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Ventilation Rates and Health: Report of an Interdisciplinary Review of the Scientific Literature

Final Report

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Executive Summary

The scientific literature on the effects of ventilation on health in non-industrial indoor environments (offices, schools, homes, etc.) has been reviewed by a multidisciplinary group of scientists with expertise in medicine, epidemiology, toxicology, environmental chemistry, aerosol science, psychology, engineering, and architecture. A total of 365 articles were retrieved from the literature. The Principal Investigators identified in this set 73 papers that could be considered relevant to the study's goals. The 73 papers were distributed among a panel of fourteen experts from Europe, North America, and Asia. Two panelists, including a health scientist and a building scientist, reviewed each paper in detail. At a three-day workshop, these papers were presented by the reviewers and discussed by the full panel to reach a consensus on its usefulness of each in elucidating the relationship between ventilation rates and health. The group eliminated from further consideration 47 papers that were judged as not relevant or uninformative; one paper was added during the workshop. The group judged 27 papers, reporting on 22 separate studies, as providing sufficient information on ventilation rates, health effects, and study methods, to warrant further examination. Based on these conclusive papers, the group agreed that ventilation rates in offices are strongly associated with sick building syndrome (SBS) symptoms. Increases in ventilation rates up to approximately 25 L/s per person are associated with reduced rates of symptoms. The very limited data available suggest that inflammation, respiratory infections, asthma symptoms, and short-term sick leave increase with lower ventilation rates. One strong study found that ventilation rates above 0.5 air changes per hour (h^{-1}) in homes are associated with a reduced risk of allergic manifestations among children in a Nordic climate. This project has identified a great need for studies of ventilation and health in warm and humid climates, in highly polluted locations and in public buildings other than offices. There is also a need to consider the quality of outdoor air and the contribution of outdoor pollutants to the health effects associated with indoor air.

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Ventilation Rates and Health:
Report of an Interdisciplinary Review of the Scientific Literature

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Abstract
The scientific literature on the effects of ventilation rates on health in non-industrial indoor environments (offices, schools, homes, etc.) has been reviewed by a multidisciplinary group of scientists with expertise in medicine, epidemiology, toxicology, environmental chemistry, aerosol physics, psychology, and engineering. The group reviewed 74 papers published in peer-reviewed scientific journals and judged 27 as providing sufficient information on ventilation rates and health effects to inform the relationship. Based on these conclusive papers, the group agreed that there is consistency across several investigators and different epidemiologic designs done on different populations. There is coherence where there are multiple health end points showing similar relationships. There is biological plausibility even though the literature does not provide evidence of a particular agent for the effects. The group found that ventilation rates in offices are associated with sick building syndrome (SBS) symptoms. Increases in ventilation rates up to approximately 25 L/s per person are associated with reduced symptoms. The very limited data available suggest that inflammation, respiratory infections, asthma symptoms, and short-term sick leave increase with lower ventilation rates. One strong study of children in a Nordic climate found that ventilation rates above 0.5 air changes per hour (h^{-1}) in homes are associated with a reduced risk of allergic manifestations. There is a great need for studies of the relationship between ventilation rates and health in warm and humid climates, in polluted locations and in buildings other than offices.

Key words: Ventilation; Outdoor air supply rate; Non-industrial indoor environments; Health; Offices; Schools; Homes;

Introduction

Ventilation comes from Latin *ventilare* meaning “to fan,” and from *ventus*, meaning “wind.” In modern usage it refers to the exchange of air, and specifically in the indoor air sciences it usually refers to the process of exchanging indoor air with outdoor air. Ventilation dilutes and removes pollutants emitted from indoor sources. Its main purpose is to create beneficial conditions for humans in indoor environments, taking into account their health, comfort, and productivity by providing oxygen, for removing and diluting indoor pollutants, and for regulating indoor moisture levels and thermal conditions.

The aim of this study was to review critically the scientific literature on the relationship between building ventilation rates and human health. The study is restricted to articles that have appeared in peer-reviewed journals and that have reported original research investigating the associations between ventilation and health. The intended audience for this review includes not only those writing

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standards and guidelines for ventilation of buildings but also other building design professionals, researchers, and policy-makers seeking a better understanding of what information and insight the available science can provide. The study was also intended to identify avenues for future research that might further elucidate the relationship between building ventilation and health.

Several literature reviews have been published on the effects of ventilation on health. Their common conclusion is that ventilation rates below 10 L/s -25 L/s per person can significantly aggravate health outcomes, mainly sick building syndrome (SBS) symptoms (Mendell, 1993; Godish and Spengler, 1996; Menzies and Bourbeau, 1997; Seppänen et al., 1999; Wargocki et al, 2002). These literature reviews included studies published in peer-reviewed journals, but some also included articles published in conference proceedings (Wargocki et al, 2002). The present review considers papers published through the end of 2005 and only includes peer-reviewed papers published in scientific journals.

The primary aims of this paper are: i) to review and summarize the results of the peer-reviewed scientific literature on the associations of ventilation rates in buildings with human health responses, and, in so doing, ii) to provide a better scientific basis for setting health-related ventilation standards. Papers were sought that both reported measured ventilation rates (or indoor carbon dioxide concentrations as a surrogate) and health outcomes and also analyzed the association between them. The review included a workshop of international experts to develop consensus regarding the evidence provided by the scientific literature.

Background

"Fresh air" — usually referring to air from outdoors used to dilute contaminants from indoor sources — has been regarded the antidote to potentially harmful or unpleasant substances indoors for centuries to millennia.

Inadequate ventilation rate or excessive carbon dioxide concentrations have historically been associated with certain health outcomes and adverse indoor air quality perceptions. Von Pettenkofer (1858), and later Heyman (1880, 1881), found that at concentrations of CO_2 above 1000 ppm(v) (700 ppm(v) in homes) people were more commonly sick (Sundell 1994c). Since then, most ventilation standards have been consistent with the so-called Pettenkofer number of 1000 ppm(v) CO_2. In a review of the North American history of ventilation and comfort, Janssen (1999) describes the co-evolution of ventilation, heating, and air-conditioning equipment, research into thermal comfort and perception of indoor air quality, and standards and guidelines that have governed the design, construction, and operation of buildings in most developed and many developing countries.

People, occupant activities, building materials, furnishings, and other sources emit pollutants into indoor air. These emissions vary greatly by contaminant species and among buildings as well as temporally and spatially within buildings. Outdoor air also contains contaminants that affect health whether inhaled outdoors or indoors. Furthermore, physical and chemical reactions between indoor air and ventilation air, as well as between indoor air and a building's contents, modify the composition of indoor air and, presumably, its effects on perceived air quality and occupant health.

Professional societies and standards-writing bodies throughout the world consider the scientific evidence and use professional judgment when establishing ventilation requirements for the protection of occupants' health. Currently, most ventilation standards focus on occupant perception of indoor air quality upon first entering a space as the outcome indicator of concern rather than on risk-related aspects of indoor pollutant exposure, such as long-term health consequences to building occupants. Extending the considerations on which ventilation standards are written to include health impacts as well as perceived air quality requires knowledge of the available science. This review is intended to summarize the available scientific evidence to inform such activities.

Methods:

A literature search was conducted beginning with retrieval of references from previously published studies including those sources reviewed by Seppänen and Fisk (2002), Wargocki et al (2002), and Mendell (1993). In addition, a further literature search was conducted according to the following criteria and procedures:

1) *Primary Search Criteria*: Peer-reviewed journal articles containing measurements of both ventilation rates and health outcomes. No reviews or case studies were included.

2) *Date range*: The primary search was conducted for the period 2000-2006, post-dating prior reviews. A supplemental search was conducted for prior years, focusing on the journals listed in item 5.

3) *Journals and Databases*: An initial search of selected individual journals (see item 5), was conducted, followed by searches of these databases: Web of Science, PubMed, Compendex, AIRBASE, and Cambridge Scientific Abstracts (including these sub-databases: Environmental Sciences & Pollution Management, Toxline, ERIC and Avery Index to Architectural Periodicals). The primary database used was the Web of Science, including the Science Citation Index and the Social Sciences Citation Index. Additional searches were performed in the other databases to include any journals not indexed in the Web of Science, and as a check on journals already searched.

