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Title

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ASSOCIATION OF VENTILATION WITH HEALTH AND OTHER RESPONSES IN COMMERCIAL AND INSTITUTIONAL BUIILDINGS

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ABSTRACT

The paper presents a summary of a review [1] of current literature on the associations of ventilation rates in non-residential and non-industrial buildings (primarily offices) with health and other human outcomes. Twenty studies, with close to 30,000 subjects, investigated the association of ventilation rates with human responses. (Twenty one studies investigating the association of carbon dioxide with human responses, although included in the previous review, are not summarized here.) Almost all studies including ventilation rates below 10 Ls^{-1} per person found these ventilation rates to be associated in all building types with statistically significant worsening in one or more health or perceived air quality outcomes. Some studies comparing only ventilation rates above 10 Ls^{-1} per person determined that increases in ventilation rate above 10 Ls^{-1} per person, up to approximately 20 Ls^{-1} per person, were associated with further significant decreases in the prevalence of SBS symptoms or with further significant improvements in perceived air quality. The studies reported relative risks of 1.5 - 2 for respiratory illnesses and 1.1 - 6 for sick building syndrome symptoms for low compared to high ventilation rates.

KEYWORDS: ventilation rate, health effects, SBS, air change rate, risk assessment

OBJECTIVES

Our primary aim was to review the evidence of the association of ventilation with health and other human responses in commercial and institutional buildings based on the studies done to date, to provide a better scientific basis for setting health-related ventilation standards. We were particularly interested in the following human responses due to their widespread occurrence and potentially great economic impact: (1) communicable respiratory illnesses; (2) sick building syndrome symptoms; and (3) unacceptability or poor perceived air quality (PAQ) among occupants or sensory evaluation panels.

We wanted to answer the following more specific questions:

Does the magnitude of ventilation rate, within the normally encountered range, affect human health and other human responses?

Can a "no-effect" threshold value for the ventilation be found, above (or below) which the prevalence of negative outcomes does not change measurably?

Can an average dose-response relationship between ventilation rates and human responses be inferred from existing research data?

METHODS

We identified the relevant papers for the review, set criteria for inclusion in the review, abstracted the available information from the included studies, processed the results into a common format, and finally drew conclusions. The papers were identified through literature searches from five computerized data bases, and proceedings of the following conference series: International Conferences on Indoor Air Quality and Climate, International Conferences on Healthy Buildings, and Indoor Air Quality Conferences organized by ASHRAE. In addition, we used our personal contacts to collect research publications relevant to the topic.

Study inclusion criteria

The power and precision of a cross-sectional study increase with the number of study buildings or study spaces in which ventilation rates and occupant health outcomes are measured, and also with the number of participants. Increased power reduces the effects of random error, but does not reduce systematic bias. We considered all reported studies which assessed relationships between ventilation rate and occupant health or perception of indoor air quality. We excluded from consideration any cross-sectional studies with only two buildings or study spaces. We excluded cross-sectional studies not including statistical analyses. We considered potential confounding so important in cross sectional studies that we excluded any studies where confounding by personal factors was not controlled either through statistical means, by including approximately similar comparison spaces, or through restrictions in study population. We included studies that assessed indoor air quality with a human panel, because use of the same panel as an instrument across study spaces and common training of panel members reduces variation in assessments due to personal differences. In summary, the criteria for including cross-sectional studies in the review were: (1) at least three buildings or ventilation zones, (2) statistical analysis of results, and (3) control for confounding by personal factors as described above.

Among experimental studies, we excluded from consideration: experiments with changes in the type of air handling system or with movement of occupants to a different building; studies that did not either use a control group or repeat the experiment, (e.g., change between baseline and modified ventilation rates) more than once in the same group; studies in which the subjects were obviously or most likely aware of the timing of the changes in ventilation rates; and studies that did not use statistical analyses to evaluate the data (unless a substantial change in symptoms was obvious from a plot of the data).

