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Publication Date
2006-02-01

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Summary: *This paper summarizes three analyses of data on building-related environmental factors and occupant symptoms collected from 100 representative large U.S. office buildings. Using multivariate logistic regression models, we found increased occupant symptoms associated with a number of building-related factors, including lower ventilation rates even at the current guideline levels, lack of scheduled cleaning for air-conditioning drain pans and cooling coils, poor condition of cooling coils, poorly maintained humidification systems, and lower outdoor air intake height. Some expected relationships were not found, and several findings were opposite of expected. Although requiring replication, these findings suggest preventive actions to reduce occupant symptoms in office buildings.*

Keywords: *indoor air quality; ventilation; moisture; building-related symptoms; sick building syndrome*
Category: *epidemiologic studies*

1 Introduction

For decades, episodes of symptom complaints, including upper and lower respiratory symptoms, eye and skin irritation, headache, and fatigue, have been reported by occupants of modern office and other commercial buildings in many countries. Explanation and resolution of these problems have often been difficult. Numerous scientific studies have documented that these building-related symptoms are surprisingly common even in buildings without widespread health complaints. Research has identified a number of risk factors correlated with these symptoms (e.g., low ventilation rates, dampness, and contaminated HVAC components), but generally not specific causal "exposures" [1-3].

Current causal hypotheses focus on indoor biological and chemical contaminants emitted from buildings, their contents, or the ventilation systems. Lower ventilation rates, which have been associated with increased prevalence of building-related symptoms, are assumed to cause higher indoor concentrations of these chemical or biologic contaminants [3].

Limited epidemiologic research on this question has been reported from the U.S. The Building Assessment and Survey Evaluation (BASE) study is the largest study to date of building environments and occupant symptoms in U.S. office buildings. Analyses of the BASE data are ongoing to identify environmental factors (called "risk factors") that may help explain the building-related symptoms.

This paper briefly summarizes the findings from three current analyses of BASE data. Risk factors assessed in these analyses include lower outdoor air ventilation rates; indicators of moisture or moisture-related contamination in buildings; and design, operation, maintenance, and condition of heating, ventilating, and air-conditioning (HVAC) systems.

2 Methods

The BASE study data were collected from 1994 to 1998 by the U.S. EPA from 100 U.S. office buildings. Descriptions of this study have been published previously [4]. Briefly, the study selected a representative set of 100 large office buildings from geographic regions throughout the U.S., and randomly selected within each building a study space with at least 50 occupants and no more than two air handling units. Data were collected from questionnaires given to all occupants of each study space, from standardized inspections of the buildings and ventilation systems, and from standardized interviews conducted with facility managers. The three analyses summarized here investigated different building-related factors as potential risk factors for prevalence of building-related symptoms.

All analyses were based on the presence or absence of "weekly, building-related" symptoms – defined as a specific symptom experienced in the building at least once per week within the last four weeks and also improving away from the building. This summary paper reports associations of risk factors with four single or combination symptom outcomes: lower respiratory (at least one of wheeze, shortness of breath, or chest tightness), upper respiratory (at least one of stuffy or runny nose, sneezing, or sore or dry throat); eye (dry, itching or irritated eyes); and headache.

Independent variables used in the analyses as risk factors or potential confounding variables included information from the occupant questionnaires (on demographics, health status, job, and workspace factors) and information collected by study personnel: inspection of ventilation systems, buildings, and occupied spaces; interviews with facility managers on building and ventilation system-related practices and history; and environmental monitoring for temperature, relative humidity, and ventilation. Personal potential confounding variables included sex, age, education, job satisfaction, job demand, job conflict, asthma, mold allergy, hay fever, and years working in building.

