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The Effects of Ventilation in Homes on Health

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Abstract

It is estimated that people in the developed world spend more than 85-90% of their time indoors. Of this, most is spent in homes. To minimize health risks from pollutants occurring in homes, exposures should be controlled. The most effective way to achieve this is to control sources of pollutants and to reduce emissions. Often, especially in existing buildings, this strategy is difficult to implement, in which case exposures are controlled by providing sufficient, presumably clean, outdoor ventilation air to dilute and remove the contaminants.

The present paper attempts to find out how much ventilation is needed in existing homes to reduce health risks. This is achieved by reviewing the published scientific literature investigating the association between measured ventilation rates and the measured and observed health problems.

The paper concludes that, generally, there are very few studies on this issue and many of them suffer from deficient experimental design, as well as a lack of proper characterization of actual exposures occurring indoors. Based on the available data, in the reviewed studies, it seems likely that health risks may occur when ventilation rates are below 0.4 air changes per hour in existing homes. No data were found indicating that buildings having dedicated natural ventilation systems perform less well than the dwellings in which mechanical ventilation systems are installed. Newly installed mechanical ventilation systems were observed to improve health conditions. In homes with existing ventilation systems this positive effect was less evident, probably due to poor performance of the system (too low ventilation rates and/or poor maintenance).

Studies are recommended in which exposures are much better characterized (by for example measuring the pollutants indicated by the WHO Guidelines for Indoor Air Quality and improving ventilation measurements). Exposures should also be controlled using different ventilation methods for comparison. Future studies should also advance the understanding of how ventilation systems should be operated to achieve optimal performance. These data would create further input and support to the guidelines for ventilation based on health developed currently in the framework of the HealthVent project (www.healthvent.eu).

Key words: ventilation, ventilation rate, ventilation system, housing, homes, health, pollutants.

1. Introduction

1.1 Background

How much ventilation is needed indoors and which requirements should be used to design ventilation? These two questions have been high on the research agenda for years. They can be readdressed again especially when strict requirements for energy use in buildings are implemented and when there is a need to make buildings tight and energy efficient (EPBD, 2010) so that the quality of life is not compromised (e.g., Fisk et al., 2011; Wargocki, 2011).

Undoubtedly human responses should be used to define ventilation requirements. However, it is relevant to ask whether comfort requirement should be used, as has been the case for years in many ventilation standards and guidelines (EN15251, 2007; ASHRAE, 2010; ECA, 1992), or if ventilation requirements should be based on health outcomes. It may be argued that both are the same thing if the World Health Organization's (WHO) definition of health is considered (1948). Still the link between comfort and health is not clearly established and it is not certain whether ensuring comfort requirements will abate health risks and vice versa.

Ventilation modifies exposures occurring indoors. It cannot reduce the emissions. It is used to dilute and remove the pollutants occurring indoors. For some pollutants the effectiveness of ventilation can be quite high, and for some pollutants it can be rather low. Ventilation can also bring the outdoor pollutants that are otherwise not present indoors. Consequently, ventilation requirements should be defined based on the exposures occurring indoors. The ventilation requirement can be estimated based on the emission rates of pollutants, so that the pollutants occurring indoors are at levels without concern for human health and comfort. The problem is that there are very limited data on the relationship between pollutants occurring indoors, their concentrations and health (WHO, 2010). Even if the data for all pollutants were available, it would be difficult to take into account all possible interactions between pollutants, reactions occurring between pollutants and all potential transformations.

A pragmatic approach for setting ventilation requirements can be proposed by observing, in real buildings, whether there is an elevated risk for health and comfort complaints in the case when the ventilation rate is at or below a certain level; this approach is now being exercised by the HealthVent project (Wargocki et al., 2012). The disadvantage of this approach is that buildings can differ between each other in terms of exposures and pollutants occurring indoors, as well as by other factors which are difficult to control, such as temperatures, moisture level and relative humidity (RH), noise, light, surroundings, etc. They all potentially can have an impact on human response and can obscure the relationship with ventilation. Furthermore, different buildings can be populated by different people and thus the experimental observations from these buildings may not be representative for the general population.

Several studies have been carried out to investigate the relationship between ventilation and human responses both in the laboratory and as field studies. Summaries and critical assessments can be found in many reviews published previously (e.g., Mendell, 1993; Godish and Spengler, 1996; Seppänen et al., 1999; Seppänen et al., 2002; Wargocki et al., 2002; Davies et al., 2004; Angell et al., 2005; Richardson et al., 2005; Grimsrud, 2006; Bonnefoy, 2007; Li et al., 2007; Bone et al., 2010; Sundell et al., 2011). An important limitation of the previous studies on ventilation and health is that they have each used different methods to characterize ventilation and

human response outcome. This makes it very difficult to compare the results obtained in these different studies. In some studies proxies for ventilation were used, such as the concentration of carbon dioxide (CO₂), as well as proxies for human response outcomes, such as the concentration and prevalence of house dust mite (HDM) allergens because there is consistent evidence that the prevalence of HDM allergens increases the risk of asthma. Another predicament is that when the performance of different ventilation systems were compared in different buildings there was insufficient control for potentially disturbing factors such as differences in exposures to air pollutants. In spite of these limitations the previous studies provide direct data on the importance of ventilation for human health and comfort.

The present work tries to recapitalize on the results of these past studies and reviews, particularly with regard to the importance of ventilation for health in residential buildings.

1.2 Objective

The main objective of the present work was to prepare a state-of-the-art report on ventilation and health in homes. In particular, the following research questions were addressed: (i) Does a relationship exist between health and ventilation in residential buildings?; (ii) What is the potential reason for the observed relationship?; (iii) Which health problems are related to ventilation?; (iv) Are there any differences in prevalence of health symptoms in residential buildings having different ventilation systems?; (v) Are there any differences in the prevalence of health problems among different population groups?; and (vi) Does ventilation itself contribute to the pollution of indoor air in residential buildings?