4) *Search Terms*: The search terms were developed after reviewing the search methodology used in the EUROVEN study (Wargocki et al, 2002,). The basic categories are similar. Specific search terms (Table 1) were suggested by our particular search criteria, and were expanded and refined as the search of individual journals was conducted, and titles, keywords, abstracts and articles were reviewed.

Three categories of search terms were used in various combinations, depending on the journal, database, number of results, etc.

Table 1. Search terms for the literature review [a]

Ventilation terms	*Health terms*	*Building terms*
Ventilation	health	building*
Ventilation rate	symptom*	home*
air change*	sick building*	house*
air exchange*	building related illness*	dwelling*
air flow	environmental illness*	residen*
air supply	allerg*	office*
supply air	asthma	school*
CO_2	disease*	hospital*
carbon dioxide	illness*	chamber
outdoor air	irritation	sick building*
outside air	infection*	building related illness*
indoor air	absenteeism	

[a] "*" indicates a wildcard in the search term

A typical search included these ventilation terms: "ventilation rate OR air change* OR air exchange* OR air supply OR supply air OR CO_2 OR carbon dioxide." Typically, in the health-oriented journals it was useful to add 'building' terms, and in the engineering journals, 'health' terms. Useful results were often obtained when the word 'symptom' was part of the search.

5) *Journals*: The journal search included specific journal titles that had been referenced in earlier studies or were determined to be likely sources of relevant articles. This search included the journal name plus several search terms. Initially, fewer terms were used, such as 'ventilation AND health,' but more useful search terms evolved quickly, and most of the journals were searched with the 'typical' search described above. These same journals were also included in one or more of the databases that were searched. Journals' titles in the initial search are listed in Appendix B with added notes.

Selection of Papers for the Review Workshop

A total of 365 articles were examined by the Principal Investigators. Papers that did not contain data on both health outcomes and ventilation rates were eliminated. References to the full set of examined articles are listed in Appendix C. This screening resulted in a set of 73 papers for further review. Papers on odor perception (perceived indoor air quality) were initially included in the set selected for further review, but the workshop panelists decided to eliminate these from additional consideration, reasoning that perceived odor was not — of itself — a health outcome. One paper was added to those carefully assessed during the review itself. The complete list of references and a brief summary of the discussion of the 74 papers is presented in Appendix B.

Expert Review Workshop Process

Scientists from America, Europe, and Asia were recruited to participate in the review. The scientists represented a range of relevant disciplines including medicine, epidemiology, toxicology, environmental chemistry, aerosol physics, psychology, engineering, and architecture. The participants are listed in Appendix D. Each paper was randomly assigned to two scientists for detailed review. No paper was assigned to a scientist who was one of its authors. Each scientist reviewed 12 or 13 papers. When reviewing a given paper, information on different aspects of the study was assembled including research design, methods, data analysis procedures, techniques for

measurement of ventilation rates and health outcomes, potential sources of bias, research results, and conclusions.

A major part of the review process occurred at a three-day workshop where all the scientists were assembled. For each of the 74 reviewed papers, one reviewer presented a summary of the paper, followed by comments from the second reviewer. A general discussion ensued, leading to the classification of each paper. Individuals who were authors of papers under review were absent from the room during the discussion of their papers. Reviewed papers were classified into the following categories:

relevant and conclusive

- providing sufficient information on ventilation rates, health outcomes, and methods used to infer something about the relationship between ventilation rates and health outcomes;

relevant but non-informative

- lacking essential information concerning ventilation rates or health outcomes and/or incomplete data processing or reporting; relevant to the subject of the review, but inconclusive

suggestive

- not conclusive but suggestive of an association between ventilation rates and health outcomes;

irrelevant

- not dealing with a subject within the scope of the review; lacking data on health outcomes or ventilation rates, or describing case studies.

Classification of each paper was first made independently by each reviewer. Then, during the workshop the whole group decided by consensus on a final classification. The papers judged during plenary discussions of the group to be *conclusive* were used to formulate the final consensus statement and conclusions.

Results

Of the 74 papers reviewed by the group, 30 papers were excluded. The reasons for exclusion were nearly always a lack of both ventilation and health outcome data and correlations, and are noted the table in Appendix A. The reviewers classified 17 papers that provided information relevant to the scope of the present work as case studies or judged them to be either non-informative or inconclusive. Of the remaining 27 papers, 3 were judged to be suggestive of a relationship between ventilation and health, and 24 were judged conclusive and, therefore, used to formulate the consensus statement. The 24 conclusive and 3 suggestive papers reported results from 23 distinct studies.

The 27 papers judged as conclusive or suggestive were published in 12 different peer-reviewed scientific journals (11 in *Indoor Air*, 2 each in *Environment International*, *The New England Journal of Medicine*, and *Occupational and Environmental Medicine*; and 1 each in 10 other journals). The papers described a total of 23 studies, 9 carried out in Sweden, 6 in USA, 3 in Finland, 2 each in Denmark and Canada, and 1 in Norway.

In sum, the studies were carried out in more than 1000 homes, more than 300 offices, and in a small number of additional buildings, including schools, a prison, and a hospital. Most studies were carried out in a cold or temperate climate and during the winter, spring, or autumn season. Appendix A lists the papers reviewed by the expert panel with overall findings regarding Relevance and Informative or Suggestive. The findings are discussed for four types of studies in the following sections.

Homes

Table 2 lists four studies on ventilation rates in homes and associated health outcomes. Each of these studies was conducted in a Nordic country (3 from Sweden, 1 from Norway). All four studies deal with asthma and allergies, three with small children and one with adults (Norbäck et al., 1995). The studies of children are of similar design (cross-sectional studies of a large number of children, followed by case-control studies including measurements of ventilation rates using a constant injection, time averaging tracer gas technique and clinical investigations of health outcomes. In the study by Bornehag et al. (2005), a dose-response relationship was found (higher ventilation rates were associated with a lower prevalence of allergies, although the link was weak according to the authors possibly due to the low statistical power of the study).

In the study by Øie et al (1999), a low ventilation rate (below 0.5 h^{-1}) was not associated with bronchial obstruction; however, low ventilation rate increased the risks of bronchial obstruction from sources of air pollution (e.g. dampness, or the presence of polyvinyl chloride). In the study by Emenius et al. (2004), no association between measured ventilation rate and wheeze was found; however; the authors report significant associations between potential indicators of a low ventilation rate, such as a high absolute indoor air humidity and condensation on window panes, and wheeze.

A main difference between these studies is that the study by Bornehag et al. included a large number (80 %) of single-family homes, mainly with low ventilation rates (mean 0.35 h^{-1}), while the other two studies included apartments in larger cities primarily with a mean ventilation rate about twice that in Bornehag et al. In total these studies suggest an association between a low ventilation rate (<0.5 h^{-1}) and asthmatic symptoms, but the relevant data are limited and results not fully consistent.

Norbäck et al. (1995) studied adults and asthmatic symptoms with results that are suggestive of an association between the CO_2 concentration in the home (the mean of the concentrations in the bedroom and living room as measured for 30 minutes) and occupant reports of “nocturnal breathlessness” CO_2 concentrations for those with and without symptoms were 1020 and 850 ppm respectively. CO_2 concentrations exceeded 1000 ppm in 26% of the dwellings studied.

Table 2. Articles relevant to residences

Reference	Findings
Bornehag et al., 2005	Case – control study where cases were defined as individuals with at least 2 out of 3 symptoms (asthma, rhinitis, and atopic eczema). A dose-response relationship was found between ventilation rate in single-family houses and the likelihood of being a case.
Emenius et al., 2004	Case-control study where cases have recurrent wheezing. No association between measured ventilation rate of the whole house and the risk of being a case. Significant associations between condensation on window interiors or absolute humidity and recurrent wheezing.
Norbäck et al., 1995	Suggestive that higher indoor CO_2 in homes is a risk factor for asthma symptoms. Relationship between reported CO_2 concentrations and ventilation rates is uncertain because the CO_2 data are from short-term measurements and, therefore, are not reliable predictors of average ventilation rates.
Øie et al., 1999	Case-control study where cases had bronchial obstruction. No association between ventilation rate and case status. However, the increase in risk of bronchial obstruction resulting from other factors, such as building dampness, was moderately to markedly higher in homes with ventilation rates below 0.5 h^{-1}. In other words, low ventilation rates increased the health risks of other building conditions.