The first analysis investigated lower outdoor air ventilation rate (VR) as a risk factor, using three different methods of estimating VR/person in units of liters per second per person (l/s-person): *volumetric* estimates of flow rates, *carbon dioxide (CO_2) ratio* in airstreams, and *peak indoor minus outdoor CO_2* concentrations (see Appendix 1 for more detailed definitions) [5]. For the first two estimators (feasible only in the 97 mechanically ventilated buildings), data were available for 92 and 90 buildings respectively, after exclusion of very high estimates for one building (VRs more than twice all others). For the peak CO_2 estimator, data were available for 100 buildings, including 3 naturally ventilated. Occupant number and density were estimated from occupant counts in each study space during the data collection. Each VR estimator was modeled both as a 7-category variable and as a continuous variable. Models also included a variable for occupant density (occupants per 100 m^2) in the study space. The second analysis investigated risk factors indicating potential moisture or moisture-related contamination in the buildings and HVAC systems. These risk factors included current or past water damage at specific locations in the building, the condition and scheduled maintenance of water-related components in the ventilation system, and frequency of wet cleaning in indoor spaces. The third analysis (overlapping some with the second analysis) investigated risk factors related to design, operation, maintenance, and condition of HVAC systems.

We estimated relationships between risk factors and health outcomes in multivariate logistic regression models, using SAS version 8 [6]. We used a common algorithm across the three analyses to select risk factor and confounding variables for inclusion in initial multivariate models and for removal to create smaller models. Potential confounding variables were included in each model only if inclusion changed the estimate of the outcome by at least 15%.

Estimates from logistic regression models are reported as odds ratios (ORs) and 95% confidence intervals (CIs). OR values exceeding 1.0 indicate increased symptom prevalence in those with the risk factor; values less than 1.0, a decreased prevalence (expected for "protective" factors such as incresaed ventilation and less frequent wet mopping); and values=1.0, no relationship. Due to space limitations, Tables 2 and 3 show ORs only for risk factors for which at least one OR has 95% CIs excluding 1.0.

3 Results

Data from 4,326 BASE building occupants and study spaces within 100 buildings were available. The overall response rate for the questionnaire was 85%.

Ventilation rate

Table 1 shows adjusted ORs and 95% CIs for the three VR estimators, using either categorical or continuous variables. These six models for each outcome provide somewhat consistent evidence for decreased lower respiratory symptoms at higher ventilation rates, with less consistent findings for upper respiratory and eye symptoms and headache. Categorical estimates for all VR estimators and outcomes generally did not show consistent trends as VR increased. Relationships were strongest for the peak CO2 estimator, which showed a mostly consistent pattern across symptoms – lower prevalence in all ventilation categories above 10.5 l/s-person (approx. 22 cfm/person), but without clear trends across these categories.

OR estimates based on a continuous variable for mean indoor minus outdoor carbon dioxide concentrations (not a VR, but an often-used proxy for VR) are provided at the bottom of Table 1. ORs for a 100 ppm decrease in mean indoor minus outdoor CO_2 concentrations are similar to the ORs above for a 10 l/s-person increase in VR estimated from peak indoor minus outdoor CO_2 concentrations.

For all ventilation estimators, occupant density higher than about 2.7 occupants per 100 m^2 was *independently* associated with increased symptoms (data not shown), even when adjusted for VR/person.

Moisture and related contamination

Among moisture factors (Table 2), infrequent cleaning of HVAC cooling coils and drain pans was a risk factor for three symptom outcomes. Dirty cooling coils were a risk factor for lower respiratory symptoms. Several water damage variables, especially history of fire damage, were associated with increased risk; however, most of the water damage variables investigated were not, and current water damage to the roof was associated with a *decreased* prevalence of eye symptoms. Wet mopping less than daily, relative to daily, was associated with decreased risk of upper respiratory symptoms and headache, although the category "none or as needed" was associated with no change or a slight increase. Of 11 risk factors investigated in this analysis, four variables had insufficient associations for inclusion in Table 2: current and past water damage in the occupied space, and current and past water damage in the basement.

