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Commemorating 20 Years of *Indoor Air*

Ventilation rates and health: multidisciplinary review of the scientific literature

Abstract The scientific literature through 2005 on the effects of ventilation rates on health in indoor environments has been reviewed by a multidisciplinary group. The group judged 27 papers published in peer-reviewed scientific journals as providing sufficient information on both ventilation rates and health effects to inform the relationship. Consistency was found across multiple investigations and different epidemiologic designs for different populations. Multiple health endpoints show similar relationships with ventilation rate. There is biological plausibility for an association of health outcomes with ventilation rates, although the literature does not provide clear evidence on particular agent(s) for the effects. Higher ventilation rates in offices, up to about 25 l/s per person, are associated with reduced prevalence of sick building syndrome (SBS) symptoms. The limited available data suggest that inflammation, respiratory infections, asthma symptoms and short-term sick leave increase with lower ventilation rates. Home ventilation rates above 0.5 air changes per hour (h^{-1}) have been associated with a reduced risk of allergic manifestations among children in a Nordic climate. The need remains for more studies of the relationship between ventilation rates and health, especially in diverse climates, in locations with polluted outdoor air and in buildings other than offices.

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Practical Implications

Ventilation with outdoor air plays an important role influencing human exposures to indoor pollutants. This review and assessment indicates that increasing ventilation rates above currently adopted standards and guidelines should result in reduced prevalence of negative health outcomes. Building operators and designers should avoid low ventilation rates unless alternative effective measures, such as source control or air cleaning, are employed to limit indoor pollutant levels.

Introduction

The relevant professional societies and standards-writing bodies throughout the world consider scientific evidence and apply professional judgment when establishing ventilation requirements in buildings for the protection of occupants' health. Currently, ventilation standards are based primarily on data that pertain to occupants' perception of indoor air quality rather than on risk-related aspects of indoor pollutant exposure, such as short- and long-term health consequences. The focus on perceived indoor air quality utilizes a relatively large set of data on the relationship of ventilation rates and perception relative to the much more limited data on indoor pollutant exposure and associated health risks. Extending ventilation standards to more explicitly include health risks as well as perceived air quality requires scientific knowledge. This review summarizes the available scientific evidence concerning health impacts of indoor environments that are directly related to ventilation rates.

The aim of this paper is to report the findings of an expert panel review assembled to evaluate the published scientific literature on the associations of ventilation rates in buildings with human health responses. In so doing, it provides a summary of the available scientific evidence for setting health-related ventilation standards. By design, the panel's review was restricted to articles published in peer-reviewed journals that reported original research explicitly investigating the associations between ventilation rates and health. The intended audience for this review includes not only those writing standards and guidelines for ventilation of buildings but also building design professionals, researchers and policy-makers seeking a better understanding of what information and insight the available scientific evidence can provide. The review also identified fruitful avenues for future research.

Several literature reviews have been published on the effects of ventilation on health. Their common conclusion is that lower ventilation rates can significantly aggravate health outcomes, mainly sick building syndrome (SBS) symptoms (Godish and Spengler, 1996; Mendell, 1993; Menzies and Bourbeau, 1997; Seppänen et al., 1999; Wargocki et al., 2002). These literature reviews included studies published in peer-reviewed journals as well as articles published in conference proceedings (Wargocki et al., 2002). The present review considers articles published through the end of 2005 and includes only articles published in peer-reviewed scientific journals. It extends prior reviews on this topic through its rigorous examination of the literature by a multidisciplinary group that was convened for this review process.

Background

Ventilation with outdoor air is intended to remove pollutants emitted from indoor sources, thereby reducing their concentrations in occupied spaces. People, their activities, building materials, furnishings, unvented combustion and other processes emit pollutants into indoor air. Emissions vary greatly by contaminant species and among buildings as well as temporally and spatially within buildings. Outdoor air also contains contaminants that can affect health whether inhaled outdoors or indoors. Ventilation can serve as a means of introducing these contaminants into indoor spaces. Physical and chemical reactions that occur in indoor environments modify the composition of indoor air and, presumably, its effects both on perceived air quality and on health risks for exposed occupants. Overall, the dependence of indoor pollutant levels on ventilation rates varies among pollutants and, although understood in principle, has not been completely characterized.

As summarized by Klauss et al. (1970), the establishment of ventilation requirements for occupied spaces has a long history. Tredgold (1836) made one of the earliest estimates of ventilation requirements. By considering the dilution of occupant-generated carbon dioxide (CO_2) and moisture, as well as the oxygen requirements of lamps and candles, he estimated a minimum required ventilation rate of about 2 l/s (4 cfm) per person. Pettenkofer (1858) theorized that CO_2 build-up and oxygen depletion were not the key issues governing appropriate ventilation rates, but rather it was other organic substances in air that were associated with poor indoor air quality, noting that CO_2 could be used as an indicator of the level of these substances. Based on the theory of human organic exhalations, late in the 19th century, Billings (1893) calculated a ventilation requirement of about 15 l/s (30 cfm) per person, using the association of the organic compounds with CO_2. Later research led to questions about the need for this higher ventilation rate, but it stood until the New York State Commission on Ventilation (1931), analysing the research available to that time and conducting additional studies, found that 5–7.5 l/s (10–15 cfm) per person was adequate in schoolrooms.