Offices

The panel found 13 conclusive papers from 11 studies of the office environment (3 studies from USA, 3 from Finland, 2 from Sweden, 2 from Denmark, and 1 from Canada). Twelve deal with reports of SBS symptoms, 1 with upper respiratory symptoms, and 2 with sick leave. These papers are derived from 2 climate chamber exposure studies in Denmark, and from epidemiological studies including 1 in Sweden, 3 in Finland, 3 in the United States, and 1 in Canada.

Three studies — one in USA (100 buildings, 4326 persons, response rate 85 %; Apte 2000, Erdmann and Apte, 2004), one in Finland (14 buildings, 399 persons, response rate 81 %; Jaakkola and Miettinen, 1995), and one in Sweden (210 buildings, measurements in 160, 5729 persons, response rate 96 %; Stenberg et al. 1994, Sundell et al. 1994a,b) — all show a dose-response association between the prevalence of SBS symptoms and outdoor airflow rate. Taken together, these studies indicate benefits from increased ventilation up to around 25 L/s per person. The experimental study in one office complex in Finland (Jaakkola et al. 1991a,b) reveals a similar, but less pronounced result, as does a longitudinal study by Chao et al. (2003). In contrast Menzies et al. (1993) did not find an association between SBS symptom prevalence and ventilation rates when changing the outdoor airflow rate in the smallest study, an experimental study in Canada in which this response is U-shaped. The total airflow was constant and the degree of recirculation of return air from the occupied space was varied between 7 % and 32 %. Similar results were found in another study including recirculation (Jaakkola et al., 1994).

Milton et al. (2000) found that short-term sick leave was reduced by 35 % at 24 L/s per person compared to 12 L/s per person outdoor air flow. Myatt et al. (2004) gives supportive evidence to this finding by showing that the probability of detecting airborne rhinoviruses is positively associated with weekly average CO_2 concentrations in the office. (The higher the CO_2 concentration, the higher is the likelihood of detecting airborne rhinovirus.)

In a climate chamber study (Wargocki et al., 2000) found a smaller prevalence of SBS symptoms at 30 L/s compared to at 10 L/s and 3 L/s per person. In an experimental

study in a call center, increased outdoor air ventilation (from 2.5 L/s to 25 L/s per person.) in the presence of a dirty filter increased some SBS symptoms, while an increased outdoor air ventilation rate in the presence of a clean filter reduced SBS symptoms (Wargocki et al., 2005). These results indicate that passing ventilation air through a dirty filter can add pollutants to indoor air

As a whole, the studies on ventilation rates in offices indicate that outdoor airflow rates up to 25 L/s per person are associated with a reduced prevalence of SBS symptoms and sick leave. This general result was found in spite of the fact that outdoor air contains potentially important pollutants in some of the locations studied. It is also noted that most studies include no (or limited) knowledge of indoor sources. The individual studies are listed in Table 3.

Table 3. Articles relevant to offices

Reference	Findings
Chao et al., 2003	Shows an association between indoor CO_2 level (380 - 1345 ppm(v), mean 690 ppm(v)) and upper respiratory symptoms. Longitudinal design.
Erdmann and Apte, 2004 Apte et al., 2000	An association is reported between CO_2 and SBS (mucous membrane) symptom prevalence. Odds ratios presented for several symptoms (mucous membrane, 1.1 - 1.2 per 100 ppm(v) increase in dCO_2; range 40 - 610 ppm(v)). The study indicates a dCO_2 dependent response relationship for some symptoms; strongest for "wheeze". Superseded by Erdmann and Apte 2004.
Jaakkola et al., 1991a Jaakkola et al., 1991b	Using ventilation rate categories (< 15, 15-25, 25-35, >35 L/s per person), found no significant association of ventilation rate with SBS symptom score, although a non-significant decrease in symptoms with increased ventilation was reported. Using ventilation rate categories of <5, 5-10, 10-15, > 15 L/s per person, reports a statistically significantly higher SBS symptom score for occupants in the lowest ventilation rate category. The results suggest a trend of decreasing SBS symptom score with increased ventilation.
Jaakkola et al., 1994	Compares 6 L/s and 20 L/s per person outdoor air in a recirculation system with a total airflow rate of 20 L/s per person. No change in SBS symptoms. Special subgroup population, selected to be sensitive to SBS.
Jaakkola and Miettinen, 1995	Dose response relationship of specific symptoms (eye and nasal symptoms, allergic reactions, below 25 L/s per person as a function of ventilation. In ventilation rate range below 25 L/s per person for most SBS symptoms, there was a trend toward decreased symptoms with increasing ventilation rate. Increases above 25 L/s per person were associated with significant increases in the prevalence rates of a few symptoms and non-significant increases in the prevalence of all other symptoms.
Menzies et al., 1993	Suggestive that changes in high ventilation rates are not associated with SBS symptom prevalence.
Milton et al., 2000	Short-term sick leave rates were reduced by 35 % at 24 L/s per person compared to 12 L/s per person ventilation.
Myatt et al., 2004	Supportive evidence for the earlier paper (Milton, 2000) on short-term sick leave.
Stenberg et al., 1994	Found a significant association between ventilation and SBS symptom prevalence. Case-control study. Suggests "monotonic dose-response" relationship between risk of SBS symptoms and ventilation rates over 2 L/s and 60 L/s per person range, but with substantial scatter.
Sundell et al., 1994a Sundell et al., 1994b	Study found a significant association between lower ventilation rate and increased SBS symptom prevalence. The study results suggests "monotonic or dose-response" relationship between prevalence of SBS symptoms and ventilation rates over the 5 L/s to 45 L/s per person range, but with substantial scatter. Study provides strong evidence of increased risks of adverse health at lower ventilation rates and suggestion of a dose-response trend. With respect to information on ventilation and health, repeats a subset of information from Sundell 1994a.
Wargocki et al., 2000	Demonstrates an association between four of twenty symptoms and ventilation rate in laboratory experiments. Ventilation rates of 3 L/s, 10 L/s and 30 L/s per person.
Wargocki et al., 2005	Increased outdoor airflow rate decreased 2 out of 17 symptoms with a new filter but not with a dirty filter. Reported outdoor air flow from mechanical system changed between 8 and 80 % of 3.5 ach, and dCO_2 varying between 250 - 800 ppm(v)

Schools

The panel found five studies relevant to schools. One study from the USA (Shendell et al, 2004) investigated the association between lower ventilation rate and increased student absence, and four Swedish studies investigated the impact of lower ventilation in schools and asthma, nasal, and respiratory effects.

Smedje and Norbäck (2000) examined ~100 classrooms with repeated measurements in 1993 and 1995. In between, 12% of the classrooms had received a new ventilation system that increased the air change rate from 0.5 h^{-1} to 4.0 h^{-1}, while the other classrooms had 3.1 h^{-1} at both times. In the classrooms with new, increased ventilation, the pupils reported less of "at least one asthmatic symptom" and there was a lower increase in reporting of symptoms from 1993 to 1995. However, this study involved a replacement of HVAC systems, not simply an increase in ventilation rates with the HVAC system unchanged. Because HVAC type and features have been associated with respiratory symptoms, this study provides no conclusive information about the association of ventilation rates with symptoms. Wålinder et al. (1997a, 1997b, 1998) reported results from a small study showing increased nasal congestion at lower air change rates but not in terms of ventilation rate per person.

Shendell et al. (2004) explored student attendance in relation to dCO_2 (difference between indoor and outdoor CO_2 level) in 434 classrooms in USA. A 1000 ppm(v) increase in dCO_2 was associated with a 0.5-0.9 % increase in annual average daily attendance after controlling for many other factors known or suspected to be associated with absence. In total, the articles suggest that a low ventilation rate is associated with increased absenteeism and more respiratory symptoms in school children. However, the available data are too limited for firm conclusions.

