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

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ABSTRACT

Insufficient information has been available on *measured* ventilation rates and symptoms in office workers. Using U.S. EPA data from 100 large U.S. office buildings, we assessed relationships in multivariate models between ventilation/person and lower respiratory and mucous membrane symptoms. Three preliminary ventilation estimates were used, based on CO_2 ratio in airstreams, peak indoor CO_2 concentrations, and volumetric estimates of flow rates. Ventilation rates (VRs) from 6-17 cfm/person *above* the current 20 cfm/person guideline for offices were associated generally with reduced symptom prevalence, but further benefits were not evident from higher VRs. For all ventilation estimates, higher occupant density was independently associated with more symptoms. Findings suggest that VRs somewhat above current guidelines would reduce symptoms in office workers, and that occupant density may play an unrecognized role in ventilation requirements. Different findings for the various ventilation estimates were surprising. Clarification of these relationships, and validation of VR measurement methods are necessary.

INDEX TERMS

Ventilation, Symptoms, Office workers, Respiratory symptoms, Indoor air quality

INTRODUCTION

Adequate outdoor air ventilation in buildings is required to dilute concentrations of indoor-generated pollutants to levels sufficiently low for the health and comfort of occupants. Increased ventilation, however, raises costs for conditioning temperature and humidity of the introduced outdoor air. Because incremental benefits of increasing outdoor air ventilation rates (VR) are expected to decrease as VR increases, the relationship is not expected to be linear; i.e., indoor pollutants and associated health effects should decrease much more with ventilation increased from 0-10 cfm/person than from 40-50 (1 cfm/person = approximately 2.1 $l/s\text{-}person^{-1}$).

Historically, VR 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 (Wargocki, Wyon et al. 2000). Furthermore, multiple studies, mostly in office buildings, have consistently associated lower VR with increased experience of health symptoms in occupants (Seppanen, Fisk et al. 1999). 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 irritation, toxicity, or odor.

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

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1) What are the quantitative relationships between ventilation and human 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, should building ventilation guidelines reflect both the number of occupants and the amount of indoor space per occupant (as ANSI/ASHRAE Standard 62-2004 now does (ASHRAE 2004)), and if so, 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 (Apte, Fisk et al. 2000; Erdmann, Steiner et al. 2002). The goal of the present analysis was to use recently produced direct estimates of VR in these buildings to analyze how occupant symptoms were related to both VR per person and occupant density.

METHODS

We used data from the Building Assessment and Survey Evaluation (BASE) Study, conducted between 1994-1998 by the U.S. Environmental Protection Agency, involving a representative sample of 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 responses from self-completed questionnaires. Descriptions of this study and the available data have been reported previously (Brightman, Wallace et al. 1999). Briefly, the study selected representative office buildings from geographic regions throughout the U.S., and within each building one randomly selected study space with at least 50 occupants.

VR/person values for the office spaces studied in BASE were estimated (Persily and Gorfain 2004) in three separate ways, using data from a preliminary report:

- "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/person estimated using the peak measured indoor – outdoor CO_2 concentration (among mean values in each study space) and a mass balance model that, based on several unverified assumptions, including an estimated rate of CO_2 production per occupant and the assumption that the peak equals the equilibrium concentration of indoor minus outdoor carbon dioxide.
- "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 VR/person estimate and occupant density (the mean of occupancy counts in each space divided by floor area) in models as multi-categorical risk variables. 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). Both outcomes required "weekly, work-related" symptoms – reported at least once per week at work in the last four weeks and improving outside the building. Other independent variables included personal information from the occupant questionnaires on demographics (gender, age, education, smoking status), health status (asthma and allergy diagnoses), job factors (years in building, hours per week at work, job satisfaction, job demand, job conflict), 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 outcome to estimate unadjusted and adjusted odds ratios (ORs) and 95% confidence intervals (CI) for both ventilation rate and occupant density. The OR, a measure of strength of association, indicates increased risk when >1.0 and decreased risk when <1.0. Models for each outcome included unadjusted models for each ventilation rate estimate and full multivariate models including ventilation rate, occupant 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 in 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) (Persily and Gorfain 2004). 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 showed different patterns of association with symptoms.