HVAC system factors

HVAC system risk factors (Table 3) associated with increased prevalence of multiple symptoms included

Table 1. Ventilation per occupant: multivariate adjusted** odds ratios (OR) and 95% confidence intervals (CI) for associations with occupant symptoms in U.S. office buildings in the BASE data

Outdoor Air Ventilation Rate Per Person	**Weekly Building-Related Symptom Outcomes**			
	Lower respiratory OR (CI)	**Upper respiratory OR (CI)**	**Eye OR (CI)**	**Headache OR (CI)**
Estimated by Volumetric Flow				
Categorical variable:				
0.0 - 7.7 l/s-person	1.0	1.0	1.0	1.0
7.7 - 14.5	1.03 (0.60-1.76)	1.35* (1.02-1.79)	1.03 (0.77-1.39)	1.25 (0.90-1.72)
15.5 - 23.8	1.13 (0.64-1.97)	1.15 (0.86-1.55)	0.93 (0.68-1.27)	1.08 (0.77-1.51)
24.2 - 38.7	0.98 (0.55-1.74)	1.03 (0.76-1.40)	0.94 (0.68-1.28)	1.13 (0.80-1.60)
41.4 - 61.9	0.92 (0.49-1.75)	1.03 (0.74-1.44)	0.91 (0.65-1.28)	0.99 (0.67-1.45)
62.3 - 106.2	0.89 (0.49-1.63)	1.08 (0.80-1.48)	1.08 (0.78-1.48)	1.15 (0.81-1.64)
109.6 - 226.4	0.63 (0.33-1.19)	1.12 (0.82-1.53)	0.93 (0.67-1.28)	1.18 (0.83-1.68)
Continuous variable (per 50 l/s-person increase)	0.85 (0.72-1.01)	0.96 (0.89-1.04)	0.99 (0.91-1.07)	1.02 (0.93-1.11)
Estimated by CO_2 Ratio in Airflows				
Categorical variable:				
3.0 - 8.2 l/s-person	1.0	1.0	1.0	1.0
8.8 - 15.5	1.61 (0.91-2.86)	1.09 (0.82-1.45)	1.12 (0.83-1.52)	0.96 (0.69-1.33)
16.1 - 25.7	1.21 (0.65-2.24)	0.95 (0.70-1.28)	0.79 (0.57-1.10)	0.95 (0.68-1.34)
27.2 - 37.5	1.17 (0.63-2.18)	0.99 (0.74-1.33)	1.22 (0.90-1.65)	0.93 (0.67-1.30)
37.7 - 52.5	1.13 (0.59-2.14)	0.99 (0.72-1.34)	0.87 (0.62-1.21)	0.85 (0.59-1.22)
54.8 - 82.1	0.69 (0.33-1.43)	0.67* (0.49-0.93)	0.77 (0.55-1.08)	0.88 (0.62-1.26)
85.3 - 207.8	0.75 (0.37-1.52)	0.96 (0.70-1.31)	1.01 (0.72-1.40)	0.92 (0.64-1.31)
Continuous variable (per 50 l/s-person increase)	0.78* (0.62-0.98)	0.94 (0.85-1.04)	0.94 (0.84-1.04)	0.98 (0.88-1.10)
Estimated by Peak CO_2 Concentrations				
Categorical variable:				
6.8 - 10.1 l/s-person	1.0	1.0	1.0	1.0
10.5 - 12.3	0.61 (0.36-1.02)	0.83 (0.64-1.09)	0.82 (0.62-1.09)	0.73 (0.53-1.00)
12.4 - 15.6	0.52* (0.30-0.92)	0.78 (0.59-1.03)	0.72*(0.53-0.97)	0.82 (0.59-1.14)
15.9 – 18.8	0.78 (0.45-1.34)	0.99 (0.75-1.31)	0.96 (0.72-1.29)	0.80 (0.57-1.12)
18.8 – 22.8	0.57* (0.34-0.96)	0.94 (0.73-1.23)	0.89 (0.67-1.18)	1.08 (0.80-1.45)
23.0 – 27.2	0.58 (0.33-1.00)	0.75* (0.56-0.99)	0.75 (0.56-1.02)	0.83 (0.60-1.15)
28.0 – 59.9	0.41* (0.22-0.76)	0.72* (0.53-0.97)	0.75 (0.55-1.02)	0.91 (0.65-1.26)
Continuous variable (per 10 l/s-person increase)	0.89 (0.76-1.03)	0.94 (0.87-1.01)	0.95 (0.88-1.03)	1.01 (0.93-1.09)
Mean indoor minus outdoor CO_2 concentration, range 40-610 ppm (not a ventilation rate estimate)				
Continuous variable (per 100 ppm decrease)	0.89* (0.79-0.99)	0.95 (0.90-1.00)	0.95 (0.90-1.01)	0.99 (0.93-1.05)
Continuous variable (per 100 ppm increase)	1.13* (1.01-1.26)	1.06 (1.00-1.12)	1.05 (0.99-1.11)	1.01 (0.95-1.08)