All studies which fulfilled the criteria described above, were included in our review whether or not statistically significant associations were reported. We were forced to reject almost half of the studies dealing with the topic due to one or more of our exclusion criteria.

Description of Studies

The review included almost 30,000 subjects and more than 350 buildings in fifteen cross-sectional and five experimental studies. Most studies included male and female office workers, but some studies were performed with special groups: army trainees, elderly people in a nursing home, inmates in a jail, pupils in a school and hospital personnel. A study may have assessed the association of ventilation rates with multiple health or perception outcomes or performed multiple analyses using different categories of ventilation rates or different subsets of study data. Consequently, many studies provided multiple assessments of the associations of ventilation rates with human outcomes.

RESULTS

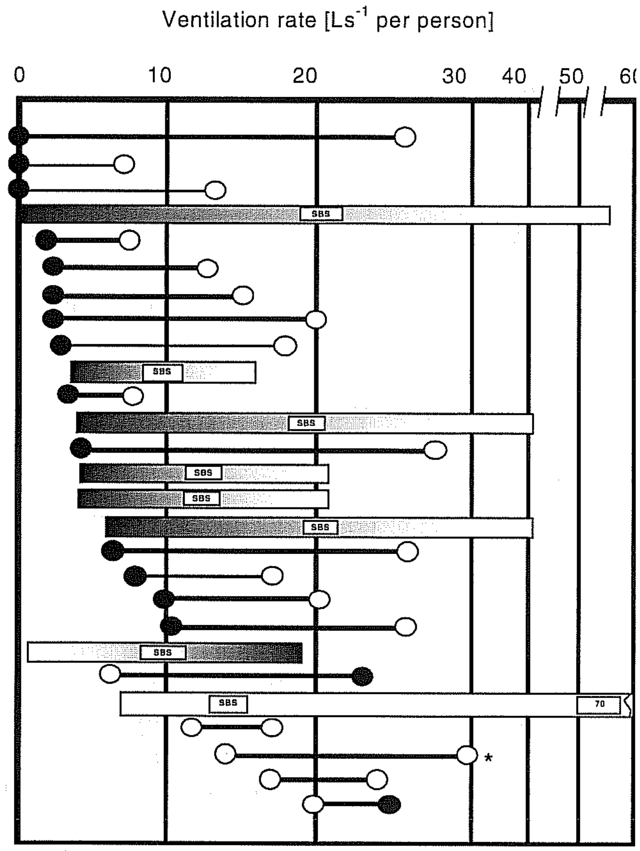
Association of ventilation rates with health and other outcomes

The presence or absence of statistically-significant associations of ventilation rates with outcomes is illustrated graphically using an adaptation of the format by Mendell in [2] .Figure 1 presents the assessments with sick building symptoms as outcome. Figure 2 presents the assessments with respiratory illness, perceived air quality, and other outcomes (Smedje: performance; Wålinder: nasal patency). The references to the papers cited in these tables are provided by Seppänen et al.[1].

Each comparison of two ventilation rates included in the reviewed studies is presented on a single row in the figures. When outcomes at two *specific levels* of ventilation rate are compared, the figure represents each level with a circle. If the study compared outcomes among groups of workers experiencing different *ranges* of ventilation rate (e.g., 0 to 10 L s^{-1} per person versus > 10 to 50 L s^{-1} per person), the graph represents with circles the approximate *mean* ventilation rate within each range. Statistically significant differences in the level of the outcomes at different ventilation rates are illustrated with a shaded circle, shading indicating at least one significantly *worsened* health or perception outcome at that ventilation rate. Both circles in a comparison being unshaded indicates a lack of statistically significant increase in any outcome with ventilation. In general the criterion for statistical significance is $p< 0.05$, or a 95% confidence interval that excludes one. A thicker connecting line between data points denotes an experimental study. Several studies did not compare specific levels or ranges of ventilation, but assessed whether ventilation rate as a continuous variable was associated with a change in the outcome. These results are illustrated with shaded or unshaded rectangular *bars.* If the study reported a statistically significant model coefficient or correlation coefficient relating the ventilation rate to the outcome, suggesting a dose-response relationship, the horizontal bar is shaded, with the darker shaded end representing a worsened outcome. For each assessment, the range of relative risks (essentially the symptom prevalence at lower ventilation rate divided by symptom prevalence at higher ventilation rate) is included in the tabulated information.