2. Method

2.1 Approach

To address these research questions the following approach was implemented: (i) hypotheses and search terms were defined; (ii) a literature search was performed; (iii) abstracts of all identified papers and reports were screened; (iv) literature was grouped as follows: literature providing information on ventilation and its proxies, and health and its proxies; literature providing information on exposure ventilation and its proxies, but not on

health and its proxies; surveys and reviews; and literature not relevant for the objective of the present work; (v) reference lists in surveys and reviews were screened to identify whether there were any other papers that were missed in the literature search, and if so they were included; and (vi) papers providing information on ventilation and health, addressing the objective, were reviewed and used to form conclusions.

2.2 Literature Survey

Scientific literature on the association between ventilation and health in nonindustrial residential indoor environments was gathered by searching through the following databases: MEDLINE by National Library of Medicine; Cambridge Scientific Abstracts (including Mechanical Engineering Abstracts, Environmental Sciences and Pollution Management Search sub-files, Biological Sciences Search sub-files, TOXLINE, ERIC, Computer and Information System Abstracts) and AIRBASE by the Air Infiltration and Ventilation Centre (AIVC). In addition, the Proceedings of Indoor Air, Healthy Buildings, RoomVent, AIVC and CLIMA congresses taking place in the last 10 years, i.e. since 1999 were also surveyed.

The term “ventilation” was considered as both the ventilation rate, i.e. amount of outdoor air supplied to indoor spaces, and as the ventilation system, i.e., the way the air is supplied to indoor spaces – using natural or mechanical forces, or combined, with or without air-conditioning (AC). Proxies for ventilation were also accepted including concentration of CO₂. Information on condensation on windows was collected as a proxy for elevated RH and low ventilation rate, but no specific term was created for relative humidity in order not to obscure the search. Health was considered to follow the basic definition of the World Health Organization (WHO, 1948): health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. Proxies for health were also accepted, i.e. pollutants for which there are documented effects on health such as concentration of HDM allergens, radon, etc. Nonindustrial residential indoor environments were considered to represent all kinds of housing: dwellings, row houses and detached houses.

Only papers including records in each of the three search categories were selected (as a source of search records, keyword indexes of the international

conferences Indoor Air '90, '93 and '99, and Healthy Buildings '97 and '00 were used): (1) the category “ventilation” including different records pertaining to ventilation rates, e.g., air change rate, air supply rate, etc., as well as ventilation systems, e.g., infiltration, dedicated natural ventilation, mechanical ventilation, etc.; (2) the category “environment” including different records pertaining to nonindustrial residential indoor environments, e.g., dwellings, houses, etc.; and (3) the category “health” including different records pertaining to health, e.g. symptoms, diseases, allergy, asthma, etc.; comfort and productivity were not included.

3. Results

More than 140 papers and reports were identified through the literature search. Among these, 34 documents were considered to provide information relevant for the objective of the present work; their details are given in Table 1. As many as 20 reviews and surveys were identified on the topic of ventilation and health. More than 60 papers were irrelevant for the present work.

3.1 Asthma and Allergy Symptoms

Several studies, in some cases with large cohorts, have been carried out to observe whether there is an association between ventilation and asthma and allergy symptoms. The results are inconsistent.

In studies with children, low ventilation rates were strongly associated with increased risk of having self-reported asthma and allergy symptoms (at least 2 out of 3 symptoms such as wheezing, eczema and rhinitis) when conditions in homes of children with symptoms (cases) and children without symptoms (controls) were compared (Bornehag et al., 2005; Hägerhed-Engman et al., 2009). The odds ratios (indicating the risk) for wheezing and rhinitis were significantly lower among infants in homes where heat recovery ventilators were installed; similarly there were reduced CO₂ levels compared with homes with placebo units without such a system (Kovesi et al., 2009). Nocturnal chest tightness in adults, a symptom of problems with the respiratory system as a consequence of asthma, was associated with higher CO₂ levels indicating lower ventilation rates in homes (Norbäck et al., 1995). Improper ventilation defined as a ventilation problem was associated with elevated risk of asthma (Ezratty et al., 2003).

*Table 1. Short summary of studies considered relevant for the purpose of the present work;
 AC=air conditioning; PM=particulate matter; GLM=general linear model; RR=response rate;
 SBS=Sick Building Syndrome; HDM=house dust mites; RH=relative humidity; PFT=perfluorocarbon tracer;
 SARS=severe acute respiratory syndrome; CFD=computational fluid dynamics.*

Reference	Results	Design	Buildings	Population	Ventilation rate	Ventilation type	Health endpoints
Bell et al. 2009	Presence of AC reduced PM exposure and associated health effects	Cross-sectional, analysis through GLM	Houses (ca. 55,000 households)	Elderly (>65 years old); 55,000 households	N/A	N/A, only whether AC present or absent (from registers)	Mortality and PM10; cardiovascular and respiratory hospitalizations and PM2.5
Bornehag et al. 2005	Lower ventilation rates associated with the risk of being the case (having asthma and allergy symptoms)	Case-control	390 houses	198 cases and 202 controls (from cohort of 14,077)	Measured with PFT method; median 0.34 h ⁻¹ (cases) 0.38 h ⁻¹ (controls)	With mechanical system present and absent	Self-estimated asthma/allergy symptoms: wheezing, eczema and rhinitis
Hägerhed-Engman et al. 2009							
Clausen et al. 2011	Ventilation rate not associated with being case	Case-base	Houses	Children, 200 cases (with asthma and allergy symptoms) and 293 bases among which 15 were cases (from cohort of 11,082)	0.46 h ⁻¹ for cases and bases estimated with CO ₂ measurements	With mechanical system present and absent	Self-assessed asthma and allergy symptoms (wheezing, eczema and rhinitis)
Toftum et al. 2011							
Bekö et al. 2010							
Coelho et al. 2005	Poorly maintained ventilation systems (dirty filters, blocked vents) associated with health complaints	Cross-sectional	Collective social habitat	Elderly (60-95 years old), 96 persons	N/A	Mechanical	Health complaints
Deger et al. 2010	Increased risk of asthma for children leaving along streets with highly dense traffic and on ground floor	Cross-sectional	Homes	Children (n=980 out of 7980)	N/A	Only building factors registered; whether adequate asthma control	Asthma
Drinka et al. 1996	Presence of recirculation increased risk of attack rates of Influenza A	Cross-sectional	4 nursing homes	Elderly (n=690)	N/A	Mechanical with 0%, 30% and 70% recirculation	Influenza A

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Table 1. (continued).

