LBNL-56381

Outdoor Air Ventilation and Work-Related Symptoms in U.S. Office Buildings – Results from the BASE Study

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This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technology Program of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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Abstract

Background: Recommendations for outdoor air ventilation rates in office buildings balance the need to dilute indoor pollutants for both health and comfort of the occupants against the costs of thermally conditioning the outdoor air. Although little scientific information has been available on the relationships between measured ventilation rates and health symptoms in office workers, a recently collected data set allows investigation of these relationships.

Methods: We performed analyses using data on work-related symptoms and ventilation rates collected by the U.S. EPA from a representative sample of 100 large U.S. office buildings – the Building Assessment and Survey Evaluation (BASE) study. Using multivariate logistic regression models for building-related lower respiratory and mucous membrane irritation symptoms, we estimated relative risks, as odds ratios, for three methods of estimating ventilation rate/person, adjusted for occupancy density and other confounders. The three ventilation rate measurement methods were based on CO_2 ratio in airstreams, peak CO_2 concentrations indoors, and volumetric estimates of flow rates.

Results: We found a general but irregular association of lower symptom prevalence with ventilation rates *above* the current recommended minimum for office space (about 20 cfm/person), but found no evidence for further increased benefits as ventilation rates continued to increase above 26, 32, or 37 cfm/person (depending on the measurement method). This relationship, however, did not hold for the volumetric method and lower respiratory symptoms. Also, for all measurement methods, even with ventilation per person held constant, medium to high occupancy density was associated with more symptoms than low occupancy density.

Discussion: These findings suggest, although not with complete consistency, that raising ventilation rates above current recommendations would reduce symptoms in office workers. The inconsistent findings for different measurement methods of ventilation were surprising. Occupancy density may play an unrecognized role in ventilation requirements. Further clarification of these relationships is necessary, as is the validation of accurate methods for measuring ventilation rates.

Background

Outdoor air ventilation in buildings removes indoor-generated pollutants by replacing some indoor air with outdoor air. Adequate ventilation is required to keep the concentrations of indoor-generated pollutants sufficiently low to provide a healthy and comfortable indoor environment for the occupants. Increased ventilation, however, increases the costs for conditioning temperature and humidity of the introduced outdoor air. Because the benefits of increasing VR are expected to decrease in magnitude as VR increases, the relationship is not expected to be linear; i.e., the reduction in indoor pollutants and associated health effects should be much greater for an increase in ventilation from 0-10 cfm/person than for an increase from 40-50.

Outdoor air ventilation rates (VR) historically were set to control odorous pollutants emitted by occupants, based on findings from laboratory and field studies. Recently it has become clear that emissions from buildings, building contents, and ventilation systems also contribute biologic and chemical air pollutants to indoor environments that need to be controlled by ventilation [1]. Furthermore, multiple studies, mostly in office buildings, have consistently associated lower VR with increased experience of health symptoms in occupants [2]. These symptoms have included eye, nose, and throat irritation, breathing problems, headache, and fatigue. The indoor pollutants that increase with lower VR and cause these symptoms might come from the occupants or their activities, or from the buildings and their contents. The biologic mechanisms might involve odor, irritation, or toxicity.

In setting protective ventilation guidelines, many questions remain, including:

1) What are the quantitative relationships between ventilation and adverse human responses of health and comfort? This understanding is necessary to weigh the human benefits for each further increase in ventilation against the energy costs of ventilation (which are fairly well understood).
2) Since both occupants and buildings are known to emit indoor pollutants that create odors and may affect health, should building ventilation guidelines reflect both the number of occupants and the amount of indoor space per occupant (as ANSI/ASHRAE Standard 62-2001 now does [3]), and how? Would scientific data support the existing judgment-based guidelines requiring less ventilation per person in more densely occupied spaces (e.g., auditoriums vs. offices)?

We report here the analyses of an existing data set on VR and symptoms from a study of 100 U.S. office buildings. Prior analyses of this study reported associations between indoor minus outdoor carbon dioxide (CO_2) concentrations, as *proxies* for VR per occupant, and several building-related symptoms among occupants [4, 5]. The goal of the present analysis was to use several recently produced direct estimates of VR in these buildings to analyze how occupant symptoms were related to both VR per person and occupancy density.