*P-value <0.05. ** adjusted for gender, smoking status, asthma, and occupant density in occupied space.

lower outdoor air intake height (relative to a reference height of >60 m), poorly maintained humidification systems, and infrequently cleaned cooling coils and drain pans. Risk factors associated with increased prevalence of one symptom included lack of scheduled inspection for HVAC systems, poorer condition of liners in ducts and air handler housing, poorer condition of filtration systems, and less frequent calibration of control systems. Poorer condition of air handler was associated with some

Table 2. Moisture and moisture-related contamination: multivariate adjusted** odds ratios (ORs) and 95% confidence intervals (CIs) for associations with occupant symptoms in U.S. office buildings in the BASE data

Risk Factors	Weekly Building-Related Symptom Outcomes			
	Lower respiratory OR (CI)	Upper respiratory OR (CI)	Eye OR (CI)	Headache OR (CI)
HVAC condition and maintenance				
Pan and coil cleaning frequency				
At least semi-annually	1.0	1.0	1.0	1.0
At least annually	2.14 (0.96-4.78)	1.37* (1.05-1.79)	1.41* (1.06-1.87)	1.42* (1.04-1.95)
None	2.16 (0.93-5.01)	1.24 (0.92-1.66)	1.38* (1.01-1.88)	1.37 (0.97-1.94)
As needed	1.77 (0.78-4.05	0.96 (0.72-1.28)	1.00 (0.73-1.36)	1.08 (0.78-1.51)
Coil condition				
good	1.0	---	---	---
dirty or bad	1.74*(1.07-2.83)	---	---	---
Moisture/water damage in building or occupied space				
Current water damage				
Roof	---	---	0.69* (0.53-0.89)	---
Past water damage				
Mechanical room in building	---	---	1.27* (1.02-1.59)	---
Roof	---	1.10 (0.94-1.28)	1.14 (0.97-1.35)	1.20* (1.00-1.44)
History of fire damage in building	1.87* (1.18-2.95)	1.22 (0.98-1.53)	1.34* (1.04-1.71)	---
Wet cleaning in study spaces				
Wet floor mopping frequency				
Daily (higher risk expected)	---	1.0	---	1.0
Less than daily	---	0.57* (0.43-0.77)	---	0.60* (0.43-0.84)
As needed or none	---	0.99 (0.78-1.27)	---	1.24 (0.94-1.62)

*P-value <0.05. ** adjusted for gender, smoking status, asthma, and other potential confounding variables.

decreased prevalence of three symptoms. Of 22 risk factors investigated in this analysis, those with insufficient association for inclusion in Table 3 include: presence of local cooling systems, supply duct material, ventilation hours per weekday, variable vs. constant air volume system, presence of return fan and duct, use of pre-occupancy ventilation, use of economizer, outdoor air intake strategy, condition of operational components of air handler, condition of cooling tower, filter fit, frequency of filter replacement, and frequency of cooling tower cleaning.

4 Discussion

The EPA BASE data allow the first broad assessment in U.S. office buildings of the associations between suspected indoor environmental risk factors and nonspecific symptoms in office workers.