Reference	Results	Design	Buildings	Population	Ventilation rate	Ventilation type	Health endpoints
Emenius et al. 2004	No association between whole-house ventilation and being a case (but with RH and condensation on windows markers of poor ventilation)	Case-control	Homes	Children 181 cases and 359 controls from 4089 BAMSE cohort)	Average $0.68 \pm 0.32 \text{ h}^{-1}$, 69% $> 0.5 \text{ h}^{-1}$ with PFT method	With mechanical system present and absent, mechanical (exhaust only)	Self-assessed recurrent wheezing
Engvall et al. 2003	Presence of mechanical ventilation system reduced ocular and nasal symptoms	Cross-sectional	231 multi-family buildings	3241 of 4815 inhabitants (RR=77%)	N/A	With mechanical system present and absent	Self-assessed ocular, nasal, dermal and respiratory symptoms
Engvall et al. 2005	Reduced ventilation caused the air to be perceived as poor and stuffy but had no effects on SBS symptoms	1-year cross-over intervention	Multifamily building	44 people	$0.5\text{-}0.8 \text{ h}^{-1}$ vs. 25-30% reduced to $0.4\text{-}0.5 \text{ h}^{-1}$	Mechanical	SBS symptoms
Ezratty et al. 2003	Asthma attacks, headache and migraine associated with poor ventilation but can also be caused by other factors	Cross-sectional	3373 households in 8 European towns (LARES survey)	8519 residents	N/A	With forced ventilation system present and absent	Self-assessed health problems
Gustafsson et al. 1996	Children symptoms not associated with type of system; mothers' complaints of poor air quality and mucous membrane symptoms related with condensation on windows	Cross-sectional	Homes	638 children	N/A	With mechanical system present and absent	Self-assessed allergic symptoms
Harving et al., 1993	Reduced ventilation rate increased concentration of HDM because of higher RH	Cross-sectional	Homes	96 families with at least 1 asthmatic	$< 0.25 \text{ h}^{-1}$ vs. $0.25\text{-}0.5 \text{ h}^{-1}$ vs. $> 0.5 \text{ h}^{-1}$ measured with PFT	With mechanical system present and absent	Medical diagnosis of asthma; skin prick test
Harving et al. 1994	Increased ventilation rates reduced HDM and RH	Case-control	Houses	53 asthmatic patients (of which 23 controls)	0.4 to 1.5 h^{-1} measured with PFT	Mechanical	N/A (measured HDM as a proxy)

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Table 1. (continued).

Reference	Results	Design	Buildings	Population	Ventilation rate	Ventilation type	Health endpoints
Howieson et al. 2003	Installation of mechanical ventilation system with heat recovery improved health conditions (reduced HDM and RH)	Case-control	Houses	68 asthmatics <15 years old, 32 +17 in active groups (cases) and 19 as controls	N/A	Mechanical	Health symptoms and self-recorder peak flow (lung functions)
Jacobs et al. 2009	Increased in lead poisoning, asthma and obesity associated with increased use of AC	Cross-sectional, longitudinal	Houses	2 national cohorts	N/A	N/A (national register of changes in use of AC from 1970s to 2000s)	National register of health
Jones et al. 1999	Building factors were not associated with case status	Case-control	Houses	Children, 100 asthmatics from 11,000 matched by age and gender	N/A	N/A (heating methods (incl. ducted heating) and other factors related to IAQ)	Doctor-confirmed asthma, wheeze and hay fever
Kishi et al. 2009	Mechanical ventilation not associated with risks of sick housing syndrome	Cross-sectional	2297 detached houses of 5589 (RR=41.1%)	Residents	N/A	With mechanical system present and absent	Self-assessed sick housing syndrome symptoms
Kovesi et al. 2009	Installation of mechanical ventilation reduced rhinitis and wheeze (and RH) and had no effect on health centre encounters and hospitalizations	Placebo-controlled intervention	51 houses of 68 selected	Inuit infants in 37 homes with placebo and 14 in homes with active ventilation units	CO ₂ measured and averaged 900 ppm with system and 1,400 ppm without	Mechanical	Self-assessed respiratory symptoms and health centre encounters
Leech et al. 2004	Self-assessed throat irritation, cough, fatigue and irritability reduced for cases	Case-control	Cases = 52 houses with energy efficient ventilation and best construction practices; Controls=53 houses in the same price range	Occupants, 128 cases and 149 controls	N/A	Mechanical ventilation system	Self-estimated health symptoms
Li et al. 2005	CFD modelling of wind pressure predicted ventilation rate and virus spread between flats	Simulation by CFD; no measurements	Multi-flat blocks	N/A	N/A	With mechanical system absent	SARS infection rate

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Table 1. (continued).