Methods

We used data from the Building Assessment and Survey Evaluation (BASE) Study, a survey conducted between 1994-1998 by the U.S. Environmental Protection Agency, involving a representative sample of 100 office spaces in 100 U.S. buildings, containing a total of 4,326 office workers. The BASE data includes environmental measurements, building characterizations, and human questionnaire responses. Descriptions of this study and the available data have been reported previously [6]. Briefly, the study selected a representative set of 100 office buildings from geographic regions throughout the U.S., and then randomly selected within each building one study space with at least 50 occupants.

VRs per person for the office spaces studied in BASE were estimated [7] in three separate ways:

- "CO_2 ratio" method –total outdoor air flow based on the percent outdoor air intake (from measurements of CO_2 concentrations in the outdoor air, supply, and recirculation airstreams) multiplied by the supply airflow measured with an air velocity traverse, divided by the number of occupants;
- "peak CO_2" method –VR per person estimated using the peak measured indoor CO_2 concentration (among mean values measured in three locations within each study space) and a mass balance models (this model, based on several unverified assumptions, estimates the VR per person that would result in that equilibrium concentration of indoor minus outdoor carbon dioxide, for a given rate of CO_2 production by each occupant).
- "volumetric" method –total outdoor air intake from air velocity traverse measurements in the outdoor airstreams of the air handlers, divided by the number of occupants;

We included each ventilation/person estimate in models as a multi-categorical risk variable to avoid assumptions of linear relationships. We also included occupancy density, defined as the mean of occupant counts over two days divided by floor area, as a multi-categorical risk variable. The analyses used two symptom-based health outcomes: lower respiratory symptoms (one or more symptoms of wheezing, shortness of breath, chest tightness, and cough) and mucous membrane symptoms (one or more symptom of dry or itchy eyes, stuffy or runny nose, and sore or dry throat). Analyses were of "weekly, work-related" symptom outcomes, defined as those experienced at least once per week within the last four weeks while at work and which improved outside of the building.

Other independent variables included personal information from the self-completed occupant questionnaires on demographics (gender, age, education, smoking status), health status (prior asthma and allergy diagnoses), job factors (years in building, hours per week at work, job satisfaction, job demand, job conflict, years in building, hours per week at work, job satisfaction), presence of mechanical ventilation, indoor temperature (summarized as degree-hours above 20 ºC), and mean indoor relative humidity.

We used logistic regression models for each symptom outcome to estimate unadjusted and adjusted odds ratios (ORs) and 95% confidence intervals (CI) for both ventilation rate and occupancy density. The OR, a measure of strength of association, when >1.0 indicates increased risk and when <1.0 indicates decreased risk. Models for each outcome included unadjusted models for each ventilation rate estimate and full multivariate models including ventilation rate, occupancy density, personal variables, and potentially confounding environmental variables.

Results

Density of occupancy in the BASE buildings varied substantially, from 1.4 - 8.4 occupants/ 1,000 sq ft (median = 3.4, interquartile range = 2.7 – 4.7). Estimated VRs were available for all 100 buildings using the peak CO_2 method, but missing in 10 buildings for the CO_2 ratio method and 8 for the volumetric method. The three ventilation rate measurement methods, even after omitting an extreme outlier, yielded rates differing substantially in range (peak CO_2, 14-127 cfm/person; CO_2 ratio, 10-440; volumetric, 4-480) [7]. The peak CO_2

Table 1. Ventilation per occupant and occupancy density: unadjusted odds ratios (OR) and 95% confidence intervals (CI) for associations with symptom outcomes