Table 4. Articles relevant to schools

Reference	Findings
Shendell, 2004	Strong evidence of an association between short-term dCO_2 (0 ppm(v)) – 3500 ppm(v)) and absenteeism.
Smedje, 2000	Decreased asthmatic symptom reported when moved to classroom with increased ventilation rate. However, because many factors other than ventilation rate that potentially affect health may have differed between the original and new classrooms, no conclusions about the effects of ventilation are possible..
Wålinder, 1997a	Suggestive of an effect of increased nasal congestion at low air-exchange rate. Limited by small number of subjects and of schools analyzed.
Wålinder, 1997b	Suggestive. Small study.
Wålinder, 1998	Suggestive of an association of air exchange rate, but not ventilation rate per person, with nasal rhinometry and biomarkers from nasal lavage. No correlation with self-reported symptoms. Suggestive that the effect of low air exchange rate worsened nasal congestion and biomarkers. Found the effect with air exchange rate but not with air flow rate per person.

Communicable Respiratory Infections

One paper from the US compared the number of respiratory illnesses, during a 47 month period, among army trainees living in 4 barracks, of which 2 were new and relatively airtight (without mechanical outdoor air supply), and 2 were older and presumably relatively leaky (Brundage et al. 1988). Rates of febrile acute respiratory disease were significantly higher among persons living in the new barracks (RR 1.51, 1.46-1.56). Another article from the US (Hoge, 1994) describes an outbreak of

pneumococcal disease in a jail. An increased risk of infection was associated with elevated levels of CO_2. In a study from Canada, Menzies et al. (2000) reported a strong association between a ventilation rate below 2 h^{-1} and tuberculosis infection among hospital workers. These studies all suggest a relationship between low ventilation rate and increased risk for airway infections. Table 5 summarizes these studies.

Table 5. Articles relevant to Communicable Respiratory Infections

Reference	Findings
Brundage et al., 1988	Suggests an association between lower ventilation rates and increased febrile respiratory illness based on study in army barracks. Uncertain whether spread of infection was airborne. Large potential for uncontrolled confounders. Ventilation reporting is ambiguous
Hoge et al., 1994	Suggestive of a relationship between reduced ventilation in a jail and an outbreak of pneumococcal infection. Difficult to separate overcrowding from ventilation as a source of the observed effect.
Menzies et al., 2000	Suggestive of a relationship between lower ventilation rates and higher tuberculosis infection of hospital workers.

Discussion

In general, conclusive papers found that that low ventilation rate is associated with an increased risk of allergies, SBS symptoms, and respiratory infections or found no association. Only one study was found giving evidence for the opposite: Jaakkola and Miettinen reported that increases above 25 L/s·per person were associated with statistically significant increases in the prevalence rates of a few symptoms (1995).

From this review it can be concluded that ventilation rates lower than approximately 25 L/s per person in offices increase the risk of SBS symptoms. The limited available data suggest that ventilation rates lower than 0.5 air changes per hour in homes in a cold climate increase the risk of negative health outcomes. For schools and day care centers, little data exists.

The threshold ventilation rate above which further increases do not improve SBS symptoms remains poorly defined. The outdoor airflow rate of 25 L/s per person suggested by this review is higher than the rate of 10 L/s per person, below which some previous reviews suggested that ventilation affects health (Godish and Spengler, 1996; Mendell, 1993; Menzies and Bourbeau, 1997; Seppänen et al., 1999). The findings of the present review are in line with those of Wargocki et al. (2002). A ventilation rate of 25 L/s per person is higher than the requirements in many existing ventilation standards and guidelines (ASHRAE, 2004a, b; CIBSE, 1978; CEN, 1998; ECA, 1992). Increasing the ventilation rate to 25 L/s per person will result in increased first costs and energy costs (if heat recovery systems are not used), thus elevating the costs of operating buildings. But the health-related economic benefits may greatly surpass the energy costs (Fisk and Rosenfeld, 1997). Furthermore, an increase in ventilation rates may not be required if effective control of indoor pollutant emission sources (Wargocki et al., 1999) or other means, such as effective air cleaning, is used to reduce indoor pollutant concentrations.

In conducting this review, each paper was examined for the ventilation measurement method used and the adequacy of its description. Several different methods were employed ranging from volumetric airflow rate measurements in ducts, tracer-gas techniques, and indoor carbon dioxide levels as a surrogate for ventilation rate per

person. In most cases important details describing the measurement method and conditions were not reported. In fact, some papers did not provide even a cursory description of the manner in which the ventilation rates were determined. Whether or not these omissions impact the conclusions of this analysis is unclear, but they do point to the need for better documentation of ventilation rate measurements in future studies of indoor environment and health.

The scientific evidence on the associations between ventilation rates and health outcomes presented in this paper is based on multidisciplinary data. Most of the studies were cross-sectional, the observed effects of ventilation on health being adjusted using models to control for a number of confounding factors in order to obtain reliable results. Such adjustment requires a large number of buildings and large populations and can be a source of errors. The experimental studies, on the other hand, are meant to be self-adjusted as only one factor is intended to be changed at a time, all other conditions being kept constant as much as possible. However, to be conclusive, experimental studies require the magnitude of intervention to be large enough to have measurable effects. In a study by Menzies et al (1993), classified as suggestive, the outdoor air supply rate was modified to obtain 14 L/s and 30 L/s per person. But these rates were only 7 and 32 % of the total supply air rates to offices, the rest being recirculated air. Although the outdoor air supply rate was doubled, the relatively small change was too low to have any significant impact on indoor conditions. Furthermore, the lower ventilation rate was already relatively high, compared to those found in many buildings. This may explain why no effects were observed in this study. In the other two experimental studies (Jaakkola et al., 1991a,b; Wargocki et al., 2000), a positive effect of the outdoor air supply rate (range 0 L/s –30 L/s per person) on health was observed.

The present work indicates that there is only limited information available on the effects of ventilation rates on health outcomes. Only 27 papers were judged by the group as providing sufficient scientific evidence on such effects. Considering the importance of ventilation rate as an influencing factor for the quality of indoor air, the number of conclusive investigations of the effects of ventilation rates on health outcomes is small. More studies that are carefully designed and well executed to study the potential relationships would be useful. This finding applies especially to schools and homes where few studies have been carried out relative to the importance of these settings. Reviewed articles showed very poor conditions indoors, especially as regards ventilation in schools and homes, many of which had ventilation rates far below the requirements in ventilation guidelines and standards (Bornehag et al. 2005; Smedje and Norbäck, 2000).

Studies of schools were mainly made in Sweden, which has some of the best public-health practices worldwide. Even so, the studies in Sweden suggest a negative health impact of current ventilation practices. A similar situation appears true with ventilation in homes. Studies were conducted mainly in Nordic countries, and suggest that a low ventilation rate was associated with increased risk of allergies. Schools and homes in most countries with a cold winter climate have ventilation rates as low as in Nordic countries (as a result of energy conservation), but actual measurements of ventilation rates have not been performed. The limited results from homes and schools do suggest, however, the potential public health concerns - more allergies and other adverse health consequences associated with energy conservation measures that

reduce ventilation rates (Harving et al., 1993; Norbäck et al., 1995; Smedje and Norbäck, 2000; Sundell et al., 1994c).

While thermal conditions and their potential effects were not examined in this review, most studies reviewed were not carried out in summer and therefore are not informative about potential thermal benefits of air-conditioning (mechanical cooling). During the summer season, buildings with air-conditioning have an advantage of being able to maintain thermal conditions by controlling the indoor air temperature and humidity. The benefits of air-conditioning in extremely hot conditions have been indicated in studies in nursing homes (Marmor, 1978) and in ordinary households (Rogot et al., 1992) where the presence of air-conditioning significantly reduced the risk of mortality compared with buildings without air-conditioning.

None of the studies reviewed assessed the impact of building ventilation rates on the risks of serious chronic health effects, such as cancer. However, the absence of data does not suggest that low ventilation rates do not increase such risks.

When evaluating the effects of ventilation, it is important to be mindful of the quality of the ventilation air. Numerous epidemiology studies have made associations between pollutants in outdoor air (primarily $PM_{2.5}$ and ozone) and both morbidity and mortality (Bell et al 2006; Dominici et al, 2006; Pope and Dockery, 2006). Increased ventilation means increased outdoor-to-indoor transport of outdoor pollutants. In locations with highly polluted outdoor air, there may be tradeoffs between health risks from outdoor pollutants and those from indoor pollutants.