Reference	Results	Design	Buildings	Population	Ventilation rate	Ventilation type	Health endpoints
Marmor 1978	Risk of mortality doubled during heat waves in homes w/o AC	Cross-sectional, retrospective	Nursing home	6930 residents	N/A	N/A (with or w/o AC)	Mortality rate
Norbäck et al. 1995	At high CO ₂ the prevalence of nocturnal breathlessness (a symptom of asthma) was higher	Cross-sectional	88 homes (51% flats and 40% single family houses)	Adult residents	CO ₂ measured averaged 1,020 ppm (natural) and 850 ppm (mechanical)	With mechanical system present and absent	Self-assessed questionnaire and clinical examination of asthma/atopy
Øie et al. 1999	Low air change rates increased risk of bronchial obstruction	Case-control	Homes	172 cases from Oslo Birth cohort and 172 matched controls	Above and below 0.5h ⁻¹ , measured with PFT (also quartiles 6.9, 11.5 and 17.6 L/s per person)	With mechanical system present and absent	Bronchial obstruction
Palonen et al. 2008	Air was perceived stuffy with natural ventilation and it was noisy with mechanical; natural and exhaust ventilation caused fluctuating temperatures and cold floors	Cross-sectional	102 single family houses	210 adults and 152 children	0.3h ⁻¹ (natural); 0.34 h ⁻¹ (exhaust) and 0.4 h ⁻¹ (mechanical); measured PFT method and in exhaust	With mechanical system present and absent, mechanical (exhaust only)	Self-assessed perceptions
Rogot et al. 1992	Risk of death 42% lower in homes with AC	Cross-sectional, retrospective	Homes	n=72,740	N/A	N/A (with or w/o AC)	Mortality rate
Ruotsalainen et al. 1991	More symptoms in dwellings than in houses; More symptoms in houses with natural ventilation and in dwellings with mechanical ventilation	Cross-sectional	242 dwellings and houses	473 occupants (RR=93.1%)	Houses 0.45h ⁻¹ ; dwellings 0.64h ⁻¹	With mechanical system present and absent	Self-assessed perceptions and SBS symptoms
Sundell 1994	Low air changes rates promoted infestation of HDM	Cross-sectional	29 homes	N/A	0.1h ⁻¹ to 0.8 h ⁻¹ measured with PFT	N/A	N/A (HDM, a proxy for allergic symptoms)

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Table 1. (continued).

Reference	Results	Design	Buildings	Population	Ventilation rate	Ventilation type	Health endpoints
Warner et al. 2000	Installation of mechanical ventilation reduced HDM and RH but no effects on health	Intervention, 12 months	40 houses	27 children and 13 adults	Aimed at 0.4-0.5 h ⁻¹	With mechanical system present and absent (mechanical intensified with vacuum cleaning)	Self-assessed asthma and allergy symptoms; Measured lung functions and bronchial hypo responsiveness
Willers et al. 2006	No associations between health outcomes and sufficient ventilation	Cross-sectional	Homes	647 children at age of 4 from 3,000 birth cohort on asthma and allergy	N/A	Assessment of whether ventilation in kitchen (with gas cooking) sufficient or not	Blood samples, self-assessed respiratory and allergic symptoms
Wong et al. 2004	Prevalence of symptoms was higher in dwellings with AC	Cross-sectional	3 residential dwellings	Generally adults, 105 in naturally ventilated and 58 in naturally ventilated with AC	CO ₂ up to 1,600 ppm in naturally ventilated with AC vs. 550-600 ppm without AC	No mechanical ventilation system (with and w/o AC)	Self-assessed SBS symptoms
Wright et al. 2009	Installation of mechanical ventilation system improved evening peak expiratory flow (not morning), reduced RH but not HDM	Placebo-controlled intervention	Homes	120 adults with asthma	N/A, aimed to provide 0.5 h ⁻¹	With mechanical system present and absent	Peak expiratory flow
Xu et al. 2010	Exhaled breath condensate nitrate concentration reduced ph improved and peak expiratory flow improved when mechanical ventilation units with air cleaner operated	Cross-over intervention	Homes	30 children diagnosed with asthma	CO ₂ averaged 1500 ppm w/o system and 800-900 ppm with system	With and w/o unit with mechanical ventilation system with air cleaner	Exhaled breath condensate and peak expiratory flow
Yu et al. 2004	SARS infection rates matched virus concentrations predicted by simulations using plumes and wind flows	Simulations, no field measurements	High-rise dwellings	N/A	N/A	N/A	SARS infection rates

Contrary to the above no association was observed between ventilation rates in homes of children with asthma and allergy symptoms (cases) and children with and without symptoms (bases) in a study which used a similar approach to that of Bornehag et al. (2005) described above (Clausen et al., 2011). Clausen et al. used a case-base design rather than case-control design and they also used CO₂ measurements to estimate ventilation rates rather than a PFT method used by Bornehag et al. (2005). This could, among other factors, contribute to the different results obtained in both studies which otherwise had the same protocols for registering symptoms. Also, no association between ventilation rate and self-estimated asthma and allergy symptoms was observed when the odds ratios for cases and controls were compared in a study of Emenius et al. (2004) in which the PFT method was used for ventilation rate measurements. In this study RH and window-pane condensation (a marker of elevated humidity) were however associated with the elevated risk of symptoms.

Data on the presence and type of ventilation system and increased risk of self-estimated asthma and allergy symptoms have also shown to be inconsistent. After installation of mechanical ventilation with heat-recovery in homes where no such system was previously present, the risk for symptoms was reduced both for infants (Kovesi et al., 2009) and adolescents (Howieson et al., 2003), but not for the adults and children with asthma (Warner et al., 2000). In the latter study the levels of RH and HDM allergens were, however, reduced. Homes judged to have sufficient or not sufficient kitchen ventilation were not a risk factor for respiratory and allergic symptoms among children (Willers et al., 2006). Neither were the houses with characteristics likely to affect indoor air quality, other than ventilation (Jones et al., 1999), a study that actually did not look specifically at the effect of ventilation. Gustafsson et al. (1996) showed that heating and ventilation systems were not associated with allergy symptoms in children.