	Work-related symptom outcomes	
Risk Factors	Lower respiratory OR (CI)	Mucous membrane OR (CI)
Ventilation rate -- CO_2 ratio (cfm/person)		
10.1 – 20.5	1.0	1.0
20.7 – 37.3	0.47* (0.30-0.73)	0.67* (0.52-0.85)
38.2 – 60.7	1.04 (0.72-1.50)	0.78* (0.61-0.99)
62.0 – 83.7	0.77 (0.51-1.14)	0.77* (0.60-0.99)
84.0 – 116.1	0.69 (0.45-1.06)	0.81 (0.63-1.04)
118.9 – 180.7	0.54* (0.35-0.86)	0.56* (0.43-0.73)
199.6 – 440.3	0.63* (0.40-0.99)	0.76* (0.58-0.99)
Ventilation rate -- peak CO_2 (cfm/person)		
14.4 – 21.3	1.0	1.0
22.4 – 26.2	0.80 (0.54-1.18)	0.77* (0.61-0.97)
26.3 – 31.9	0.59* (0.39-0.89)	0.68* (0.53-0.86)
33.1 – 39.3	0.75 (0.50-1.12)	0.80 (0.63-1.02)
39.8 – 48.4	1.02 (0.71-1.46)	0.97 (0.77-1.22)
48.7 – 57.7	0.70 (0.46-1.05)	0.74* (0.58-0.94)
59.4 – 126.9	0.75 (0.49-1.14)	0.78 (0.60-1.00)
Ventilation rate -- volumetric (cfm/person)		
3.6 – 18.1	1.0	1.0
20.5 – 32.9	0.71 (0.46-1.08)	0.70* (0.55-0.90)
33.8 – 51.4	1.16 (0.79-1.70)	0.84 (0.66-1.06)
51.6 – 82.0	0.88 (0.58-1.33)	0.74* (0.57-0.94)
87.7 – 131.2	0.80 (0.51-1.26)	0.65* (0.50-0.85)
132.1 – 225.1	1.02 (0.69-1.52)	0.89 (0.70-1.13)
232.1 – 479.7	0.82 (0.53-1.26)	0.80 (0.63-1.03)
Occupancy density (occupants/1,000 sq ft)		
1.44 – 2.52	1.0	1.0
2.61 – 3.04	1.09 (0.73-1.63)	1.18 (0.94-1.48)
3.07 – 3.76	1.34 (0.92-1.95)	1.32* (1.06-1.64)
3.77 – 4.79	1.24 (0.85-1.82)	1.24* (1.00-1.55)
4.79 – 8.43	1.63* (1.14-2.33)	1.64* (1.33-2.03)

*P-value <0.05.

method had closest to the range we expected. By all methods, few or no buildings had very low VR (e.g., less than 5 or 10 cfm/person). VRs from the different methods also differed in the analyses in their patterns of association with symptoms.

Table 2. Occupancy density and ventilation per occupant: multivariate adjusted** odds ratios (OR) and 95% confidence intervals (CI) for associations with symptom outcomes

		Work-related symptom outcomes	
	Risk Factors	Lower respiratory OR (CI)	Mucous membrane OR (CI)
CO2 Ratio Method	Ventilation rate		
	10.1 – 20.5 cfm/person	1.0	1.0
	20.7 – 37.3	0.60 (0.36-1.01)	0.74* (0.55-0.99)
	38.2 – 60.7	1.47 (0.91-2.38)	0.88 (0.65-1.20)
	62.0 – 83.7	1.11 (0.69-1.80)	1.00 (0.74-1.34)
	84.0 – 116.1	0.83 (0.50-1.38)	0.90 (0.66-1.22)
	118.9 – 180.7	0.67 (0.40-1.14)	0.62* (0.46-0.84)
	199.6 – 440.3	0.89 (0.50-1.58)	0.92 (0.65-1.29)
	Occupancy density		
	1.44 – 2.52 occ's/1,000 sq ft	1.0	1.0
	2.61 – 3.04	1.35 (0.82-2.21)	1.33* (1.00-1.77)
	3.07 – 3.76	1.42 (0.90-2.25)	1.54* (1.19-2.00)
	3.77 – 4.79	1.35 (0.86-2.13)	1.23 (0.95-1.59)
	4.79 – 8.43	1.40 (0.89-2.20)	1.39* (1.07-1.80)
Peak CO_2 Method	Ventilation rate		
	14.4 – 21.3 cfm/person	1.0	1.0
	22.4 – 26.2	0.70 (0.45-1.09)	0.70* (0.53-0.92)
	26.3 – 31.9	0.63 (0.38-1.03)	0.70* (0.52-0.93)
	33.1 – 39.3	0.88 (0.54-1.45)	0.98 (0.73-1.32)
	39.8 – 48.4	0.89 (0.57-1.38)	0.90 (0.68-1.19)
	48.7 – 57.7	0.75 (0.46-1.23)	0.75 (0.56-1.01)
	59.4 – 126.9	0.80 (0.49-1.31)	0.79 (0.58-1.06)
	Occupancy density		
	1.44 – 2.52 occ's/1,000 sq ft	1.0	1.0
	2.61 – 3.04	1.19 (0.75-1.90)	1.36* (1.04-1.78)
	3.07 – 3.76	1.36 (0.89-2.09)	1.46* (1.14-1.88)
	3.77 – 4.79	1.27 (0.81-1.98)	1.29 (0.99-1.67)
	4.79 – 8.43	1.21 (0.80-1.85)	1.52* (1.19-1.95)
Volumetric Method	Ventilation rate		
	3.6 – 18.1 cfm/person	1.0	1.0
	20.5 – 32.9	0.99 (0.60-1.63)	0.80 (0.60-1.06)
	33.8 – 51.4	1.61* (1.04-2.51)	1.00 (0.76-1.32)
	51.6 – 82.0	1.26 (0.79-2.03)	0.88 (0.66-1.18)
	87.7 – 131.2	1.36 (0.77-2.39)	0.80 (0.57-1.12)
	132.1 – 225.1	1.07 (0.68-1.70)	0.84 (0.64-1.12)
	232.1 – 479.7	1.14 (0.67-1.93)	0.88 (0.64-1.20)
	Occupancy density		
	1.44 – 2.52 occ's/1,000 sq ft	1.0	1.0
	2.61 – 3.04	1.07 (0.66-1.73)	1.14 (0.87-1.51)
	3.07 – 3.76	1.48 (0.96-2.30)	1.32* (1.02-1.72)
	3.77 – 4.79	1.31 (0.84-2.04)	1.17 (0.90-1.53)
	4.79 – 8.43	1.29 (0.83-1.99)	1.39* (1.07-1.80)