Subsequently, Yaglou et al. (1936) did a series of studies in chambers to determine the ventilation rates required to reduce the odour from human bioeffluents to acceptable levels (Janssen, 1999; Jennings and Armstrong, 1971). That work, and subsequent research by others, supported the adequacy of ventilation rates as low as 5 l/s (10 cfm) per person, but more typically indicating that 7.5 l/s (15 cfm) per person was needed for bioeffluent odour control only, with even higher rates necessary under some circumstances. These studies also used CO_2 levels as an indicator of the bioeffluent level, supported by the assumption that CO_2 and other human-generated bioeffluents would be well correlated. When American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) Standard 62 was first issued in 1973, it contained a minimum ventilation requirement of 2.5 l/s (5 cfm) per person in some spaces, but specified higher rates in others, and this minimum was maintained in the 1981 version of the standard (ASHRAE, 1973, 1981). When the standard was again revised in 1989, the minimum rate was increased to 7.5 l/s (15 cfm) per person (ASHRAE, 1989). There was a major revision to the standard in 2001, which changed the procedure by which ventilation requirements were calculated, but the rates themselves did not change much except in densely occupied spaces (e.g., auditoria), where they were reduced to levels close to 2.5 l/s (5 cfm) per person (Stanke, 1999).

Methods

A literature search was conducted using the on-line 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). Details of the search and the search terms used are provided in Appendix 1. Additional papers were identified in references found in the reviews cited above and in other retrieved papers. From the identified papers, those meeting the following criteria were selected for initial review, which was conducted by the principal investigators (PIs) for this project (J Sundell and H Levin):

- published in peer-reviewed scientific journals;
- reported measured ventilation rates (or indoor CO_2 levels as a surrogate) *and* health outcomes; and
- investigated associations between specifically identified health outcomes and reported ventilation rates or CO_2 levels.

In all, 313 articles were examined by the PIs. Papers that did not contain data on both health outcomes and ventilation rates were eliminated from further consideration. This screening effort resulted in a set of 73 papers selected for further review by the expert panel. The panel reviewed the selected papers prior to a workshop and at the workshop discussed the papers and developed a consensus statement regarding the available evidence.

Expert panel review

The expert panel, co-authors of this paper, comprised 14 members drawn from the United States, England, Denmark, and Hong Kong and representing a range of relevant disciplines including medicine, epidemiology, toxicology, environmental chemistry, environmental engineering, psychology, mechanical engineering and architecture. Each paper was randomly assigned to two experts (one a health scientist and one a building or environmental scientist) for detailed review. No paper was assigned to one of its authors.

Each panelist reviewed 12 or 13 papers. Reviewers extracted key information from each paper including research design, characteristics of buildings and populations studied, data analysis procedures, techniques for measuring ventilation rates and health outcomes, potential sources of bias, research results, and conclusions. Papers on odour perception (perceived indoor air quality), initially included by the PIs in the set selected for panel review, were eliminated from further consideration by workshop panelists, reasoning that perceived odour is already embedded into common practice as a basis for ventilation rate standards and does not directly represent a health outcome. During the review, one paper suggested by a workshop panelist was added to those assessed, resulting in a total of 74 papers that were considered.

At the workshop, a primary reviewer orally summarized each of the 74 papers. A second reviewer added comments. Authors of papers under review were absent from the room during discussion of their papers. A general discussion of each paper by the group led to its final classification into one of the following categories:

- *relevant and informative (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 noninformative* — 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, or lack of an association, between ventilation rates and health outcomes; and
- *irrelevant* — not dealing with a subject within the scope of the review; lacking data on health outcomes or ventilation rates, or describing case studies.

The papers judged by the group to be *conclusive* were used to formulate the final consensus statement and conclusions. The workshop was convened in the summer of 2006 and considered research articles published through 2005. Relevant articles published since then are listed in Appendix 2.

Results

Of the 74 papers reviewed by the group, 30 were excluded from further consideration. The reasons generally involved a lack of either ventilation data or health outcome data or their relationship. Seventeen papers were classified as case studies or judged as either noninformative or inconclusive because they failed to provide information relevant to the scope of the review. Of the remaining 27 papers, three 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. A summary of the panel review results for the 74 papers is presented in the Data S1.

The 27 papers judged as conclusive or suggestive cumulatively described a total of 23 studies, eight carried out in Sweden, seven in USA, three in Finland, two each in Denmark and Canada, and one in Norway. Note that none of the papers reported on studies carried out in Asia, South America, or Africa, among many other places. The combined studies were carried out in more than 1000 homes, more than 300 offices, and in a small number of additional buildings including schools, an army barracks, a jail, and a group of 17 hospitals. Most studies were carried out in a cold or temperate climate during the winter, spring or autumn season. During the review, each study was assigned to one of three categories: homes, offices and schools. Another group of papers explored communicable infectious disease in special building categories: army barracks, jails and hospitals. Each of these four categories is discussed separately in the following sections and summaries are presented in Tables 1–4.

Homes

Four studies in residences, all from Scandinavian countries, were deemed conclusive or suggestive by the panel (Table 1). Three of these were on-going, large scale studies of children (Øie – Norway, Emenius – Sweden, and Bornehag – Sweden), and one (Norbäck – Sweden) studied adults.

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-averaged tracer gas technique and clinical investigations of health outcomes. Differences among these studies included ventilation rates, location and type of residence. The study by Bornehag et al. (2005) included a large proportion (80%) of single-family homes, mainly with low ventilation rates (mean 0.35 h^{-1}), while the other studies included apartments in larger cities primarily with mean ventilation rates about twice those in the homes studied by Bornehag et al.