Ventilation rate and ventilation system type were in some studies associated with exposures and markers of exposures likely to cause allergic symptoms. One of these markers is the concentration of HDM allergens. Any methods and remedial actions reducing this allergen can be considered as effective methods for improving health conditions. Several studies showed that increased ventilation rate reduced the concentration of HDM allergens (Harving et al., 1993; 1994; Sundell, 1994). Also

installation of a new mechanical ventilation system in homes which did not previously have this system, reduced the concentration of HDM allergens (Warner et al., 2000). This was most likely because the ventilation rates were increased. In these studies no direct measurements of symptoms or complaints among building occupants were made. In some studies increased ventilation rate reduced RH, which was often observed and documented by lack of condensation on window panes. Also proliferation of HDM allergens depends on moisture level and is inhibited when the relative humidity is low. Because both elevated RH and window-pane condensation are indicators of potential dampness problems in homes, which are considered to be strong risk factors for health problems (Bornehag et al., 2001; 2004), these data suggest indirectly that increased ventilation rate can reduce health problems by reducing the moisture level in homes.

3.2 Building-Related Symptoms and Complaints

The presence of mechanical ventilation systems in homes was associated with reduced self-estimated health symptoms, typical of sick building syndrome symptoms among adults, compared with homes without mechanical ventilation (Engvall et al., 2003; Leech et al., 2004; Palonen et al., 2004), probably because of higher ventilation rates. This is implied by Ruotsalainen et al. (1991) who showed that the presence of mechanical ventilation was associated with a lower prevalence of symptoms when the air change rates were higher. Kishi et al. (2009) found no relationship between the existence and operation of mechanical ventilation systems and the risk of building-related symptoms. Maintenance of the mechanical ventilation system could cause the inconsistency between the results from different studies. For example, Coehlo et al. (2005) showed that mechanical ventilation systems in homes having dirty filters, blocked vents, etc. were associated with increased rates of health complaints of elderly people. Also noise generated by the mechanical ventilation system could contribute to complaints and cause the association between mechanical ventilation systems and health complaints to be inconsistent (Palonen et al., 2008).

Generally, no studies were found directly associating ventilation rates in homes with self-estimated building related symptoms. Indirectly Wong et al. (2004) showed that houses where AC is used increase the risk of health symptoms; these houses were usually sealed and had much lower ventilation rates. Indirect evidence on the

association between ventilation and health was also suggested in studies showing that increased ventilation rate lowered the perceptions of poor air quality and stuffy air (Engvall et al., 2005; Palonen et al., 2008), under the assumption that these perceptions are markers of a health risk.

3.3 Respiratory Tract/Lung Functions and Bronchial Obstruction

Reduced ventilation rates were associated with the risk of bronchial obstruction but only when homes had verified dampness problems and plasticizer containing surfaces (Øie et al., 1999). Increased ventilation rates following installation of new mechanical ventilation systems with heat recovery in homes without such a system was associated with improved lung functions (Wright et al., 2009; Xu et al., 2010). In the study of Xu et al. the effect could not be separated from the effect of an air cleaner installed together with the system. No effect on lung functions was observed by Warner et al. (2000) after new mechanical ventilation systems were installed in homes without such a system, although ventilation rates were increased. In their study the installation of mechanical ventilation systems reduced levels of RH and HDM allergens.

Installation of heat recovery ventilators in homes of infants, previously without such systems, brought levels of CO₂ down to 900 ppm compared with placebo units installed in other homes where CO₂ levels were 1400 ppm. Levels of RH were also reduced but did not affect health centre encounters and hospitalizations due to respiratory problems (Kovesi et al., 2009). Actually, no hospitalizations occurred during the study. Since the population of homes where interventions were made was small it was unlikely to expect that a rather small change in ventilation would have a strong effect on respiratory problems that can be demonstrated by the effect on hospitalizations.

3.4 Infectious Diseases

No studies have been found that directly associate infectious diseases with the ventilation rate or type of ventilation system in homes. However, the design of ventilation systems should avoid mixing of return air with supply air and assure proper air distribution, considering that increased recirculation of air in nursing homes was associated with an increased risk of attack rates of Influenza A among the elderly (Drinka et al., 1996). Also air distribution played an

important role in the spread of SARS (Yu et al., 2004; Li et al., 2005).

3.5 Other Outcomes

Studies with other health outcomes than those listed above have also been found including mortality, cardiovascular hospitalizations, obesity and lead poisoning. None of them was directly associated with either ventilation rate, ventilation system type, or the maintenance of ventilation systems in homes. These are mentioned here only because the data provide some indirect evidence.

Use of central AC in homes has been shown to reduce exposure to particulate matter (PM) mainly from outdoor traffic, and was associated with reduced cardiovascular and respiratory hospitalizations, as well as mortality among the elderly (Bell et al., 2009). The data on both AC and health outcomes were obtained from the local community registers and it is difficult to judge whether proximity to PM sources outdoors was included in the models. Nevertheless, it can be hypothesized that reducing exposures to outdoor sources, by e.g. sealing houses, which is usually the case when central AC are used, may have a positive effect on health. This is somewhat confirmed by studies of Deger et al. (2010), who showed that children living along streets with highly dense traffic have an increased risk of asthma, particularly for children living on the ground floor and having no adequate control of pollution causing asthma. Proper filtration of outdoor air would thus be important. Sealing houses can, at the same time, reduce the outdoor air supply rate which may be detrimental for health as well.

The data from two national longitudinal studies in the US on house characteristics show that increased use of AC, resulting in most cases in lowered ventilation rates as a response to energy saving, was associated with obesity and lead poisoning (Jacobs et al., 2009). It must be emphasized though that many other factors could also contribute to the observed association including changes in lifestyle, nutrition, etc. AC has also been shown, in many studies, to reduce mortality for elderly during hot weather (Marmor, 1978; Rogot et al., 1992). This is most likely due to control of indoor temperature by cooling, but may also be caused by reduced exposure to outdoor air pollutants occurring during hot weather because AC is often associated with sealing houses.