Research needs:

Ventilation is fundamental to buildings intended for human occupancy. While the articles identified in this review support a positive benefit with increased ventilation above current ASHRAE standards, there is a dearth of well designed studies that more fully account for multiple factors in the complex indoor environment. Research in this field has not yet made great progress, in part because of difficult methodological challenges. Many research needs were identified by the group.

- An important need is for studies in other parts of the world, especially in hot and humid climates, and other situations differing from those in North America and Northern Europe. These studies should include all the building types where people spend extensive time.

- Schools, day care centers and homes need to be studied more extensively both in Europe and North America as well as elsewhere.

- There is a need to look at different types of ventilation systems, air cleaning and filtration technologies, and humidification as well as the cleanliness of HVAC systems.

- There is a need to examine the health effects of ventilation in locations with highly polluted outdoor air, especially high concentrations of $PM_{2.5}$ and ozone.

The type and concentrations of contaminants have not been specifically considered in this review. Future research can go beyond the results of this review to consider the impact of pollutant sources together with ventilation rates on occupant health.

Ventilation rates determine the time available for homogeneous reactions among indoor pollutants. This aspect of ventilation, as it influences human health, requires further study.

Future studies should carefully document the ventilation measurement methods employed. Information should include methods, timing, and location, as well as the method for calculating results from measured parameters.

CONCLUSIONS

The peer-reviewed scientific literature on health outcomes shows an association between ventilation rates and SBS symptoms in offices, where higher ventilation rates up to about 25 L/s per person are associated with reduced symptoms. Despite the substantial research on the ventilation-SBS relationship in offices, we still have a poor understanding of the nature of that relationship. Uncertainty as to the form of the ventilation-health relationship is a major uncertainty in establishing ventilation standards.

The panel members were divided as to whether the evidence for an association between ventilation rates and other health outcomes, including inflammation, communicable respiratory infections, asthma, allergy and short-term sick leave, was strong or only suggestive.

The very limited data available suggest that indicators of inflammation, rates of communicable respiratory infections, frequency of asthma symptoms, and rates of short-term sick leave increase with lower ventilation rates in the other building environments studied.

The very limited evidence available indicates that air change rates above about 0.5 h^{-1} in homes in Nordic countries are associated with lower likelihood of symptoms of asthma and allergy from other building conditions (e.g., humidity, mold, dust mites, and other contaminants).

Implications for Standards and Guidelines

This study was not intended to produce a particular ventilation rate for use as minimum value for regulation. While the conclusions of this study are limited by the number and thoroughness of the studies to date, they may inform ongoing efforts to develop and revise ventilation standards and related guidance documents. These standards, particularly those intended for regulatory use, are appropriately motivated by risk for health effects, but they are also developed mindful of other factors not considered in this study such as occupant comfort and odor perception, economics and the limits of current technology.

The study's results suggest that lowering existing minimum rates would be inappropriate since suggestive evidence indicates that higher rates may be health-protective in many instances. There is also evidence that lower rates will generally increase risks of SBS symptoms in offices, both in North America and in northern Europe.

The results provide some support for having higher rates in standards and guidelines that aim for a higher level of indoor environmental quality, though an appropriate level of increase can not be determined with any precision. Health benefits of higher rates may be more likely in places where outdoor air quality is very good, as was found in many of the studies done in the Nordic countries that are the subject of a large fraction of the literature reviewed. Any recommendations to increase ventilation must address the issue of poor ambient air quality and not just assume that more outdoor air will always improve the indoor environment.

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Sundell, J, Lindvall, T, and Stenberg, B, 1994a. ''Association between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants'', *Environment International*, 20, 239-251.

Sundell, J, Lindvall T, Stenberg, B, and Wall, S, 1994b. Sick Building Syndrome (SBS) in office workers and facial skin symptoms among VDT-workers in relation to building and room characteristics: two case-referent studies, *Indoor Air*, 4, 83-94.

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Wargocki, P, Wyon, DP, and Fanger, PO, 2005. The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air*; 14 (Suppl 8): 7-16

APPENDICES TO FINAL REPORT

APPENDIX A – Papers reviewed by expert panel with overall findings by Workshop

(I = informative, conclusive; S = suggestive; N = non-informative or not relevant)

LName, Year	Reference	I, S, N	Conclusion
Apte, 2000	Apte, M.G., Fisk, W.J. and Daisey, J.M. (2000) Associations between indoor CO_2 concentrations and sick building syndrome symptoms in US office buildings: an analysis of the 1994-1996 BASE study data, *Indoor Air*, 10, 246-257.	I	Superseded by Erdmann and Apte 2004.
Bakó-Biró, 2004	Bakó-Biró, Z., P. Wargocki, C. J. Weschler, and P. O. Fanger (2004.) Effects of pollution from personal computers on perceived air quality, SBS symptoms and productivity in offices. *Indoor Air* 14: 178-187	N	Did not study ventilation.
Berg-Munch, 1986	Berg-Munch, B., Clausen, B.G. and Fanger, P.O. (1986) "Ventilation requirements for the control of body odor in space occupied by women", Environment International 12, 195-199	N	The paper is not informative, because no statistics; significance of results is not obvious from visual inspection. Don't describe how they measured the ventilation.
Bluyssen, 1996	Bluyssen, P.M., de Oliviera Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjorn, O., Bernhard C.A. and Roulet, C.A. (1996) "European indoor air quality audit project in 56 office buildings", *Indoor Air*, 6, 221-238.	N	No health data.
Bornehag, 2005	Bornehag, C-G, et al (2005) Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air* 2005; 15: 275–280	I	Association observed between lower ventilation rate in single family houses and higher prevalence of at least two of three rhinitis, wheezing, and eczema. Small differences in ventilation rates between case and control homes. Both whole house and child's bedroom. Differences were significant for some outcomes. Case control study where cases had a significantly lower ventilation rate than the controls.
Bourbeau, 1996	Bourbeau, J., Brisson, C. and Allaire, S. (1996) Prevalence of the sick building syndrome symptoms in office workers before and after being exposed to a building with an improved ventilation system, Occup. Environ. Med., 53, 204-210.	N	Reviewed together with Bourbeau 1997.
Bourbeau, 1997	Bourbeau, J., Brisson, C. and Allaire, S. (1997) Prevalence of the sick building syndrome symptoms in office workers before and six months and three years after being exposed to a building with an improved ventilation system, Occup. Environ. Med., 54, 49-	N	Studies of a move from building to building, it is invalid. Too many confounding factors that cannot be controlled. Not relevant. Compares different buildings. Too many variables changed.
Brundage, 1988	Brundage, J.F., Scott, R.M., Lednar, W.M., Smith, D.W. and Miller, R.N. (1988) "Building-associated risk of febrile acute respiratory diseases in army trainees", Journal of the American Medical Association, 259, 2108-2112	I	Suggests an association between lower ventilation rates and increased febrile respiratory illness. Uncertain whether spread of infection was airborne. Large potential for uncontrolled confounders. Ventilation reporting is ambiguous