Almost all the studies included in the review that included ventilation rates below 10 Ls^{-1} per person found that these rates were associated with a significantly worse prevalence or value of one or more health or perceived air quality outcomes. Most assessments included multiple statistical tests (e.g., for the association of multiple symptoms with ventilation rate). In 25 of 34 assessments for which information was provided, 50% or more of the statistical tests indicated a significant association with ventilation rate. Available studies further showed that increases in ventilation rates above 10 Ls^{-1} per person, up to approximately 20 Ls^{-1} per person, were sometimes associated with a significant decrease in the prevalence of SBS symptoms or with improvements in perceived air quality. The less consistent findings for relationships in the range above 10 Ls^{-1} per person are compatible with the prediction that benefits per unit increase in ventilation would be likely to diminish at higher ventilation rates and, thus be more difficult to detect epidemiologically.

First author of the paper	Year	Range of Relative Risk
Jaakkola	91a	1,1
Gamble	86	1,8
Gamble	86	2,4
Groes	95	NA
Jaakkola	91b	1,3
Jaakkola	91b	1,2
Jaakkola	91b	1,1
Jaakkola	95	5.4 - 37
Cochet	95	1.7 - 3.8
Sundell	94	see [1]
Ruotsalainen	94	2,8
Sundell	94a	NA
Stenberg	94	see [1]
Wu	96	NA
Wu	96	NA
Sundell	94a	NA
Jaakkola	91a	1,1
Sundell	94b	see [1]
Jaakkola	95	5.0 - 6.0
Jaakkola	91a	1,1
Nordström	95a	see [1]
Jaakkola	94	0.35 - 0.46
Jaakkola	91a	NA
Wyon	92	NA
Menzies	93	0.8 - 1.2
Wyon	92	NA
Jaakkola	95	4.2 - 5.2



* estimated ventilation rates

Figure 1. Summary of studies with measured ventilation rates per person and sick building syndrome. Circles in the chart denote ventilation rates compared. Rectangular bars denote assessment of dose-response relationships.

Findings from multiple studies including data on a range of ventilation rates indicated a dose-response relationship between ventilation rates and health and perceived air quality outcomes, up to approximately 25 Ls^{-1} per person; however, available data are not sufficient to quantify an average dose-response relationship. Only five studies were conducted in hot humid climates, thus, the results of this review apply primarily for moderate and cool climates. Most of these studies have been conducted in office buildings.

First author of the paper	Year	Range of Relative Risk (or Odds ratio)
Respiratory illnesses		
Brundage	88	1,51
Hoge	94	1,94
Drinka	96	2.2 - 4.7
Milton	99	1,53
Perceived air quality		
Bluyssen	95a	NA
Groes	95	NA
Nordström	95b	see [1]
Palonen	90	see [1]
Ruotsalainen	94	2,8
Cochet	95	NA
Zweers	90	NA
Jaakkola	94	0,47
Other outcomes		
Smedje	96	see [1]
Wålinder	98	NA