*P-value <0.05. ** adjusted for personal variables, temperature, relative humidity, occupancy density, and, for peak CO_2 model, presence of mechanical ventilation.

In the study population, 7.9% overall had work-related lower respiratory symptoms, and 29.4% had work-related mucous membrane symptoms. For all VR measurement methods, both symptoms tended to be less prevalent at all ventilation levels above the lowest, but did not decrease continually in a linear fashion (Table 1). Increasing occupancy density was consistently associated with increased symptoms.

In multivariate models, prevalence of both symptoms was generally decreased at ventilation rates above the lowest level, with occupancy density held constant (Table 2). This was most consistent for the peak CO_2 metric, and least for the volumetric method. Increased ventilation by the volumetric method was associated with irregularly *increased* lower respiratory symptoms. Occupancy density, with constant ventilation per person by any method, was associated with an approximately 20-40% increased odds of symptoms at all densities greater than about 2.5 persons per 1,000 sq ft.

Discussion

Current ventilation standards, although intended to protect occupants from a broad range of indoor airborne contaminants, have been based historically on non-health-related criteria such as perception of odor and may not be health protective. Available reviews of the literature, in fact, suggest that VR above current standards for offices may further reduce symptoms among workers [2, 8]. Essentially all such available data is on VR and symptoms in office workers. However, proper setting of health-protective VR requires estimation of exposure/response relations and joint consideration of these relations with issues of technologic and economic feasibility. An additional need is to assess the relative need for ventilation to remove pollutants produced by occupants versus pollutants produced by buildings and contents. This would allow ventilation standards to be set appropriately for indoor spaces of varying occupant density, such as auditoriums and offices.

At least three different analysis outcomes could be hypothesized for this analysis. If all symptom-related indoor contaminants that could be controlled by ventilation came from occupants, or were directly proportional to the number of occupants, the need for ventilation would be simply proportional to number of occupants. As ventilation per person increased, symptoms would decrease in some fashion, unrelated to occupancy density. As occupancy density increased with ventilation per person held constant, symptom prevalence would *not change*. On the other hand, if densely populated spaces such as auditoriums required *less* ventilation per person than sparsely occupied spaces, then as occupancy densities increased with ventilation per person held constant, symptom prevalence would *decrease*. A possible explanation for this latter case would be that part of the symptom-related contaminant load removed by ventilation comes from building surfaces or materials proportional to the *size* of the occupied space, rather than to the number of occupants. Thus, equal numbers of people in smaller spaces would require less total ventilation, and less ventilation per person. A third possibility is that, if some aspect of increasing occupancy density increased symptoms in ways *not reversible by ventilation*, then as occupancy density increased with ventilation per occupant held constant, symptoms would *increase*.

We have analyzed the BASE data to examine which of these situations is most compatible with the data. Increased ventilation per occupant above the lowest levels seen, with occupancy density constant, showed a generally consistent association with lower symptom prevalence for all ventilation measurement methods, even within the high range of VR present in these buildings, except for the volumetric method and lower respiratory symptoms. The shape of the relationship was irregular and did not suggest a dose response. Analyses suggested that symptoms decreased as VR increased above about 20 cfm/person, but did not decrease further in any systematic way as VR by any method increased further. At mid to high rates of volumetric VR, however, lower respiratory symptoms were more prevalent.