Ventilation

Findings here suggest, fairly consistently across the three VR estimators, that VRs above the commonly used minimum ventilation guideline for offices of 10 l/s-person [9] may substantially reduce the prevalence of lower respiratory symptoms. Findings are less consistent on relationships at specific higher ventilation levels, or on effects of VR on upper respiratory or eye symptoms, and offer least evidence of any effect on headache. As each of the three VR estimators has limitations related to possible incorrect assumptions, it is not clear which is more accurate, or if any is more accurate across the range of VRs studied.

Despite smaller ORs at the highest vs. the lowest VRs for some outcomes, intermediate VR categories did not decrease monotonically. If VR has an underlying consistent and monotonic effect on symptoms, the variability in category-specific ORs for the VRs may be from imprecision due to small numbers or to other risk factors not considered in models.

In constructing models to estimate associations between VR and symptoms, we found the estimates not to be very robust. Forcing additional potential confounding covariates sequentially into the model led to progressive reduction in the size of VR effects for some symptom outcomes. Associations found here between symptoms and mean indoor minus outdoor CO_2 concentrations were generally similar to those found in earlier analyses of these data using different modeling approaches [7] and findings in other studies [3].

Moisture

A large body of research has documented associations between risk factors related to moisture or mold in residences and respiratory health effects [8]. This, with the few studies reported on these relationships in offices (e.g., [2]), would predict increased respiratory symptoms in association with moisture and related contamination in BASE data. Findings here of

Table 3. HVAC system risk factors: multivariate adjusted** odds ratios (ORs) and 95% confidence intervals (CIs) for associations with occupant symptoms in U.S. office buildings in the BASE data

Risk Factors	**Weekly Building-Related Symptom Outcomes**			
	Lower respiratory OR (CI)	**Upper respiratory OR (CI)**	**Eye OR (CI)**	**Headache OR (CI)**
Height of outdoor air intake above ground				
> 60 m	1.0	1.0	---	1.0
>30 – LE 60 m	1.75 (0.74-4.16)	3.02* (1.81-5.05)	---	1.72* (1.07-2.76)
≥ 0 to LE 30 m	1.39 (0.65-2.99	2.93* (1.83-4.70)	---	1.64* (1.11-2.41)
> -3 to 0 m	2.15 (0.94-4.89)	3.12* (1.85-5.26)	---	1.94* (1.22-3.08)
Central humidification system				
no humidification system	1.0	1.0	1.0	1.0
humidified, condition fair/good	0.52 (0.26-1.04)	0.87 (0.65-1.17)	0.92 (0.66-1.26)	1.44* (1.06-1.97)
humidified, condition poor	1.33 (0.72-2.47)	2.25* (1.64-3.10)	1.28 (0.92-1.76)	1.48* (1.09-2.02)
Frequency of cleaning of cooling coils and drain pan				
semi-annually or more	1.0	---	1.0	1.0
annually	3.45* (1.48-8.07)	---	1.18 (0.85-1.63)	1.55* (1.08-2.22)
as needed or none	3.34* (1.41-7.91)	---	0.98 (0.70-1.36)	1.42 (0.98-2.04)
Frequency of HVAC inspection				
semi-quarterly or more	---	---	1.0	---
annually to quarterly	---	---	1.05 (0.85-1.29)	---
as needed or none	---	---	1.96* (1.48-2.59)	---
Condition of filtration system				
good	1.0	---	---	---
fair	1.72* (1.15-2.58)	---	---	---
poor	0.70 (0.33-1.51)	---	---	---
Condition of liner in ducts and air handler housing				
good	---	1.0	---	1.0
fair or poor	---	1.26* (1.01-1.57)	---	1.17 (0.93-1.46)
Condition of air handler				
good/fair	----	1.0	1.0	1.0
fair	---	0.78* (0.62-1.00)	0.83 (0.67-1.02)	0.77* (0.59-0.99)
fair/poor	---	0.87 (0.68-1.11)	0.92 (0.72-1.16)	0.99 (0.74-1.33)
Frequency of controls calibration				
semi-annually or more	----	1.0	----	----
annually	---	1.55* (1.07-2.24)	---	---
none or as needed	---	1.10 (0.85-1.42)	---	---