*estimated ventilation rates

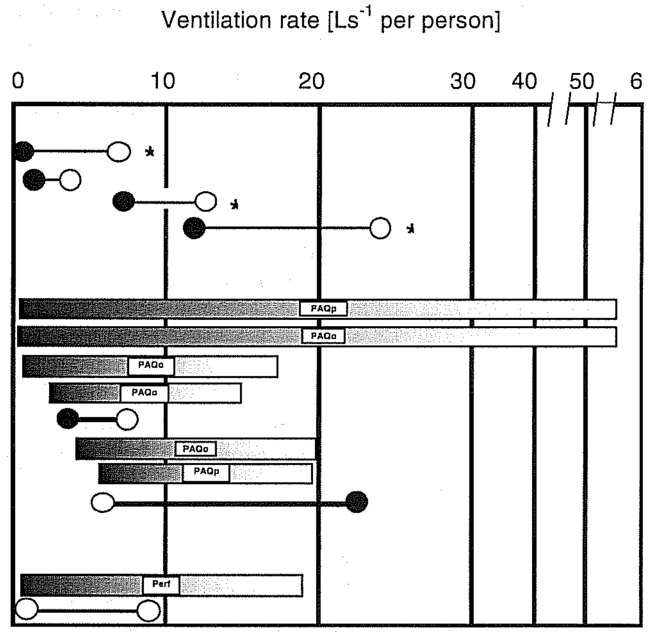


Figure 2. Summary of studies with measured ventilation rates per person, and respiratory illnesses, perceived air quality and other outcomes. The circles in the chart denote mean ventilation rates compared. Rectangular bars denote assessments of dose-response relationships.

DISCUSSION

Based on these results, we conclude that in office buildings or similar spaces constructed using current building practices, increases in ventilation rate in the range between 0 and 10 Ls^{-1} per person will, on average, significantly reduce occupant symptoms and improve perceived air quality. Increases in ventilation rate above 10 Ls^{-1} per person up to 20 Ls^{-1} per person may further reduce symptoms and improve air quality, although these benefits are currently less certain based on available data. No threshold for effects is evident at 10 Ls^{-1} per person or at any other specific ventilation rate. As ventilation rates increase, benefits gained for occupants per additional unit of ventilation are likely to decrease in magnitude and to require larger studies for convincing demonstration. Benefits which have yet to be consistently demonstrated in this way (e.g., for ventilation rates above 10 Ls^{-1} per person) may still be of substantial public health importance. Ventilation standards thus may need to periodically revisit the available evidence for occupant benefits at particular ventilation rates, and the magnitude of these benefits, weighed against the current incremental costs of increasing ventilation. This process would be new, as minimum ventilation rates in existing codes and standards do not substantially reflect health data such as is reviewed here.

The complex relationship between ventilation rate and indoor air quality greatly complicates research on the associations of ventilation rates with health outcomes and perceived air quality. Many of the studies have failed to control for important potential confounders or have incompletely characterized the study buildings and study methods. The difficulties and inaccuracies in ventilation rate measurements have also served as a barrier to this area of research. Limitations in existing data make it essential that future studies better assess health and PAQ changes in the ventilation rate range between 10 and 25 Ls^{-1} per person. Future research should be based on well-controlled cross-sectional studies or well-designed blinded and controlled experiments. The most effective studies will include high quality measurements of ventilation rates, ample study power to detect effects considered of public health importance, and if possible, improved measures of adverse occupant outcomes; e.g., more sensitive or more objective assessment tools. Future research, to be optimally useful for policy efforts, should increase emphasis on: dose-response relations useful for quantitative risk assessment, associations of health outcomes with ventilation rates per unit floor area (to assess the effects of pollutants from building sources as well as those from occupant source), and buildings that are not offices.

In addition to new studies of ventilation effects on occupants, we also need studies to specify the causative agents of adverse health outcomes. The most effective strategies to improve indoor air quality (e.g., source removal) cannot be specified before the agents and their sources are known.

Because increases in ventilation may increase building energy consumption, research is also needed to identify practical methods of decreasing minimum ventilation requirements by reducing pollutant emissions from buildings and building air handling systems. Methods to increase ventilation rates without increasing energy consumption, or to increase the effectiveness of ventilation in controlling pollutant exposures, should also be investigated.

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