4. Discussion

The present data provide important reference material to the project HealthVent defining health-based ventilation guidelines for Europe (HEALTHVENT.eu) (Wargocki et al., 2012). The guidelines will have two parts, one prescribing rates at which ventilation is supplied to reduce health risks among the population exposed in buildings, and on prescribing how to achieve compliance, proper design, operation and maintenance of ventilation systems. Both aspects are addressed in the reviewed studies.

4.1 Ventilation Rate in Homes and Health

The results of studies on ventilation and health risks in homes suggest that increased ventilation rates, also demonstrated by reduced concentration of CO₂, generally reduce health problems; only in a few cases were no effect or reverse effect observed.

To observe which level of ventilation rate can be considered to protect people in homes against negative health effects Figures 1 and 2 were created. Figure 1 shows that increasing ventilation rate

consistently reduced the concentration of HDM allergens in houses. The effect was significant over a large range of ventilation rates, from about 0.1 to 1.4 h⁻¹, suggesting that there can be a dose–response relationship, i.e. a lower concentration of HDM allergens when ventilation rate is increased. Lung functions were seen to be improved by ventilation rates above 0.5 h⁻¹, but the data are only from one study so it would be imprudent to form recommendations based only on these results. For self-reported asthma and allergy symptoms the results seem to be equivocal and only one study shows that increased ventilation rate reduced the risk of asthma/allergy; in two studies no statistically significant effect was observed. Figure 2 shows that lowering CO₂ levels, i.e. increasing ventilation rate, reduced significantly symptoms of asthma and allergy. No effects of increased ventilation rate on SBS symptoms were shown, and sometimes symptoms increased with increased ventilation rate (Figure 1). Only one study showed that reduced CO₂, i.e. increased ventilation rate, reduced symptoms (Figure 2). These results suggest that this health outcome may not be very sensitive to changes in ventilation in homes, although SBS symptoms are clearly associated with changes in ventilation rates

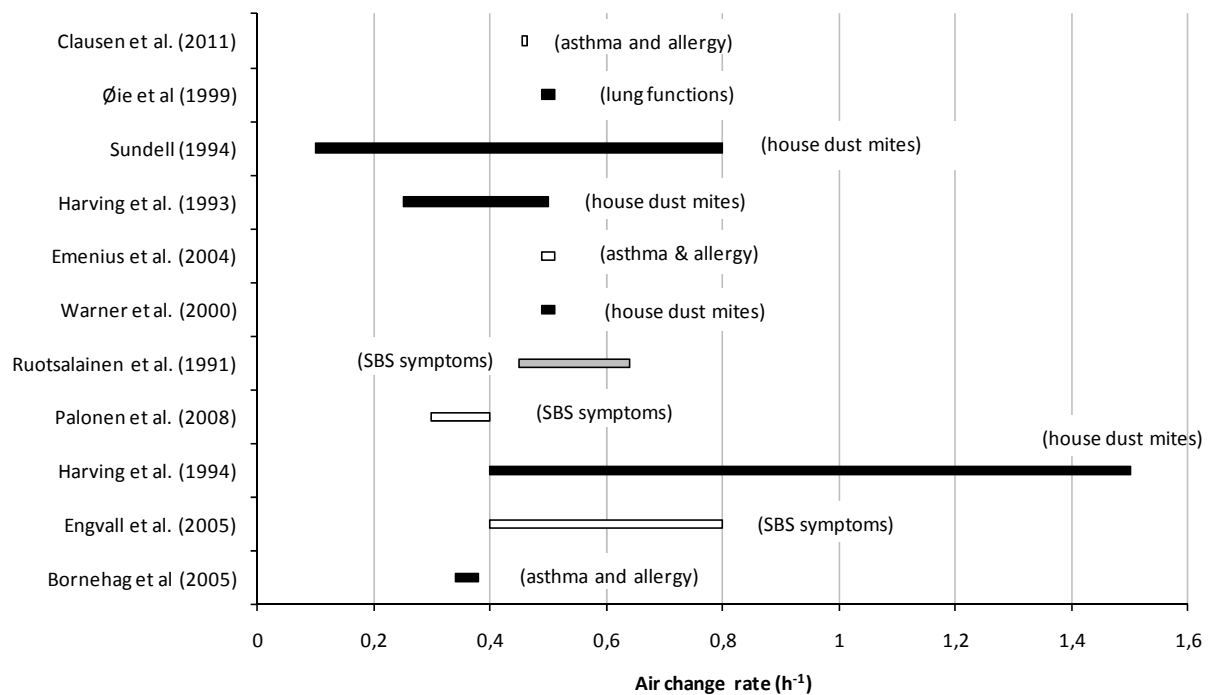


Figure 1. Ventilation rate in homes and health; black bars show the studies in which increase in ventilation rate caused statistically significant reduction in health outcomes; empty bars show that health outcome has not been statistically significantly changed in the indicated range of air change rates, while grey bars show that increasing ventilation rates increased significantly health problems.