In the study population, 7.9% overall had work-related lower respiratory symptoms, and 29.4% had work-related mucous membrane symptoms. In multivariate models controlling for occupant density, prevalence of both symptoms generally decreased at VRs above the lowest level (Table 1). 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. Occupant density, with ventilation per person controlled for, was associated for all ventilation estimates with approximately 20-40% increased odds of symptoms at densities greater than about 2.5 persons per 1,000 sq ft.

DISCUSSION

Current ventilation standards, based historically on non-health-related criteria such as perception of odor, may not be health protective. Available reviews of the literature, in fact, suggest that VR above current minimum standards for offices may reduce symptoms among workers (Seppanen, Fisk et al. 1999). Health-protective VRs would require balancing of estimated exposure/ response relations with economic costs and technologic feasibility. We must also quantify both the ventilation necessary to remove pollutants produced by occupants and that to remove pollutants produced by buildings and contents. This would inform appropriate ventilation standards for indoor spaces of varying occupant density, such as auditoriums and offices.

At least three different 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, ventilation needed would be simply proportional to number of occupants. As ventilation per person increased, symptoms would decrease in some way unrelated to occupant density. Thus, with ventilation per person held constant, symptom prevalence would not change as occupant density increased. On the other hand, if densely populated spaces such as auditoriums required *less* ventilation per person

Table 1. *Occupant 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)
	Occupant 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)
	Occupant 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)
	Occupant 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, occupant density, and, for peak CO_2 model, presence of mechanical ventilation.

than sparsely occupied spaces, then with ventilation per person held constant, symptom prevalence would *decrease* as occupant densities increased. One explanation for this latter case might 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 occupant density increased symptoms in ways not reversible by ventilation, then with ventilation per occupant held constant, symptoms would *increase* as occupant density increased.

In these analyses, increased ventilation per occupant above the lowest levels seen, with occupant 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 suggested a threshold rather than a dose response: 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 finding was consistent: with ventilation per occupant held constant, as occupant density increased, symptom prevalence was neither constant nor decreasing. These results are consistent only with the third hypothesis. The 20-40% increase in odds for both symptom outcomes at greater than 2.5 occupants per 1,000 sq ft, seen with all ventilation methods, 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 occupant density; however, the analysis did adjust for a wide range of job factors.

The BASE data provide the only available representative U.S. data on ventilation rate and occupant symptoms in offices. Prior reported analyses of BASE buildings (Erdmann, Steiner et al. 2002) have assessed relationship between symptoms and carbon dioxide-based proxies 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. Previous analyses also did not consider possible nonlinear ventilation/symptom relationships, or possible confounding of the ventilation/ symptom relationship by density of occupancy.

The BASE data set lack very low VR, thus limiting contrasts. Also, differences between the VR determined by different measurement methods raise questions about their relative accuracy and interpretation. The peak CO_2 estimates involve unverified assumptions and differed substantially from the other estimates, which agreed more closely; however peak CO_2 estimates had maximum values closer to our expectations, and had no missing data values for the 100 buildings. Estimated uncertainty in VRs from the CO_2 ratio method was very high (Persily and Gorfain 2004) because calculations were often based on small concentration differences. Accuracy of estimated VRs from the volumetric method is questionable (Fisk, Faulkner et al. 2004) unless measurements were made in long sections of straight ductwork (very unlikely). It is unclear which VR estimate is more accurate, or if any one is more accurate across the full observed range of VR. This makes it impossible to know which set of ventilation/symptom relationships is more accurate. Finally, this analysis used ventilation estimates from a preliminary report, and findings using final values may be different.

Better scientific data are essential for setting 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 up to 6-17 cfm/person above the current 20 cfm/person standard in offices would lead to reduction in some health symptoms, and that medium to high occupant 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, in order to establish scientifically based health-protective ventilation guidelines that can balance health benefits with costs.

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