential HVAC system problems related to indoor air quality and climate.

Building process or phase	**Example Problems**
Selection, specification and quality of equipment	Condensed water leaks from poor quality cooling coil drain pans
	Air filters fit poorly in air handling units allowing unfiltered air to bypass filters
	Very low efficiency filters are specified leading to high indoor particle concentrations
	Ducts and other HVAC equipment are dirty from manufacturing processes (e.g., residual oils) and emit pollutants
	Interior duct liner has a poor coating that degrades
	Packaged roof-top air handling equipment has outside air intake adjacent to exhaust stream, causing pollutant re-entrainment
	Air leaks in rotary heat exchangers cause pollutant transfer from exhaust to supply airstreams
	HVAC heating and cooling capacity is excessive or inadequate leading to poor temperature and humidity control
Design	Rain and snow enter HVAC systems due to excessive outside air inlet velocities or poor inlet louvers
	Location of outdoor intakes causes entrainment of exhaust air or intake of other pollutants from exhaust stacks
	Equipment design does not enable access for maintenance
	Poor duct system design or fan selection causes poor outside air distribution within building
	Specified ventilation rates are too low
	Low ventilation rates due to poor adjustment/control, accompanied by high recirculation rates
	Higher pressure of exhaust air than supply air in heat recovery system causes pollutant transfer to supply air
Installation	Construction debris and dust left in HVAC systems is a pollutant source
	Blocked or missing drainage lines from cooling coil drain pans cause water spillage and microbiological contamination
	Poorly balanced air flows due to blocked, leaky, or improperly sized ducts cause thermal comfort problems, HVAC noise, and insufficient ventilation
	Ducts are left disconnected from duct system or closed dampers in ducts cause thermal and ventilation problems
Building-operation	Missing or badly mounted filters allow unfiltered air to by-pass filters
	Indoor temperatures out of comfort range due to improper set points or control system malfunctions
	Operation hours of HVAC system are insufficient for control of thermal conditions and pollutants
	Excessive humidity in the occupied spaces because of high temperatures at cooling coils
	Insufficient HVAC operation in humid climate causes high humidities and microbiological contamination
	Building under-pressurization causes pollutants to enter from nearby exterior sources
	Failures to pressurize buildings in hot humid climates leads to moisture problems
	Failures to under-pressurize buildings in cold climates leads to moisture problems
Building maintenance	No scheduled maintenance of HVAC system
	Air filters are replaced too infrequently, leading to reduced air flows or odorous emissions
	Infrequent inspection and cleaning of cooling coils and drain pans leads to blockage and microbiological contamination
	No inspection and calibration of temperature and other controls leads to thermal, humidity, and ventilation problems
	No or very infrequent inspection and service of humidification systems leads to microbiological contamination
	Additives in humidifier water or steam are source of pollutants in indoor air
	Poor treatment of cooling tower water with biocide, and scale and corrosion inhibitors leads to degraded performance and microbiological contamination
	Dirt and dust accumulates in ducts and outside air intake system and emits pollutants
	Failure of fans, pumps, compressors, or chillers, is not rapidly detected or corrected
Building or HVAC renovation	Indoor space is subdivided and new rooms are not served by HVAC system
	Building is expanded without increasing HVAC system capacity leading to thermal and ventilation problems
	Air supply (or return/exhaust) ducts added without rebalancing of airflows, causing poor air distribution or pressure imbalances
Occupancy	Changes in indoor thermal loads overwhelms HVAC system capacity
	New unanticipated pollutant sources or increased number of occupants and no increase in ventilation rates leads to excessive indoor pollutant concentrations

capability of maintenance personnel was recently made in Germany, where training recommendations where recently published as guidelines (VDI 6022a 1997, VDI 6022b 1997). The ease of maintenance and the adverse consequences of sub-optimal maintenance could also be reduced through HVAC design improvements.

Conclusions

Relative to natural ventilation, air conditioning with or without humidification was consistently (17 of 18 assessments) associated with a statistically significant increase in the prevalence of one or more SBS symptoms. Prevalences were typically higher by roughly 30% to 200% in the air conditioned buildings. In two of three available assessments (from a single study), symptom prevalences were also significantly higher in air conditioned buildings than in buildings with simple mechanical ventilation and no humidification. In approximately half of assessments, SBS symptom prevalences were significantly higher in buildings with simple mechanical ventilation than in buildings with natural ventilation. Insufficient information was available for conclusions about the potential increased risk of SBS symptoms with humidification. The statistically significant associations of mechanical ventilation and air conditioning with SBS symptoms are much more frequent than expected from chance. The consistent associations reported in this review are not likely to be a consequence of confounding by personal or job factors, textiles, building age, indoor temperature, indoor humidity, depth of building bays, and dusty surfaces.

The reasons for the consistent increases in symptom prevalences with mechanical ventilation and particularly with air conditioning remain unclear. Multiple deficiencies in HVAC system design, construction, operation, or maintenance may contribute to the increases in symptom prevalences, including deficiencies that lead to pollutant emissions from HVAC systems.

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