Cain, 1983	Cain, W., Leaderer, R., Isseroff, L., Berglund, R., Huey, E., Lipsitt, E. and Perlman, D. (1983) "Ventilation Requirements in buildings - I. Control of occupancy odor and tobacco smoke", Atmospheric Environment, 17, 1183-1197	N	Useful in demonstrating the flow rates and difficulty of adequately removing ETS in particular. When it comes to population we don't know demographics.
Chao, 2003	Chao, H. Jasmine, Joel Schwartz, Donald K. Milton, and Harriet A. Burge, 2003. The Work Environment and Workers' Health in Four Large Office Buildings. EHP Vol. 111(9), 1242-1248	I	Shows an association between CO_2 (380 - 1345 ppm(v), mean 690 ppm(v)) and upper respiratory symptoms. - Longitudinal design.
Emenius, 2003	Emenius, G., G Pershagen, N Berglind, H-J Kwon, M Lewné, S L Nordvall and M Wickman (2003) NO2, as a marker of air pollution, and recurrent wheezing in children: a nested case-control study within the BAMSE birth cohort. Occup Environ Med 2003;60:876–881	N	No analysis reported of relationship between ventilation and health.
Emenius, 2004	G. Emenius, M. Svartengren, J. Korsgaard, L. Nordvall, G. Pershagen, M. Wickman (2004) Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE.) *Indoor Air*; 14: 34-42	I	No association between ventilation rate of the whole house and wheezing. NO_2 has both indoor and outdoor sources. So ventilation could increase or decrease indoor concentration.
Engvall, 2005	K. Engvall, P. Wickman, D. Norbäck (2005) Sick building syndrome and perceived indoor environment in relation to energy saving by reduced ventilation flow during heating season: a 1 year intervention study in dwellings. *Indoor Air* 15: 120-126	N	Very small study with limited statistical power.
Erdmann, 2004	Erdmann, Christine A. and Michael G. Apte (2004). Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset. *Indoor Air* 14 (Suppl 8): 127-134	I	Reasonable connection between CO_2 and SBS symptom prevalence. - Odds ratios for several symptoms (mucous membrane, 1.1 - 1.2 per 100 ppm(v) increase in dCO_2 (range 40 - 610 ppm(v)). - There is - Adjusted OR's were statistically significant for MM complex (and some individual symptoms). OR's ranged from 1.1 to 1.2 for a 100 ppm(v) dCO_2. Also there was an indication of a dose response for some of the individual symptoms, strongest for "wheeze". 5 out of 8 individual symptoms had their ORs for the upper 10 % of the building significantly greater that the lowest 10 % for buildings (the reference group). - Authors calculate that between 64 - 85 % reduction in symptoms might be possible if all buildings had ventilation rates as low as the lower 10 % of the buildings.
Fanger, 1988a	Fanger, P.O., Lauridsen, J., Bluyssen, P. and Clausen, G. (1988) Air pollution sources in offices and assembly halls, quantified by the olf unit, Energy and Buildings, 12, 7-19	N	reported no association of a health outcome with ventilation rate or CO_2 concentration. These studies used initial perceived air quality as an outcome, and initial perceived air quality is not known to be a predictor of health.
Fanger, 1988b	Fanger, P.O. (1988) Introduction to the olf and the decipol units to quantify air pollution perceived indoors and outdoors, Energy and Buildings, 12, 1-6.	N	No health data, Provides evidence that visitor's initial perception of air quality are associated with ventilation rate.
Fisk, 1993	Fisk, W.J., Mendell, M.J., Daisey, J.M., Falkner, D., Hodgson, A.J., Nematollahi, M. and Macher, J.M. (1993) "Phase I of the California Healthy Building Study: A Summary", *Indoor Air*, 3, 246-254.	N	Lack of reported analysis of association between CO_2 and health.

Gibert, 1992	Gibert, I., Chevalier, A. and Lambrozo, J. (1992) No difference in rates of absenteeism between workers in air-conditioned offices and naturally ventilated ones: a data base study, Indoor Environment, 1, 279-284.	N	No ventilation rates
Gunnarsen, 1997	Gunnarsen, L. (1997) The influence of areaspecific ventilation rate on emission from construction products, *Indoor Air*, 7, 116- 120.	N	No health data.
Haghighat, 1999	Haghighat, F. and Donnini, G. (1999) Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings, *Building and Environment*, 34, 479-503	N	Did not report investigation of a relationship of ventilation and health symptoms.
Harving, 1993	Harving, H., Korsgaard, J. and Dahl, R. (1993) House-dust mites and associated environmental conditions in Danish homes, *Allergy*, 48, 106-109.	N	No ventilation data.
Harving, 1994	Harving, H., Korsgaard, J. and Dahl, R. (1994) Clinical efficacy of reduction in house-dust mite exposure in specially designed, mechanically ventilated "healthy" homes, *Allergy*, 49, 866-870.	N	Too many potential confounders. Subjects moved between old and new "healthy" houses.
Hedge, 1994	Hedge, A., W.A., Erickson and G. Rubin (1994.) The effects of alternative smoking policies on indoor air quality in 27 office buildings. *Ann Occup Hyg* 38:265-278.	N	No ventilation rates
Hill, 1992	Hill, B.A., Craft, B.F. and Burkart, J.A. (1992) "Carbon dioxide, particulates, and subjective human responses in office buildings without histories of indoor air quality problems", *Applied Occupational Environmental Hygiene*, 72, 101-111	N	Doesn't find an association due to population that is too small. Too small differences between rooms. Does not add to the literature.
Hoge, 1994	Hoge, C.W., Reichler, M.R., Dominguez, E.A., Bremer, J.C., Mastro, T.D., Hendricks, K.A., Musher, D.M., Elliott, J.A., Facklam, R.R. and Breiman, R.F. (1994) "An Epidemic of pneumococcal disease in a overcrowded, inadequately ventilated jail", *The New England Journal of Medicine*, 331, 643-648.	I	Suggestive of a relationship between reduced ventilation and outbreak of pneumococcal infection. Difficult to separate overcrowding from ventilation as a source of the observed effect. Caution needed.
Iwashita, 1990	Iwashita, G., Kimura, K., Tanabe, S., Yoshizawa, S. and Ikeda, K. (1990) Indoor air quality assessment based on human olfactory sensation, J. Arch. Plann. Environ. Eng., 410, 9-19	N	Lacking good stat analysis. Not clear what the authors are trying to convey. Lack of visual, clear relationships.
Jaakkola, 1991a	Jaakkola, J.J.K., Heinonen, O.P. and Seppanen, O. (1991a) "Mechanical Ventilation in Office Buildings and the Sick Building Syndrome. An Experimental and Epidemiological Study", *Indoor Air*, 1, 111-122	I	Using ventilation rate categories (< 15, 15-25, 25-35, >35 L/s-person) and found no significant association of ventilation rate with SBS symptom score, although the study results indicate a non-significant decrease in symptoms with increased ventilation.
Jaakkola, 1991b	Jaakkola, J.K.K., Reinikainen, L.M., Heinonen, O.P., Majanen, A. and Seppanen, O. (1991b) "Indoor air requirements for healthy office buildings: recommendations based on an epidemiologic study", Environment International, 17, 371-378	I	Using ventilation rate categories of <5, 5-10, 10-15, > 15 L/s-person, reports a statistically significantly higher SBS symptom score for occupants in the lowest ventilation rate category. - The results suggest a trend of decreasing SBS symptom score with increased ventilation