These studies suggest an association between three allergic conditions (asthma, rhinitis, and eczema) and

Table 1 Articles relevant to residences

Reference	Study characteristics	Panel findings
Bornehag et al., 2005	Children in 390 Swedish homes. Case–control (actually case–noncase) study where cases were defined as individuals with at least two of three symptoms (asthma, rhinitis and atopic eczema). Ventilation rates characterized for whole house and for child's bedroom	Association observed between lower ventilation rates in single-family houses and higher prevalence of at least two of three symptoms: rhinitis, wheezing and eczema. Differences in ventilation rates were small but statistically significant, with cases having lower ventilation rates than controls. Risks associated with any of the factors found are associated with duration or severity of the symptoms rather than with the induction of disease. Potential selection bias. Parents knew they had an asthmatic child and may have attempted to protect the children by modification of ventilation through operation of windows
Emenius et al., 2004	Case–control study of children where cases have recurrent wheezing. Followed 4089 children during first 2 years of life. Four-week measurements of air change rate, indoor temperature, and humidity were performed. Emphasis on NO_2 as an air pollutant. Some houses had gas cook stoves; others did not. Air-exchange rate was measured in all rooms of each home, using a passive tracer gas technique. Parental questionnaires on housing characteristics and subjects' wheezing	No association between measured ventilation rate of the whole house above or below 0.5 h^{-1} and the risk of being a case. However, significant associations between potential indicators of a low ventilation rate (e.g., high indoor air humidity and condensation on window panes) and wheeze. Noteworthy that NO_2 has both indoor (e.g., gas cooking) and outdoor (e.g., motor vehicles) sources. So an increase in ventilation rate could either increase or decrease the indoor NO_2 concentration
Norbäck et al., 1995	Studied 88 homes in Uppsala, Sweden, roughly half single-family homes and half apartments. All had electric cooking, most had mechanical exhaust ventilation, 26 had natural ventilation, and 16% had visible signs of dampness or mold. Subjects were 88 adults aged 20–45; 47 were case subjects with asthma symptoms, nocturnal breathlessness, or asthma medication in the past 12 months; 41 control subjects were selected from the same population without matching	Findings suggest that higher indoor CO_2 level is a risk factor for asthma symptoms but not for objective asthma outcomes. Relationship between reported CO_2 concentrations and ventilation rates is uncertain
Øie et al., 1999	Investigated 172 infants having bronchial obstruction matched to 172 controls in a birth cohort of 3754 children born in Oslo homes. Households were single family (76), duplexes (93), and apartments (175), with natural ventilation (227), mechanical exhaust (110) and balanced ventilation (7)	Ventilation rate and bronchial obstruction were not directly related, but the association of bronchial obstruction with strong indoor pollutant sources was found to be higher at low ventilation rates

Table 2 Articles relevant to offices

Reference	Study characteristics	Panel findings
Chao et al., 2003	A 1-year, longitudinal, cross-sectional study of 98 subjects (81 females and 17 males) in 21 offices in four Boston office buildings. Environmental sampling (temperature, humidity, CO_2, fungi in air, chairs and floor) every 6 weeks and concurrently administered detailed questionnaires on work-related symptoms, psychosocial factors, and perceptions of the office environment	A negative association was found between indoor CO_2 level and upper respiratory systems. Indoor CO_2 varied between 380 and 1345 ppm(v) [mean = 690 ppm(v)]
Erdmann and Apte, 2004; Apte et al., 2000	Stratified random sample of 100 US office buildings without known IAQ problems distributed throughout the country. Utilized questionnaires and a wide range of environmental measurements. Authors analyzed differences in symptoms per change in the difference between indoor and outdoor carbon dioxide levels (dCO_2), an indicator of outdoor air ventilation rate per occupant	Association observed between dCO_2 [range 40–610 ppm(v)] and prevalence of SBS symptoms. Adjusted odds ratios (ORs) were statistically significant for mucous membrane complex and for some individual symptoms. ORs ranged from 1.1 to 1.2 for a 100 ppm(v) increase in dCO_2. There was an indication of a dose-response for some of the individual symptoms, strongest for 'wheeze.' Five of eight individual symptoms had their ORs for the 10% of the buildings with the highest dCO_2 values, significantly greater than for the 10% of buildings with the lowest dCO_2, the reference group. Authors estimate that a 64–85% reduction in symptom prevalence might be possible if all buildings had ventilation rates as high as the 10% of the buildings with the highest ventilation rates
Jaakkola et al., 1991a,b	Compared ventilation rate categories (<15, 15–25, 25–35, >35 l/s per person) and SBS symptoms in Helsinki	Using ventilation rate categories, authors found no significant association with SBS symptom score, although the study did indicate a nonsignificant decrease in symptoms with increased ventilation rate
Jaakkola et al., 1994	Intervention study in two identical office buildings. Study population was 75 office workers, representing the most sensitive of a total of 470 workers. Buildings had central mechanical ventilation and operable windows. For the week before experimental intervention, both buildings were ventilated without recirculation at 20 l/s per person. Then based on random selection, building A operated at 70% recirculation (6 l/s per person of outdoor air) and building B at no recirculation (20 l/s per person of outdoor air). Repeated three times	Comparing 6 l/s per person and 20 l/s per person outdoor air in a recirculating system with a total airflow rate of 20 l/s per person, they found no difference in SBS symptoms. Study included a special subgroup population selected to be sensitive to SBS
Jaakkola and Miettinen, 1995	Cross-sectional study of 14 buildings with 399 workers (46% men, 54% women). Mechanical ventilation without air recirculation or humidification. Ventilation rates were classified into four groups based on flow rates in L/s per person: very low $\leq$ 5; low = 5–15; medium = 15–25; high $\geq$ 25	Dose-response relationships of specific symptoms (eye and nasal symptoms, allergic reactions) and ventilation rate category were found below 25 l/s per person. There was a trend towards decreased symptoms with increasing ventilation rate. Ventilation rate increases above 25 l/s per person were associated with significant increases in the prevalence rates of a few symptoms and nonsignificant increases in the prevalence of all other symptoms
Menzies et al., 1993	Intervention study in four mechanically ventilated office buildings, with 1546 office workers. Average high outdoor air ventilation rate was 32 l/s per person. Average low value was 15 l/s per person. Indoor CO_2 level changed from 1000 to 600 ppm(v)	Suggest that changes in *high* ventilation rates are not associated with reduced SBS symptom prevalence
Milton et al., 2000	Cross sectional study in 40 buildings, covering 115 work areas and 3720 employees. Mechanical ventilation with high rates (24 l/s per person) and moderate rates (12 l/s per person)	Short-term sick leave rates were reduced by 35% at an outside air ventilation rate of 24 l/s per person compared to 12 l/s per person
Myatt et al., 2004	Longitudinal study in three office buildings in Boston area, 200 adults. Measured CO_2 levels (as surrogate for ventilation rate per person). Collected airborne rhinovirus from building filters for 20 months. Variable air volume HVAC system in one building; constant air volume HVAC system in two others. No additional humidification. Ventilation system adjusted every 3 months to change outdoor air supply rates. Rates determined using average CO_2 differences between indoor and outdoor air and number of building occupants	Probability of detecting airborne rhinoviruses was positively associated with weekly average CO_2 differential in the office. Supportive evidence for the earlier paper (Milton et al., 2000) on short-term sick leave
Stenberg et al., 1994	Case–control study with questionnaire in 412 rooms located in 160 buildings in northern Sweden. Studied 464 workers: 232 cases and 232 matched controls, with 83% women in each group. Cases reported at least one SBS symptom per month and one dermal and one mucosal symptom per week. A recall period of 3 months was used. Controls had fewer symptoms. Pair-matched with cases by age (±5 year), gender, geographical area. All cases and controls had <1 h of video display work per day. Ventilation measurements were made using a bag method for supply airflow rate, a hot wire anemometer, or tracer decay using N_2O as the tracer gas	Found a significant association between ventilation and SBS symptom prevalence. Suggests 'monotonic dose-response' relationship between risk of SBS symptoms and ventilation rates over range of 2 l/s per person to 60 l/s per person, but with substantial scatter