*P-value <0.05. ** adjusted for gender, smoking status, asthma, and other potential confounding variables.

increased symptom prevalence related to infrequently cleaned cooling coils and drain pans, and with dirty cooling coils, generally agreed with expectations. Findings on other risk factors related to moisture damage, however, did not consistently support prior findings or hypothesized relationships. This may be due to imprecision of subjective assessements for water damage.

HVAC factors

Findings here of increased symptom prevalence related to infrequently cleaned cooling coils and drain pans and poorly maintained humidification systems agree with expectations. Many other factors for which associations with increased symptoms could be reasonably expected were not associated in the multivariate models. BASE assessments of moisture damage or HVAC conditions generally did not predict increased risk of symptoms, A prior study of office buildings with complaint-based health investigations reported debris in air intakes, poor pan drainage, and water damage in occupied spaces as significant risk factors for increased lower respiratory symptoms among occupants [2]. The greater contamination levels in selected “complaint” buildings may be too rare to detect in only 100 “normal” BASE buildings.

The consistent association found here of symptom prevalence with outdoor air intake height has not been previously reported, to our knowledge. The estimates show decreasing symptom prevalence as outdoor air intake height increases up to 60 m. A previously unrecognized effect of ground-level vehicular exhaust on indoor air quality seems unlikely to fully explain the strong effect seen with air intakes even eight to fifteen stories (30-60 m) above the ground.

Overall limitiations

The BASE data, although the largest and most comprehensive collection of standardized data from representative office buildings in the U.S., was conducted primarily to obtain normative data and has limitations for epidemiologic analyses. The subjective, self-reported health outcome assessments used are imprecise, as are environmental reports from inspection, and this imprecision could have resulted in bias toward the null and obscured true associations. Although the study contained over 4,000 occupants, the environmental variables were collected in only 100 buildings, allowing limited analysis of variation in these factors. Intercorrelated environmental factors assessed could often not be included in the same models, making it impossible to assess risks for some factors of interest while holding other closely related factors constant. Finally, this analysis included many risk factors and statistical tests. Thus, some associations found here may have occurred without true underlying associations.

Findings here and elsewhere indicate that some forms of moisture and related contamination in buildings and outdoor air intakes closer to the ground may increase risk of building-related symptoms in office buildings. Findings also suggest that office VRs above current minimum guidelines would reduce at least lower respiratory symptoms, and that occupant density may play an unrecognized role in ventilation requirements. Although requiring replication, these findings suggest initial preventive actions to reduce occupant symptoms in office buildings. Future research should clarify the relationships reported here, using better validated VR measurements and more rigorous environment and health measurements.

Appendix 1. Ventilation Rate Estimators [5]

1) Volumetric method – total outdoor air intake from air velocity measurements in outdoor airstreams of air handlers, divided by number of occupants.

2) 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, divided by the number of occupants.

3) Peak CO_2 method – VR/person estimated using peak measured indoor minus outdoor CO_2 concentration and a mass balance model based on unverified assumptions including uniform spatial CO_2 concentrations, estimated CO_2 production per person, and equilibrium CO2 assumed to equal the peak CO2.

Acknowledgements

This work was supported by the Indoor Environments Division, Office of Radiation and Indoor Air, Office of Air and Radiation of the U.S. Environmental Protection Agency (EPA) through interagency agreements DW89939365-01-0 and DW89921695-01-1 with the U.S. Department of Energy (DOE). Conclusions in this paper are those of the authors and not necessarily those of the U.S. EPA. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. DOE under contract DE-AC02-05CH11231. We thank Andy Persily of the U.S. National Institute of Standards and Technology for producing ventilation rate estimates.

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