Jaakkola, 1994a	Jaakkola, J.J.K., Tuomaala, P. and Seppanen, O. (1994) "Air recirculation and sick building syndrome:Ablinded crossover trial", American Journal of Public Health, 84, 422-428	I	Compares 6 L/s·p + 14 l//s·per person recirculated to 20 L/s·p OA ventilation reports no change in SBS symptoms. - Special subgroup population - selected to be sensitive to SBS.
Jaakkola, 1995	Jaakkola, J.J.K. and Miettinen, P. (1995) "Ventilation rate in office buildings and sick building syndrome", *Occupational and Environmental Medicine*, 52, 709-714.	I	Dose response relationship of specific symptoms (eye and nasal symptoms, allergic reactions, below 25 L/s·per person as a function of ventilation. - In ventilation range below 25 L/s·per person for most SBS symptoms there was a trend toward decreased symptoms with increasing ventilation rate. Increases above 25 L/s·per person were associated with significant increases in the prevalence rates of a few symptoms and non-significant increases in the prevalence of all other symptoms.
Knudsen, 1997	Knudsen, H.N., Clausen, G. and Fanger, P.O. (1997) Sensory characterization of emissions from materials, *Indoor Air*, 7, 107-115.	N	reported no association of a health outcome with ventilation rate or CO_2 concentration. These studies used initial perceived air quality as an outcome, and initial perceived air quality is not known to be a predictor of health.
Knudsen, 1998	Knudsen, H.N., Valbjørn, O. and Nielsen, P.A. (1998) Determination of exposure- response relationships for emissions from building products, *Indoor Air*, 8, 264-275.	N	No health data.
Mendell, 1996	Mendell, M.J., Fisk, W.J., Deddens, J.A., Seavey, W.G., Smith, A.H., Smith, D.F., Hodgson, A.T., Daisey, J.M. and Goldman, L.R. (1996) Elevated symptom prevalence associated with ventilation type in office buildings, *Epidemiology*, 7, 583- 589	N	Due to the lack of reported analysis of association between CO_2 and health. - "Preliminary analyses of these data showed no important association between mean indoor CO_2 concentrations and symptom outcomes, although the low CO_2 levels in our study buildings provided limited ability to assess such relations."
Menzies, 1993	Menzies, R., Tamblyn, R., Farant, J.-P., Hanley, J., Nunes, F. and Tamblyn, R., 1993 "The effect of varying levels of outdoorair supply on the symptoms of sick building syndrome", *The New England Journal of Medicine*, 328, 821-827.	I	Suggestive that changes in high ventilation rates are not associated with SBS symptom prevalence.
Menzies, 1996	Menzies, D., Tamblyn, R.M., Nunes, F., Hanley, J. and Tamblyn, R.T. (1996) Exposure to varying levels of contaminants and symptoms among workers in two office buildings, *Am. J. Pub. Health*, 86, 1629-1633.	N	Did not report any analysis between symptom prevalence and ventilation. - The absence of an association between health outcome and ventilation in Menzies 1993 may be explained by the results of this study.
Menzies, 2000	Menzies et al, 2000. *Ann Intern Med*, 2000, 133: 779-789	I	Suggestive of relationship between ventilation rate and TB conversion in hospital workers.
Milton, 2000	Milton, D., Glencross, P. and Walters, M. (2000) Risk of sick-leave associated with outdoor air supply rate, humidification and occupants complaints, *Indoor Air*, 10, 212-221	I	Short-term sick leave rates are were reduced by 35 % at 24 L/s/per person compared to 12 L/s/per person ventilation.
Muhic, 2004	Muhic, S., and Butala, V. (2004) The influence of indoor environment in office buildings on their occupants: expected - unexpected. *Bldg and Env*., Vol 39: 289-296	N	No analysis of relationship between vent and health.
Myatt, 2002	TA Myatt, J Staudenmayer, Kate Adams, Michael Walters, Stephen Rudnick, Donald K Milton. 2002 A study of indoor carbon dioxide levels and sick leave among office workers. *Environ Health*	N	Intervention periods too short for a communicable respiratory disease that is season-dependent. - Study design based on a seasonal disease, total was two buildings with two cycles. Rhinovirus is virus of concern.

Myatt, 2004	Myatt TA, Johnston SL, Zuo Z, Wand M, Kebadze T, Rudnick S, Milton DK. 2004. Detection of airborne rhinovirus and its relation to outdoor air supply in office environments. *Am J Respir Crit Care Med*. Jun 1;169(11):1187-90.	I	Supportive evidence for the earlier paper on short-term sick leave.
Nardell, 1991	Nardell, E., Keegan, J., Cheney, S. and Etkind, S. (1991) "Airbone infection. Theoretical limits of protection achievable by building ventilation", *American Review of Respiratory Disease*, 144, 302-306.	N	Modeling study. No measurements made.
Nelson, 1995	Nelson, N.A., Kaufman, J.D., Burt, J. and Karr, C. (1995) "Health symptoms and the work environment in four non-problem United States office buildings", *Scandinavian Journal on Work Environment and Health*, 21, 51-59.	N	No measured rates, no information on the ventilation system, lack of ventilation information not mentioned in discussion
Norbäck, 1995	Norbäck, D., Bjornsson, E., Janson, C., Widstrom, J. and Boman, G. (1995) Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings, *Occup. Environ. Med.,* 52, 388-395.	I	Study results suggest that higher indoor CO_2 in homes is a significant risk factor for asthma symptoms but not for objective asthma outcomes. Because the CO_2 data are from short term measurements, they are not likely accurate predictors of average ventilation rates.
Norbäck, 2000	Norbäck, D., R. Walinder, G. Wieslander, G. Smedje, C. Erwall and P. Venge (2000) Indoor air pollutants in schools: nasal patency and biomarkers in nasal lavage. *Allergy* 2000: 55: 163-170	N	Inadequate design. Time relationship between ventilation assessment and health effects was asynchronous
Nordstrom, 1995	Nordstrom, K., Norbäck, D. and Akselsson, R. (1995b) "Subjective indoor air quality in hospitals - The influence of building age, ventilation flow, and personal factors", Indoor Environment, 4, 37-44.	N	No health outcome
Øie, 1999	Øie, L., Nafstad, P., Botten, G., Magnus, P. and Jaakkola, J.K. (1999) Ventilation in homes and bronchial obstruction in young children, Epidemiology, 10, 294- 299.	I	Ventilation rate was not associated with bronchial obstruction; however, low ventilation rates increased the strength of association between bronchial obstruction and two indoor pollutant sources – building dampness and polyvinyl chloride.
Ruotsalainen, 1991	Ruotsalainen, R., Jaakkola, J.J.K., Rönnberg,R., Majanen, A. and Seppänen, O. (1991) Symptoms and perceived indoor air quality among occupants of houses and apartments with different ventilation systems, *Indoor Air*, 1, 428-438.	N	Did not report their any analyses of the relationships between ventilation rates and health outcomes
Ruotsalainen, 1994	Ruotsalainen, R., Jaakkola, N. and Jaakkola, J.J.K. (1994) "Ventilation rate as a determinant of symptoms and perceived odors among workers in daycare centers", Environment International, 20, 731-737.	N	Lack of adequate data on ventilation rates
Sakr, 2003	Sakr, W. , H. N. Knudsen, L. Gunnarsen and F. Haghighat (2003.) Impact of varying area of polluting surface materials on perceived air quality. *Indoor Air* 13: 86-91	N	No health data.
Sakr, 2006	Sakr, W., C. J. Weschler and P. O. Fanger (2006.) The impact of sorption on perceived indoor air quality. *Indoor Air* 16: 98-110.	N	No health data.

Shendell, 2004	Shendell, D.G., Prill, R., Fisk, W.J., Apte, M.G., Blake, D., and Faulkner, D. (2004) Associations between classroom CO_2 concentrations and student attendance in Washington and Idaho. *Indoor Air*; 14: 333-341	I	Strong evidence of an association between short term dCO_2 (0 – 3500 ppm(v)) and absenteeism.
Skov, 1987	Skov, P. and Valbjørn, O. (1987) The sick building syndrome in the office environment: The Danish Town Hall study, *Environment International*, 13, 339-349	N	Found an association between symptom prevalences and type of ventilation, with higher rates for mechanically ventilated buildings. Association was not statistically significant. Did not report any investigation of association between symptoms and CO_2 level (as indicator of ventilation rate)
Skov, 1990	Skov, P., Valbjørn, O. and Pedersen, B.V. (1990) Influence of indoor climate on the sick building syndrome in an office environment, *Scand. J. Work Environ. Health*, 16, 363-371	N	Small number of buildings and potentially large errors in ventilation rate determination
Smedje, 1997	Smedje, G., Norbäck, D. and Edling, C. (1997) "Subjective indoor air quality in schools in relation to exposure", *Indoor Air*, 7, 143-150.	N	No health outcome
Smedje, 2000	Smedje, G. and Norbäck, D. (2000) New ventilation systems at select schools in Sweden - effects on asthma and exposure, *Arch. Environ. Health*, 55, 18-25.	I	Confounded by several factors. - Decreased asthmatic symptom reported when moved to classroom with increased ventilation rate. - Assuming that the effect was real, the reduction was due to increase ventilation. Suggestive that effect was not due to the home environment
Stenberg, 1994	Stenberg, B., Erikson, N., Hoog, J. Sundell, J. and Wall, S. (1994) "The sick building syndrome (SBS) in office workers, a case-reference study of personal, psychosocial and building-related risk indicators", *International Journal of Epidemiology*, 23, 1	I	Found a significant association between ventilation and SBS symptom prevalence. Case-control study. - Suggests "monotonic dose-response" relationship between risk of SBS symptoms and ventilation rates over 2 L/s and 60 L/s·per person range, but with substantial scatter.
Sterling, 1983	Sterling, E. and Sterling, T. (1983) The impact of different ventilation levels and fluorescent lighting types on building illness: an experimental study, *Can. J. Pub. Health*, 74, 385-392	N	Inconclusive study. No ventilation rate data reported (only % outdoor air).
Sundell, 1993a	Sundell, J. and T. Lindvall (1993a.) Indoor Air Humidity and Sensation of Dryness as Risk Indicators of SBS. *Indoor Air* 3: 382-390	N	No data on outdoor airflow rates or air exchange rates
Sundell, 1993b	Sundell, J., B. Andersson, K. Andersson and T. Lindvall (1993b) Volatile Organic Compounds in Ventilation Air in Buildings at Different Sampling Points in the Buildings and their Relationship with the Prevalence of Occupant Symptoms. *Indoor Air* 3: 82-93	N	No reporting of investigation of an association between ventilation and health outcomes.
Sundell, 1994a	Sundell, J., Lindvall, T. and Stenberg, B. (1994a) "Association between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants", *Environment International*, 20, 239-251.	I	Study found a significant association between lower ventilation rate and increased SBS symptom prevalence. -The study results suggests "monotonic or dose-response" relationship between prevalence of SBS symptoms and ventilation rates over the 5 to 45 L/s·per person range, but with substantial scatter. Overall, this is one of the strongest studies of the relationship of ventilation rate with health. - Study provides strong evidence of increased risks of adverse health at lower vent rates and a suggestion of a dose response trend.