Table 2 (Continued)

Reference	Study characteristics	Panel findings
Sundell et al., 1994a,b	Studied same 160 office buildings in northern Sweden as Stenberg et al. (1994). Ventilation rates measured at room level via physical flow rate measurement or tracer decay. Considered SBS symptoms using two approaches: (i) cross-sectional (CS) investigation assessed association of symptom prevalence with ventilation rate in building; (ii) case–control investigation assessed risk of being a case vs. room ventilation rate. Cases reported at least one general symptom per month, one mucous membrane symptom per week, and one skin symptom per week over previous 3 months. Health outcomes of CS study were prevalence rates of general, mucous membrane, and skin symptoms. Cross-sectional analysis had 725 women in 27 buildings and 625 men in 24 buildings. Multivariate analyses in case–control study had 266 adult office workers; crude case–control analyses had up to 414 subjects. Most study rooms (93%) had mechanical exhaust and supply ventilation with or without heat recovery. A small fraction had only mechanical exhaust or natural ventilation. Ventilation rates (L/s per person): mean ± standard deviation = 17 ± 13; range = 5–45	Study found a significant association between lower ventilation rates and increased SBS symptom prevalence. Study results suggest a 'monotonic or dose-response' relationship between prevalence of SBS symptoms and ventilation rates over the range 5 to 45 l/s per person, but with substantial scatter. Study provides strong evidence of increased risks of adverse health at lower ventilation rates and is suggestive of a dose-response trend
Wargocki et al., 2000	Experiment in which subjects performed tasks following a strict protocol. Five groups of six female subjects were exposed to three ventilation rates, one group and one ventilation rate at a time. SBS symptoms were assessed by questionnaire. Mechanical ventilation provided with an axial fan mounted in one of the windows providing 3, 10 or 30 l/s per person, resulting in CO_2 levels that were 1270, 480, or 200 ppm(v) above outdoor levels	Demonstrated an association between four of twenty symptoms and ventilation rate in laboratory experiments. These 'experienced' subjects may not have been fully blinded. Also, the presence of a strong pollution source was noted
Wargocki et al., 2004	Intervention study investigating performance and SBS symptoms of 26 operators at a call centre. Mechanical ventilation with rates of 2.5 or 25 l/s per person	Increased outdoor airflow rate decreased 2 of 17 symptoms with a new filter but not with a dirty filter. Reported outdoor airflow from mechanical system changed between 8 and 80% of 3.5 ach, and difference between indoor and outdoor CO_2 varied between 250 and 800 ppm(v)

SBS, sick building syndrome.

living in dwellings with lower ventilation than the control or noncase groups to which they were compared. Taken as a whole, these studies suggest an association between a low ventilation rate ($<0.5\ h^{-1}$) and allergic symptoms, but the data are limited, and the results not fully consistent.

Bornehag et al. (2005) found a dose-response relationship between higher ventilation rates and a lower prevalence of allergies, although the authors characterized the linkage as weak, possibly owing to the low statistical power of the study. Øie et al. (1999) reported finding no direct association between a low ventilation rate ($<0.5\ h^{-1}$) and bronchial obstruction, but the authors reported that the associations of bronchial obstruction with strong indoor sources of air pollution were enhanced in homes with low ventilation rate. Emenius et al. (2004) reported that no association was found between measured ventilation rate and wheeze, but they did find significant associations between potential indicators of a low ventilation rate (e.g., high indoor air humidity and condensation on window panes) and wheeze.

In the only relevant study of adults in residences, Norbäck et al. (1995) studied asthmatic symptoms and short-term CO_2 levels. The results are suggestive of an association between the mean of the 30-min CO_2 levels in the bedroom and living room and occupant reports of 'nocturnal breathlessness.' Levels of CO_2 for those with and without symptoms were 1020 and 850 ppm(v), respectively; CO_2 levels exceeded 1000 ppm(v) in 26% of the dwellings studied. The relationship between reported CO_2 levels 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.