One negative finding was fairly clear: as occupancy density increased with ventilation per occupant held constant, symptom prevalence clearly was neither constant nor decreased. These results are consistent with the third, but not the first two hypotheses. The 20-40% increase in odds for both symptoms seen with all ventilation methods at greater than 2.5 occupants per 1,000 sq ft showed no clear further increase with further increased occupant density. This finding may be due to confounding by other aspects of buildings or jobs correlated with occupancy density; however, the analysis did adjust for a wide range of job factors.

Alternate analyses we performed, not reported here, included variables for ventilation *per person* and for ventilation *per area* in the models, rather than occupancy density. These models, for all three ventilation measurements, estimated more consistent reductions in all symptoms at ventilation rates per person above the lowest level, but also, as ventilation per person was statistically held constant, consistently *increase* in both symptoms at higher levels of ventilation per area. This is equivalent to our primary finding that, as ventilation per person is held constant, increasing occupant density was associated with increased symptom prevalence.

The BASE data provide the only available representative U.S. data on ventilation rate and occupant symptoms. Prior reported analyses for subsets of the BASE buildings [5] and from all 100 BASE buildings [4] have assessed relationship between symptoms in BASE buildings and carbon dioxide concentrations as a proxy for outdoor air ventilation. These analyses showed a dose-response relation between some building-related symptoms in unadjusted analyses using four categories of CO_2 concentrations, and a significant relationship of some outcomes to a linear term for CO_2 concentrations in multivariate models. The previous analyses did not have available for use the set of ventilation rate values based on measured airflows or CO_2 in air streams. These analyses also did not explore the data for evidence of thresholds or other nonlinear shape in the ventilation/symptom relationship, or for possible confounding of the ventilation/symptom relationship by density of occupancy.

The data set lacked very low VR, thus limiting contrasts. The dataset contained only 100 ventilation data points, although analyses were performed at the level of the 4,326 occupants. Differences between the VR determined by different measurement methods raise questions about their relative accuracy and interpretation. The peak CO_2 metric is based on several unverified assumptions and differed substantially from the other metrics, which agreed more closely; however this metric had maximum values closer to our expectations, and had no missing data values among the 100 buildings. The estimated uncertainty in VR from the CO_2 ratio method was often very high [7] because calculations were often based on small concentration differences. The accuracy of measurements of ventilation rate using the volumetric method is questionable ([9] unless the measurements are made in a long section of straight ductwork, which is very unusual. It is unclear which set of metrics is more accurate, or even if any one metric is more accurate across the full range of VR observed. This limitation makes it impossible to know which set of ventilation/symptom relationships is more accurate.

These analyses provide little information on the mechanisms relating ventilation rate to acute symptoms. That most of the patterns of association with ventilation rate were similar for lower respiratory and mucous membrane symptoms is consistent with either related mechanisms or with different but correlated causal pollutants.

Available epidemiologic studies of VR have generally assessed only whether symptoms or some other outcome differed *significantly* between two VRs or within a range of VRs. However, they generally have not assessed *magnitude* of effect on symptoms related to specific VR, or the shape of the overall ventilation/response relationship, in ways to provide appropriate input to the standard-setting process (e.g., with respect to slope, shape of curve, or evidence for threshold). Previous studies also have generally not collected data in ways allowing comparison of ventilation effects relative to occupancy density in the building. Furthermore, previous studies have generally used crude estimates of VR, with methods differing across studies, making synthesis difficult. Better scientific data are essential for setting more scientifically based ventilation standards, using a traditional health risk assessment approach. Ultimately, these standards should: (1) reflect a comparison of costs of increased outdoor air ventilation with the magnitude of health effects expected at different VRs, and (2) reflect the relative need for ventilation to control person-proportional contaminants and space-proportional contaminants, in specifying ventilation for spaces of widely differing density of occupancy, such as office space and auditoriums.

Conclusions and Implications

Findings from this study of representative large U.S. office buildings suggest, but not with complete consistency, that increases in VR even above 20 cfm/person, the current standard in office space, leads to decrease in some health symptoms, and that medium to high occupancy density is independently associated with increased symptoms. Additional research is necessary to document the magnitude of health benefits from increased ventilation, considering both occupant number and density, to help establish scientifically based health-protective ventilation guidelines that can balance health benefits with costs.

Acknowledgements

We thank the Indoor Environments Division of the U.S. Environmental Protection Agency for funding the National Institute of Standards and Technology to produce the ventilation rate estimates used in these analyses, and for creating the BASE study. We also thank Richard Diamond and Michael Bates for their helpful reviews of the manuscript.

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