Sundell, 1994b	Sundell, J., Lindvall, T., Stenberg, B. and Wall, S. (1994b) Sick Building Syndrome (SBS) in office workers and facial skin symptoms among VDT-workers in relation to building and room characteristics: two case-referent studies, *Indoor Air*, 4, 83-94.	I	With respect to information on ventilation and health, repeats a subset of information from Sundell 1994a.
Sundell, 1994c	Sundell, J., Wickman, M., Pershagen, G. and Nordvall, S.L. (1994c) Ventilation in homes infested by house-dust mites, Allergy, 50, 106-112.	N	Studied the association between house dust mite allergen in mattress dust and residential ventilation. But the study did not include direct health outcomes.
Tuomainen, 2003	M. Tuomainen, A. Tuomainen, J. Liesivuori, A.-L. Pasanen (2003) The 3-year follow-up study in a block of flats - experiences in the use of the Finnish indoor climate classification. *Indoor Air*; 13: 136-147	N	The study found better health among occupants of special buildings built for superior IAQ relative to occupants of a standard control building; however, the evidence is insufficient to show that the better health in the special is a consequence of the higher ventilation rates in these buildings.
Wålinder, 1997a	Wålinder, R., Norbäck, D., Wieslander, G., Smedje, G. and Erwall, C. (1997) "Nasal Congestion in Relation to Low Air Exchange Rate in Schools", *Acta Otolaryngol*, 117, 724-727.	S	Suggestive of an effect of increased nasal congestion at low air exchange rate. - Limited by small number of subjects and of schools analyzed.
Wålinder, 1997b	Wålinder, R., Norbäck, D., Wieslander, G., Smedje, G. and Erwall, C. (1997b) Nasal mucosal swelling in relation to low air exchange rate in schools, *Indoor Air*, 7, 198-205	S	Suggestive. Same study as Wålinder, 1997a.
Wålinder, 1998	Wålinder, R., Norbäck, D., Wieslander, G., Smedje, G., Erwall, C. and Venge, P. (1998) "Nasal patency and biomarkers in nasal lavage - the significance of air exchange rate and type of ventilation in schools", *International Archives Occupational Environ*	S	Suggestive of an association of air change rate but not ventilation rate per person with nasal rhinometry and biomarkers from nasal lavage. No correlation with self-reported symptoms. - Suggestive that the effect of low air exchange rate worsened nasal congestion and biomarkers. Found the effect with air exchange rate but not with air flow rate per person.
Wargocki, 2000	Wargocki, P., Wyon, D.P., Sundell, J., Clausen, G. and Fanger, P.O. (2000) The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity, *Indoor Air*, 10, 222-236	I	Demonstrates an association between four of twenty symptoms and ventilation rate in laboratory experiments. Ventilation rates of 3, 10 and 30 L/s per person·p. - Caution: These experienced subjects may not have been fully blinded. Also, presence of a strong pollution source. DG note. I agree with the cautionary note. However, the experimental site is extrememly clean. If one wants to investigate the impact of ventilation with clean outdoor air on a clean working site effects will be more difficult to see than if there is a source of pollution present.
Wargocki, 2004	Wargocki, Pawel, David P. Wyon, and P. Ole Fanger (2004). The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air*; 14 (Suppl 8): 7-16	I	Increased outdoor air flow rate decreased 2 out of 17 symptoms with a new filter but not with a dirty filter. - Reported outdoor air flow from mechanical system changed between 8 and 80 % of 3.5 ach and roughly dCO_2 = 250 - 800 ppm(v)
Wargocki, 2005	Wargocki, Pawel, David P. Wyon, and P. Ole Fanger (2005). The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air*; 14 (Suppl 8): 7-16	N	No health, it is performance

Yaglou, 1936	Yaglou, C.P., Riley, E.C. and Coggins, D.I. (1936) Ventilation requirements, *ASHRAE Trans*., 42, 133-162.	N	No association between ventilation rate and perception of body odor
Yaglou, 1955	Yaglou, C.P. (1955) Ventilation requirements for cigarette smoke, *ASHRAE Transactions*, 61, 25-32.	N	No health data.
Zitter, 2002	Zitter JN, Mazonson PD, Miller DP, Hulley SB, Balmes JR. 2002. Aircraft cabin air recirculation and symptoms of the common cold. *JAMA*. 2002 Jul 24-31; 288(4):483-6.	N	Studied relationship between recirculation in airplane air handing system and symptoms of the common cold. However, there were no measurements of ventilation rate in this study.
Zweers, 1990	Zweers, T., Skov, P., Valbjørn, O. and Mølhave, L. (1990) "The effect of ventilation and pollution on perceived indoor air quality in five town halls", *Energy and Buildings*, 14, 175-181.	N	Small variation in health endpoints; small variation in air exchange rates; air exchange rates are snapshots; reported association is driven by one data point.
Zweers, 1992	Zweers, T., Preller, L., Brunekreef, B. and Boleij, J.S.M. (1992) "Health and comfort complaints of 7043 office workers in 61 buildings in the Netherlands", *Indoor Air*, 2, 127-136	N	Didn't measure OA rates. Measure CO_2. Overall between CO_2 and health symptoms inversely related. - Did type of building ventilation rather than ventilation rate.

Appendix B – All journals in the initial search

Journals titles in the initial search are listed below, with added notes:

Acta Derm Venereol
Acta Otolaryngol
Allergy
Am J Epidemiol
Am J Infect Control
Am J Pub Health
Am J Resp Crit Care Med
Am Rev Resp Dis (ceased publication 1993, see *Am J Resp Crit Care Med* 1994-)
Ann Am Conf Gov Indust Hygienists (ceased publication 1988)
Ann Occup Hyg
Appl Occup Environ Hyg
Archives of Environmental Health
ASHRAE Transactions
Atmospheric Environment
Br J Indust Med (ceased publication 1993, see *Occ & Env Med* 1994-)
Br Med J
Building and Environment
Building Res and Info
Can J Pub Health
Central African J Med
Energy and Buildings
Environment Internat
Environmental Health Persp
Environmental Res
Environmental Tech
Epidemiology
Indoor Air
Indoor Environ (became *Indoor* + *Built Environ* 1996-)
Int Arch Occup Environ Health
Int J Energy Research
Int J Epidemiol
J Air & Waste Manag Assoc
J Allergy Clin Immunol
J Am Geriatric Society
J Arch Plann Environ Eng (split in 2003: *J Arch & Plann* and *J Environ Eng* [Japanese])
J Arch Plann Res
J Clin Epidemiol
J Expos Anal & Env Epid
J Infect Diseases
J Occup Med
J Occup Environ Med
NEJM
Occup Environ Health
Occup Environ Med
Occup Med
Public Health Rep
Resp Med
Scand J Work Environ Health

Appendix C. All References Retrieved During Literature Collection

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APPENDIX D. Participants in the interdisciplinary workshop

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