Offices

The panel found 15 papers to be conclusive, reporting on 12 studies of the office environment: four from the USA, three from Finland, two from Sweden, two from Denmark and one from Canada (Table 2). Twelve papers addressed SBS symptoms, one focused on upper respiratory symptoms, and two were concerned with sick leave. One of the studies from Denmark was based on exposure experiments conducted in climate chambers.

Four studies — one in USA (100 buildings, 4326 individuals, response rate 85%; Apte et al., 2000; Erdmann and Apte, 2004), one in Finland (14 buildings, 399 individuals, response rate 81%; Jaakkola and Miettinen, 1995), and two in Sweden (210 buildings, measurements in 160, 5729 individuals, response rate 96%; Stenberg et al., 1994; Sundell et al., 1994a,b) — show a dose-response relationship between the prevalence of SBS symptoms and outdoor airflow rate. Taken together, these studies indicate benefits from increased ventilation up to about 25 l/s per person. An

Table 3 Articles relevant to schools

Reference	Study characteristics	Panel findings
Shendell et al., 2004	Associations between ventilation rate and absenteeism in 409 traditional and 25 portable classrooms in 22 schools in Idaho and Washington. All but two classrooms had individual ventilation units. Measured indoor minus outdoor difference in CO_2 level (dCO_2) as an indicator of per-person ventilation rates during occupancy. One time, short-term (<5 min) measurements made over a wide range of times throughout the school day	Strong evidence of an association between high short-term dCO_2 [0–3500 ppm(v)] and absenteeism. A concern is that the measured CO_2 level may be less than steady-state value, which would lead to overestimation of ventilation rates
Smedje and Norbäck, 2000	Questionnaire administered to 1476 primary school students in 100 classrooms in 39 schools, comparing the schools in 1993 and 1995. Among the schools studied, 12% received new ventilation systems between 1993 and 1995. Ventilation rates were characterized by system type: seven schools had new systems with an average change in ventilation of +11.5 l/s per person and 50 had no new system with an average change of +0.5 l/s per person. In 1993, 77% of classrooms did not meet Swedish standard of 8 l/s per person and CO_2 levels below 1000 ppm(v); this proportion was reduced to 65% by 1995	Decreased asthmatic symptoms reported when moved to classroom with increased ventilation rate. However, because many factors other than ventilation rate may have differed between the original and new ventilation systems, no definitive conclusions about the effects of ventilation rate are possible. Ventilation rate results lacked clear information on timing of measurements, method and measurement uncertainty
Wålinder et al., 1997a,b	Cross-sectional study involving 27 school personnel: 15 in a school with natural ventilation with a low air change rate (0.6 h^{-1}; 2.5 l/s per person); 12 in a school with mechanical ventilation and high ventilation rates (5.2 h^{-1}; 8.9 l/s per person). Acoustic rhinometry used to determine cross-sectional areas and volumes of nasal cavity. Questioned by physician: social status, occupational data, disease, allergy, atopy, smoking, medication	Findings suggestive of an effect of increased nasal congestion at low air-exchange rate. Limited by small number of subjects and of schools studied
Wålinder et al., 1998	Study examined relationships between nasal symptoms, nasal mucosal swelling and lavage biomarkers, and degree and type of ventilation. Subjects were 234 school personnel (not students), mean age 45–47, from 12 schools in Uppsala, Sweden. Study period: March 1993–March 1995. Ventilation measurements (tracer decay) made in two selected classrooms of each school during March–May, 1993; repeated January–March, 1995. Air change rates ranged from 0.5 to 5.2 h^{-1} (average 1.9 h^{-1}); corresponding ventilation rates ranged from 1.1 to 9.0 l/s per person (average 4.4 l/s per person). Information on nasal symptoms gathered by self-administered questionnaire. Nasal mucosal swelling measured by acoustic rhinometry. Lavage biomarkers also measured. Examinations made during February 1994 & October–March 1995, to avoid pollen exposures	Suggestive of an association of results from nasal rhinometry and biomarkers from nasal lavage with air exchange rate, but not with ventilation rate per person. No correlation with self-reported symptoms. Suggestive that the effect of low air-exchange rate worsened nasal congestion and biomarkers of swelling

experimental study in one office complex in Finland (Jaakkola et al., 1991a,b) reveals a similar, but less pronounced result, as does the longitudinal study by Chao et al. (2003). In contrast, in the smallest study in this group, Menzies et al. (1993) did not find an association between SBS symptom prevalence and ventilation rates when changing the outdoor airflow rate. However, relatively high ventilation rates were investigated in the Menzies et al. study.

Milton et al. (2000) found that short-term sick leave was reduced by 35% when the outdoor air ventilation rate was 24 l/s per person when compared to 12 l/s per person. Myatt et al. (2004) provides supporting evidence by showing that the probability of detecting airborne rhinoviruses is positively associated with weekly average CO_2 levels in the office. That is, the higher the level of indoor CO_2 (and therefore the lower the per person ventilation rate) the higher was the likelihood of detecting airborne rhinovirus.

In a climate-chamber study, Wargocki et al. (2000) found a lower prevalence of SBS symptoms at per person ventilation rates of 30 l/s when compared with 10 and 3 l/s. In an experimental study in a call centre, increased outdoor air ventilation (from 2.5 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., 2004). These results suggest that a dirty filter in a ventilation system can be a source of pollutants that have health significance.

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 reduced prevalence of SBS symptoms and sick leave. This general result emerged even though outdoor air contains potentially important pollutants in some of the locations studied. It is also noted that most studies in this group include no (or limited) information about outdoor air quality or about indoor pollutant sources.

Schools

The panel found five relevant articles for schools, one US study and four from Sweden (Table 3). The US study (Shendell et al., 2004) investigated the association between lower ventilation rates and increased student absence, and the four Swedish studies investigated the impact of lower ventilation rates in schools on asthma, nasal and respiratory effects.