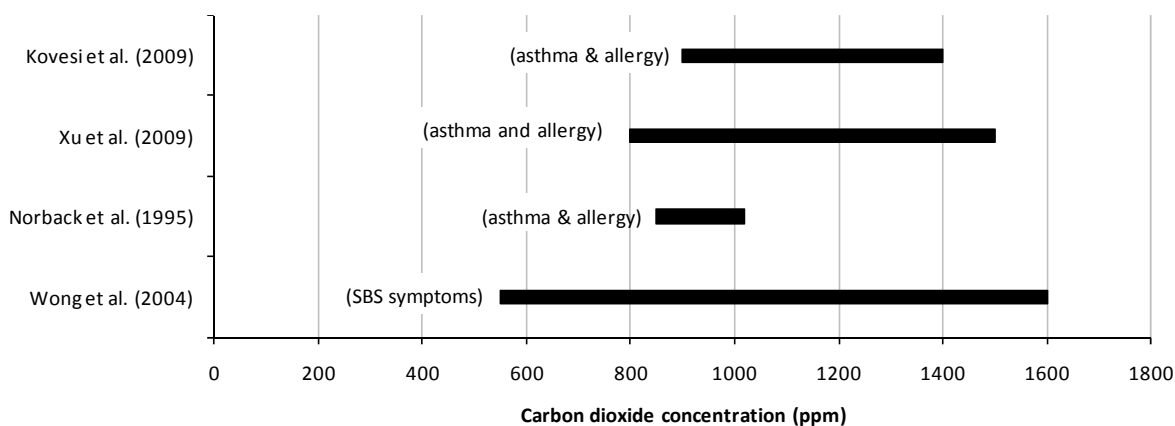


Figure 2. Concentration of CO₂ in homes and health; black bars show the studies in which reduction of CO₂ (i.e. increase in ventilation rate) caused statistically significant reduction in health outcomes.

in offices (Seppänen et al., 1999; Wargocki et al., 2002; Sundell et al., 2011).

Taking only the studies in which significant effects of ventilation rate on health were observed, the minimum ventilation rate in homes at which no health risk exist seems to be about 0.4 h⁻¹ (Figure 1). This is the lowest ventilation rate at which no increased health risk was observed in the reviewed literature. This level is close to the requirements of, e.g. Danish Building Regulations (BR10, 2010) set at 0.5 h⁻¹, as well as the measured ventilation rates in US residencies, which is from 0.5 to 0.7 h⁻¹ (Pandian et al., 1998). Taking the studies in which significant effects of CO₂ on health were observed, the maximum level of CO₂ in homes at which no health risk was observed seem to be about 900 ppm (Figure 2).

4.2 Ventilation System in Homes and Health

Present results show consistently that newly installed mechanical ventilation systems reduced health risks in homes. The reason for this is most likely that outdoor air supply rates were also increased when the system was installed, and the system when new was not a source of pollution. Furthermore, the installation of a mechanical ventilation system could also contribute to fixing other problems in homes which could, if existing, contribute to health problems, such as e.g. leaky roof, unsealed ceilings, etc.

Present results show also that there was less evident effect on health in buildings with already existing

mechanical ventilation systems. Mechanical ventilation systems can become strong pollution sources as a result of their poor maintenance, as e.g. shown in a recently published study in 299 Dutch homes (Dijken et al., 2011). Although there is a wealth of data showing that dirty filters and dirty ventilation systems contribute to elevated health risks (e.g., Sieber et al., 1996; Seppänen et al., 2002; Mendell et al., 2003; 2008), these data are mainly from offices. On the other hand the present survey found no studies which associated the maintenance of ventilation systems in homes with health. Only the study of Coehlo et al. (2005) showed association between improper operation of the system (blocked vents, switched-off fans, etc.) and elevated health complaints. Poor performance of ventilation systems could also contribute to less evident effects on health in buildings with existing mechanical ventilation systems. Mechanical ventilation systems should be properly designed, balanced and operated because, as shown by Palonen et al. (2005), they can become a source of nuisance, e.g. due to increased noise levels indoors. This result was confirmed recently by Bogers et al. (2011).

No studies were found which associated dedicated natural ventilation systems and hybrid systems with health.

4.3 Source Control and Filtration

Increasing ventilation rates reduces the concentration of HDM allergens. These results may also suggest that ventilation modifies moisture levels, thus it is modifying conditions which are

promoting the proliferation of HDM. Most of the studies on the association between HDM allergens and ventilation were performed in Nordic countries and in the UK, where increased ventilation rates during cold periods reduce RH in homes, thereby inhibiting the growth of mites. Reduction of moisture has also many other benefits for health, as moisture is generally known to be a marker of elevated health risk in homes (Bornehag et al., 2001).

Too low RH can also cause problems and could be one of the reasons why Ruotsalainen et al. (1991) observed in Finland that increased ventilation rate caused an increase of SBS symptoms, such as dryness, nasal problems and itching. Their study was actually performed from November to April so it is likely that RH was quite low, although measured to be on average approximately 36%. Moisture can also be controlled by creating barriers in the building structure and/or local exhaust in laundries, bathrooms and kitchens, as well as by the banning of drying of laundry in spaces where people live.

Ventilation air can also transport outdoor pollutants (particles, pollens, etc.) into indoor spaces. This is suggested by studies of Bell et al. (2009) who showed that the use of AC reduced health effects related with PM from outdoors because houses were sealed. These results show the connection between indoor and outdoor environment and the need for reducing exposures to particles entraining indoors. This should rather be achieved by, e.g. efficient filtration, than by sealing homes, i.e. reducing ventilation rates, which can also be detrimental for health. The risk of elevated health effects due to exposure to particles will depend on the location of houses (urban, rural), proximity to outdoor sources, etc. Again, reviewed studies have not sufficiently documented these factors so it is difficult to assess their impact on the presented results.

4.4 Populations Studied

Among all studies reviewed in the present report, thirteen studies concerned health risks for children, twelve for adults and five for the elderly. They have thus reasonably well addressed different population groups.

All studies that did not show association between ventilation system type and ventilation rate and self-reported asthma and allergy symptoms were carried out with children. In most cases the prevalence of

asthma and allergy is based on parental reports (self-assessments). Perhaps this caused inconsistent results. Verification of parental reports with objective methods would be useful.

All studies in which there was no association between ventilation type and/or ventilation rate, and self-reported SBS symptoms concerned adults.

In the case of exposure of the elderly none of the studies showed direct association between ventilation type and or ventilation rate and health outcome.

4.5 Limitations

There are numerous confounding factors that could influence and disturb the observed associations. They include among others: study design, controlling and measuring of ventilation rates, differences in source strength; interactions between sources and ventilation rates; dose-response effects that are likely to be log-linear; ventilation systems as sources of pollution, multifactorial genesis of health problems, climatic differences, different thresholds of effects for people and location of the study, as well as different methods by which health outcomes were measured.