Table 4 Articles relevant to communicable respiratory infections

Reference	Study characteristics	Panel findings
Brundage et al., 1988	Longitudinal and cross-sectional study at four US army training centres. Modern barracks housed approximately 55 trainees per bay. Older barracks housed approximately 20–25 trainees per bay. Modern barracks had mechanically controlled heating, ventilation and air conditioning. Older barracks had windows and ceiling exhaust fans; some had heating and air conditioning. Ventilation rates of modern barracks were estimated to be approximately 0.9 l/s per person of mechanical outdoor air (approximately 17 l/s per person of total air supply with 5% outdoor air) at maximum occupancy. Older barracks, when mechanically ventilated, had approximately 40% outside air or 6.8 l/s per person assuming the same total air supply as in modern barracks	Suggest 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
Hoge et al., 1994	Cohort study in jails over 4 weeks with nested case–control design to identify risk factors for infection. Building was 13-story, divided into 20–22 cell blocks and housed 6700 male inmates. Ventilation rates based on measured indoor minus outdoor CO_2 levels. Three cell styles had these estimated ventilation rates in l/s per person: Style A - 4; Style B - 2; Style C - 3	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	Studied TB conversion rates in several hospitals in each of four large Canadian cities. One-time CO_2 measurements averaged over all similar occupancy types in each city. Conversion rates for 3-year period compared to average of single ventilation rate measurements for the several facilities in each city	Suggestive of a relationship between lower ventilation rates and higher rates of tuberculosis infection of hospital workers. Uncertain accuracy and adequacy of ventilation rate measurements, which were extended to the past in the analysis

Smedje and Norbäck (2000) studied students in approximately 100 classrooms in 39 randomly selected schools with repeated measurements in 1993 and 1995. In between, 12% of the classrooms received a new ventilation system that increased the air change rate from 0.5 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 replacement of ventilation systems, not simply an increase in ventilation rates with the ventilation system unchanged. Because ventilation system type and features have been associated with respiratory symptoms, the panel concluded that this study provides suggestive information about the association of ventilation rates with symptoms.

Wålinder et al. (1997a,b) reported results from a small study showing increased nasal congestion at lower air change rates but not in terms of ventilation rate per person. A later study confirmed the findings of an association between lower air change rates and increased nasal congestion (measured, not self-reported) in a study of 12 schools involving 234 adult subjects. Again, no association was found with ventilation rates per person (Wålinder et al., 1998).

Shendell et al. (2004) explored student attendance in relation to dCO_2 (the difference between simultaneously measured indoor and outdoor CO_2 level) in 434 classrooms in the states of Washington and Idaho, USA. A 1000 ppm(v) increase in dCO_2 was associated with a 0.5–0.9% decrease in annual average daily attendance after controlling for many other factors known or suspected to be associated with absence.

In sum, these articles suggest that low ventilation rates in schools are associated with increased absenteeism and more respiratory symptoms in school children. However, the available data are too limited for firm conclusions.

Communicable respiratory infections

Three conclusive studies on this topic have been conducted in distinctive building types: army barracks (USA), a jail (USA), and hospitals (Canada) (see Table 4). One paper from the United States compared the prevalence of respiratory illness, during a 47-month period, among army trainees living in barracks (Brundage et al., 1988). Some barracks were new with low rates of mechanical outdoor air supply and windows infrequently opened, and some were older with higher rates of mechanical air supply and/or frequent use of windows. Rates of febrile acute respiratory disease were significantly higher among persons living in the new barracks (relative risk of 1.51, with 95% confidence interval 1.46–1.56). Another article from the United States (Hoge et al., 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 inverse association between an air change rate below 2 h^{-1} and tuberculosis infection among hospital workers in general patient areas. Collectively, these studies suggest a relationship between low ventilation rate and increased risk for airway infections.

Discussion

Papers deemed conclusive generally indicated that a low ventilation rate is associated with an increased risk of allergies, SBS symptoms and respiratory infections although not all studies found significant associations. In general, ventilation rates lower than approximately 25 l/s per person in offices were found to be associated with an increased risk of SBS symptoms. One study (Jaakkola and Miettinen, 1995) reported that increases above 25 l/s per person were associated with statistically significant *increases* in the prevalence rates of a few symptoms; however, overall, the data on symptoms at ventilation rates above 25 l/s per person are too sparse to support broad conclusions about high-ventilation conditions.

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 required minimum 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 would result in increased first costs and energy costs, thus elevating the costs of operating buildings. But the health-related economic benefits may greatly outweigh the energy costs (Fisk and Rosenfeld, 1997; Mendell et al., 2002). Furthermore, an increase in ventilation rates might not be essential to limit SBS symptom prevalence if effective control of indoor pollutant emission sources (Wargocki et al., 1999) or other control measures, such as effective air cleaning, could be used to reduce indoor pollutant concentrations.

The limited available data suggest that household ventilation rates lower than 0.5 air changes per hour in cold climates are associated with increased risks of negative health outcomes. However, for schools and day care centres, little data exists.

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: volumetric airflow rate measurements in ducts, tracer-gas techniques and measurement of the indoor carbon dioxide concentration increment above the outdoor level. It is important to note that measuring building and space ventilation rates in the field can be challenging and that each of the techniques employed has limitations.

In most of the studies cited in this review, important details describing the ventilation 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. Overall, the problems identified included an incomplete description of the measurement method used, limited (or no) description of the instruments employed and no estimates of the uncertainty associated with the reported ventilation rates. Whether or to what extent these omissions impact the conclusions of this analysis is unclear, but the concerns 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 research. 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 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 internally controlled 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. For example, a study by Menzies et al. (1993) investigated two ventilation-rate conditions: 14 and 30 l/s per person. In that study, no effects of ventilation rate on health were observed. In two other experimental studies (Jaakkola et al., 1991a,b; Wargocki et al., 2000), a broader range of outdoor air supply rate (range 0–30 l/s per person) was investigated, and a positive effect of increased ventilation rates on health indicators was observed.

Cumulatively, this review indicates that relatively few studies explicitly inform the relationship between building ventilation rates and health outcomes. We judged only 27 papers among those reviewed as providing sufficient scientific evidence to help inform such effects. Considering the importance of ventilation rate as an influencing factor for the quality of indoor air and the diverse range of building types and health outcomes that may be influenced by indoor environmental quality, the number of conclusive investigations of the effects of ventilation rates on health outcomes is simply too small. More studies that are carefully designed and well executed to study the potential relationships would be valuable. This finding applies especially to schools and to homes where few studies have been carried out relative to the importance of these settings for public health. Although limited in scope, reviewed articles revealed poor ventilation conditions to be common in schools and homes, in relation to requirements in guidelines and standards (Bornehag et al., 2005; Smedje and Norbäck, 2000).

Most of the school studies were conducted in Sweden, an economically strong country with a high public commitment to social welfare. Even so, the studies in Sweden suggest a negative health impact of current practices that could be alleviated by increased ventilation rates. A similar situation appears true with ventilation in homes where studies, conducted mainly in Nordic countries, suggest that a low ventilation rate was associated with increased risk of allergies. Schools and homes in other areas with cold winter climates may also have ventilation rates as low as in Nordic countries (as influenced by energy conservation goals), but actual measurements of ventilation rates have rarely been performed. The limited results from homes and schools do suggest, however, a potential public health concern: more allergies and other adverse health consequences may result from measures that reduce ventilation rates (Harving et al., 1993; Norbäck et al., 1995; Smedje and Norbäck, 2000; Sundell et al., 1995). This finding is relevant as current programs promoting energy efficiency in buildings have the potential to reduce ventilation rates in homes and other buildings.

Thermal conditions and their potential effects were not examined in this review. Most of the reviewed studies were carried out in other-than-summer months and therefore are not informative about potential 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 health 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 reviewed studies assessed the impact of building ventilation rates on the risks of serious chronic health effects, such as cancer, which have been associated with indoor air pollutants. Studies on such outcomes would need a far longer timeframe than has been employed in studies to date. To the extent that indoor sources emit carcinogens (e.g., formaldehyde, benzene, benzo[a]pyrene) or other pollutants with chronic health effects, one would anticipate that reduced ventilation rates would increase such risks. However, the absence of data precludes any conclusions on this matter.

There is a lack of good studies that have measured natural ventilation rates in offices and their relationship with health. In a large majority of comparison studies, SBS symptom prevalence rates are lower in naturally ventilated buildings than in mechanically ventilated, air-conditioned buildings, despite the limited evidence that particle and viable fungi concentrations are higher in naturally ventilated buildings (Seppänen and Fisk, 2002). Studying this apparent contradiction is an important research need.

When evaluating the effects of ventilation rates on health, it is important to be mindful of the quality of the outdoor air used to provide ventilation. Numerous epidemiological studies have demonstrated associations between pollutants in outdoor air (primarily PM_{10}, $PM_{2.5}$ and ozone) and both morbidity and mortality (Bell et al., 2006; Dominici et al., 2006; Pope and Dockery, 2006). The studies reviewed here generally did not consider the potential for adverse health outcomes to be associated with higher exposure to outdoor air pollutant concentrations. Increased ventilation means increased outdoor-to-indoor transport of outdoor pollutants (Weschler, 2006). In locations with highly polluted outdoor air, there may be ventilation-rate-mediated tradeoffs between health risks from outdoor pollutants and those from indoor sources.

Implications for standards and guidelines

This study was not intended to yield a particular ventilation rate for use as minimum value for regulation. Nevertheless, while the number and thoroughness of published studies limit this review's conclusions, the findings may still inform ongoing efforts to develop and revise ventilation standards and related guidance documents. Such standards, particularly those intended for regulatory use, are appropriately motivated by health-effect risks, but they are also developed with consideration of other factors not addressed in this review, such as occupant comfort and odour perception, economics and the limitations of current technology.

The review's results suggest that lowering existing minimum ventilation rates would generally be inappropriate, as suggestive evidence indicates that higher rates than are currently common may be health-protective in many instances. There is evidence that lower rates will generally increase risks of SBS symptoms in offices, both in North America and in northern Europe, and also exacerbate other health effects, such as asthma and allergy symptoms in residences.

The results provide some support for having higher rates in standards and guidelines that aim for a higher level of indoor environmental quality, although an appropriate level of increase cannot be determined without regard to the quality of outdoor air and the potential for improving ventilation air through filtration and other air-cleaning technologies. Health benefits of higher rates may be more likely to occur in places where outdoor air quality is very good. A large fraction of the reviewed studies were conducted in the Nordic countries or in the United States where outdoor air quality is better than in many parts of the developing world. Any recommendations to increase ventilation must address the issue of poor ambient air quality and not just assume that more outdoor air will necessarily improve indoor environmental quality.

Research needs

Achieving sufficient ventilation is a fundamental need for buildings that are intended for human occupancy. While the articles identified in this review support a positive benefit with ventilation rates above current ASHRAE ventilation standards, there is a dearth of well-designed studies that adequately account for the multiple factors encountered in typical indoor environments. Research in this field has made only limited progress, in part because of difficult methodological challenges and also because of a lack of dedicated funding. Many research needs were identified by the group and are briefly noted here.