Quality of data plays an important role when forming conclusions on ventilation and health. No attempt however was made in the present report to grade the studies according to their quality as regards experimental design, measurements and analysis of results.

If such a grading had been based on the study design, case-base, case-control and placebo-controlled interventions with double blinding would be ranked high while cross-sectional studies and longitudinal observations would be ranked quite low. In the former, many of the confounding factors are controlled experimentally while in the latter the control can only be made by adjusting the statistical models for the factors likely to obscure the association.

If such a grading had been based on the method of ventilation measurements, the method using perfluorocarbon as tracer (PFT method) would be ranked high (although largely debated as regards its accuracy in the scientific community) because it accounts only for outdoor air supply rate, while using CO₂ would be ranked low because the calculated ventilation rates provide information on

total dilution including outdoor air and make-up air (the air from other rooms in a house) rather than only outdoor air supply rate (Bekö et al., 2009) as is the case for PFT method.

If such a grading had been based on categorization of the ventilation systems, the studies which installed mechanical ventilation systems would be ranked high compared with the buildings with existing mechanical ventilation systems because of their good maintenance and close to design performance. Also studies in which categorization of the system had been made through inspections rather than by examining registers or blue-prints would be ranked high because they would use the actual data rather than unverified information.

The grading could have also been made based on the measurements of health outcomes. Many studies used self-administered questionnaires and may be ranked low compared to objective medical measurements and/or diagnosis made by the doctors which would be ranked high. However using questionnaires is the most efficient, low-cost method of collecting data, widely used in large epidemiological studies of the type discussed in the present report. Besides, there is some evidence on the consistency between self-reports of health problems and doctor-diagnosed health problems. Even if objective medical measurements had been used, the information on the thresholds at which health effects are observed would be needed. These can vary between people and in many cases are not available. Also lack of the effect on objectively measured health symptoms does not preclude the effect on health, especially if the objective method is not properly selected and not properly applied. Consequently the studies in which self-reported and doctor-diagnosed symptoms were used can be ranked evenly.

It is worth noting that consistent observations regarding associations between ventilation rate and ventilation system and health stem generally from the studies which would have been ranked high.

4.6 Implications for Future Work

Present results show that more evidence of the role of ventilation for health is needed. Despite the paramount importance of ventilation, especially considering the impact on energy, it has not received proper attention. The need for reducing energy and future buildings being much tighter than today will require that the proper ventilation of

homes, obtained by, e.g. mechanical systems with heat recovery in cold periods and dedicated natural ventilation systems in warm periods, will be the essential part of the future building structure.

The performance of different ventilation solutions and their impact on health should be better understood. There is an obvious need for producing guidelines as regards commissioning and installation as well as maintenance of systems supplying air to indoor spaces, not only for mechanical systems but also for other systems. Regular inspections of ventilation systems can be forced, as it is done for example in Sweden (Boverket, 2009); these inspections can actually become a part of energy certification of buildings.

Future studies should try to answer the fundamental question on how much ventilation is actually needed. This question is only partially answered by the present report due to limited data and the limitations of different studies. A series of studies on ventilation and health would be needed to answer this question. They should take into account all possible limitations and, what is probably most important, should link ventilation to actual exposures, admitting thus that ventilation is not a mitigation measure and should not be used as such.

5. Conclusions

- Ventilation rate in homes is associated with health in particular with asthma, allergy, airway obstruction and SBS symptoms. This association is based on the limited evidence.
- Ventilation rates above 0.4 h^{-1} or CO_2 below 900 ppm in homes seem to protect against health risks.
- No specific ventilation system can be recommended to provide minimum ventilation rates.
- Increasing ventilation rates in homes reduces house dust mites known to cause allergic symptoms, most likely because of reduced moisture levels which inhibits their proliferation.
- Newly installed mechanical ventilation systems nearly always reduced the risk of health problems. This was not the case for buildings with existing mechanical ventilation systems,

most likely due to their poor maintenance, lack of commissioning, regular checks and inspections, etc.

- Buildings in which air conditioning is installed increase the risk of health problems probably due to lowered ventilation rates (tightening and sealing of buildings to reduce energy).
- No differences were observed in the prevalence of health problems between different age groups, children, adults and elderly.
- A series of studies on ventilation and health in buildings with different ventilation systems would be desirable.

6. Practical Implications

Required ventilation rates depend strongly on exposures, i.e. with a high load of pollution more ventilation is needed than if the loads are low. The ventilation rates can be reduced by controlling sources of pollution both being of outdoor origin (e.g., particulate matter) and indoor origin (e.g., relative humidity (RH), particulate matter (PM), house dust mite (HDM) allergens, emissions from building products and appliances, anthropogenic emissions). Future homes should secure proper control of exposures to pollutants in order to reduce health risks for occupants on one hand, and at the same time they should secure that the energy needed to support sufficient ventilation is as low as possible. This control can be implemented by different solutions including provision of sufficient ventilation, which should be closely connected to estimated exposures.

Different ventilation systems can be applied from dedicated natural ventilation systems, hybrid systems to mechanical ventilation systems with heat recovery, all depending on the conditions which promote application of one system over another. Ventilation should not be considered to be the only mitigation measure to control exposures but complementary and supplementary to other measures, such as, e.g. source control, air cleaning and/or local exhausts. These measures are easy to implement in newly constructed homes, and more difficult but still possible to apply in existing homes unless they are renovated or refurbished.

It is of utmost importance that systems securing ventilation rates in homes are inspected for their

performance. Regular annual or bi-annual inspections should be implemented and regulated so that the proper operation and maintenance of systems is ensured. They can become, e.g., a part of energy audits, chimney sweep control, etc., or can be performed completely separately.

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