- There is an overarching need to expand the scope of studies on the relationship between ventilation rates and health to more diverse regions of the world. The greatest need is to include buildings in hot and humid climates where a significant fraction of global population is found and to include other situations differing from those in North America and northern Europe. Special attention should be paid to the different ways indoor environments are ventilated and conditioned. These studies should include all the building types where people spend extensive time. In this context, there is a growing need to address the challenges presented by increasing pressures from sustainability and energy considerations.
- Schools, day care centres and homes need to be studied more extensively everywhere.
- There is a need to look at different types of ventilation systems, fraction of recirculated air, air cleaning and filtration technologies, and humidification as well as the hygienic state of HVAC systems.
- There is a need to look at HVAC systems with air conditioning that lack an adequate outdoor air intake, which is typical of many smaller buildings.
- There is a need to examine the health effects of ventilation in locations with highly polluted outdoor air, especially those with high concentrations of $PM_{2.5}$ and ozone.
- Types 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. Reported 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 an incomplete understanding of the nature of that relationship. Uncertainty as to the form of the ventilation–health relationship is an important limitation in establishing rational 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 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 building environments studied.

The 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 indoor pollutants.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1 Part I: Papers reviewed by the expert panel with overall findings from the workshop (I, informative, conclusive; S, suggestive; N, non-informative or not relevant). II: References from archival literature retrieved during literature acquisition.

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Appendix 1: Description of literature search

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.

- *Primary search criteria*: Peer-reviewed journal articles containing measurements of both ventilation rates and health outcomes. No reviews or case studies were included.
- *Date range*: The primary search was conducted for the period 2000–2005, post-dating prior reviews. A supplemental search was conducted for prior years.
- *Journals and databases*: An initial search of selected individual journals 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.
- *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

1.1) 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.

- *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. Journal titles in the initial search are listed in Table 1.2 with added notes.

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

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.

Table 1.1. 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*
Airflow	Environmental illness*	Residence*
Air supply	Allergy*	Office*
Supply air	Asthma	School*
CO_2	Disease*	Hospital*
Carbon dioxide	Illness*	Chamber
Outside air	Irritation	Sick building*
Indoor air	Infection*	Building-related illness*
	Absenteeism	

[a]'*' indicates a wildcard in the search term.

Table 1.2. Journals titles in the initial search

Journal title	Journal title	Journal title
Acta Derm Venereol	*Building and Environment*	*J Allergy Clin Immunol*
Acta Otolaryngol	*Building Res and Info*	*J Am Geriatric Society*
Allergy	*Can J Pub Health*	*J Arch Plann Environ Eng*[a]
Am J Epidemiol	*Central African J Med*	*J Arch Plann Res*
Am J Infect Control	*Energy and Buildings*	*J Clin Epidemiol*
Am J Pub Health	*Environment Internat*	*J Expos Anal & Env Epid*
Am J Resp Crit Care Med	*Environmental Health Persp*	*J Infect Diseases*
Am Rev Resp Dis[b]	*Environmental Res*	*J Occup Med*
Ann Am Conf Gov Indust Hygienists[c]	*Environmental Tech*	*J Occup Environ Med*
Ann Occup Hyg	*Epidemiology*	*NEJM*
Appl Occup Environ Hyg	*Indoor Air*	*Occup Environ Health*
Archives of Environmental Health	*Indoor Environ*[d]	*Occup Environ Med*
ASHRAE Transactions	*Int Arch Occup Environ Health*	*Occup Med*
Atmospheric Environment	*Int J Energy Research*	*Public Health Rep*
Br J Indust Med[e]	*Int J Epidemiol*	*Resp Med*
Br Med J	*J Air & Waste Manag Assoc*	*Scand J Work Environ Health*

[a]Split in 2003: *J Arch & Plann* and *J Environ Eng* [Japanese].
[b]Ceased publication 1993, see *Am J Resp Crit Care Med* 1994–.
[c]Ceased publication 1988.
[d]Became *Indoor + Built Environ* 1996–.
[e]Ceased publication 1993, see *Occ & Env Med* 1994–.

Appendix 2: Note on recent publications

The review reported in this article was conducted in 2006 and reviewed the literature published through 2005. We have conducted a supplemental search for publications from January 2006 through August 2010. The results of that search include the following relevant articles:

Apte, M.G., Buchanan, I.S.H. and Mendell, M.J. (2008) Outdoor ozone and building-related symptoms in the BASE study, *Indoor Air*, **18**, 156–170.

Fisk, W.J., Mirer, A.G. and Mendell M.J. (2009) Quantitative relationship of sick building syndrome symptoms with ventilation rates, *Indoor Air*, **19**, 159–165.

Fraga, S., Ramos, E., Martins, A., Samúdio, M.J., Silva, G., Guedes, J., Oliveira Fernandes, E. and Barros, H. (2008) Indoor air quality and respiratory symptoms in Porto schools, *Rev. Port. Pneumol.* **14**, 487–507. (In Portuguese and English).

Mi, Y-H. Norbäck, D., Tao, J., Mi, Y-L., and Ferm, M. (2006) Current asthma and respiratory symptoms among pupils in Shanghai, China: influence of building ventilation, nitrogen dioxide, ozone, and formaldehyde in classrooms, *Indoor Air*, **16**, 454–464.

Norbäck, D. and Nordström, K. (2008) Sick building syndrome in relation to air exchange rate, CO_2, room temperature and relative air humidity in university computer classrooms: an experimental study, *Int. Arch. Occup. Environ. Health*, **82**, 21–30.

Simoni, M., Annesi-Maesano, I., Sigsgaard, T., Norbäck, D., Wieslander, G., Nystad, W., Canciani, M., Sestini, P. and Viegi, G. (2010) School air quality related to dry cough, rhinitis and nasal patency in children, *Eur. Respir. J.*, **35,** 742–749.

Zuraimi, M.S., Tham, K.W., Chew, F.T. and Ooi, P.L. (2007) The effect of ventilation strategies of child care centers on indoor air quality and respiratory health of children in Singapore, *Indoor Air*, **17**, 317–327.