Indoor Air 2000; 10: 212–221
http://journals.munksgaard.dk/indoorair

INDOOR AIR
ISSN 0905-6947

Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints

DONALD K. MILTON[1]*, P. MARK GLENCROSS[1,2] AND MICHAEL D. WALTERS[2]

Abstract We analyzed 1994 sick leave for 3,720 hourly employees of a large Massachusetts manufacturer, in 40 buildings with 115 independently ventilated work areas. Corporate records identified building characteristics and IEQ complaints. We rated ventilation as moderate (≈25 cfm/person, 12 ls^{-1}) or high (≈50 cfm/person, 24 ls^{-1}) outdoor air supply based on knowledge of ventilation systems and CO_2 measurements on a subset of work areas, and used Poisson regression to analyze sick leave controlled for age, gender, seniority, hours of non-illness absence, shift, ethnicity, crowding, and type of job (office, technical, or manufacturing worker). We found consistent associations of increased sick leave with lower levels of outdoor air supply and IEQ complaints. Among office workers, the relative risk for short-term sick leave was 1.53 (95% confidence 1.22–1.92) with lower ventilation, and 1.52 (1.18–1.97) in areas with IEQ complaints. The effect of ventilation was independent of IEQ complaints and among those exposed to lower outdoor air supply rates the attributable risk of short-term sick leave was 35%. The cost of sick leave attributable to ventilation at current recommended rates was estimated as $480 per employee per year at Polaroid. These findings suggest that net savings of $400 per employee per year may be obtained with increased ventilation. Thus, currently recommended levels of outdoor air supply may be associated with significant morbidity, and lost productivity on a national scale could be as much as $22.8 billion per year. Additional studies of IEQ impacts on productivity and sick leave, and the mechanisms underlying the apparent association are needed.

Key words Sick leave; Ventilation; Humidity; Common cold; Air conditioning; Air pollution, indoor; Absenteeism; Occupational exposure; Environment and public health.

Practical Implications
This paper demonstrates an association between expert ratings of outdoor air supply rate and the presence of sick leave among 3,720 employees (and particularly among 600 office employees) of a large U.S. manufacturer. The paper shows that in this large sample the cost of providing additional ventilation may be more than offset by the savings that result from reduced sick leave. It is important to note that the range of ventilation rates compared [moderate with approximately 12, and high with approximately 24 l/s-person] are at the upper end of rates seen in these facilities. That indicates that benefits continue to accrue when ventilation is increased above 10 l/s-person, and that experimental studies to validate and to determine mechanisms for these observational findings should be a priority for indoor air research.

Received for review 28 October 1999. Accepted for publication 5 January 2000.

Introduction

Studies of indoor environmental quality and health generally concentrate on the relationship of building environments either to common symptoms or to asthma and rare illnesses such as hypersensitivity pneumonitis. Non-specific building related symptoms (BRS) have been associated with a variety of building features including low levels of outdoor air supply per occupant in mechanically ventilated buildings (Mendell, 1993). Above approximately 20 cfm/person (10 ls^{-1}/person) of outdoor air supply, however, increased dilution ventilation usually does not reduce occupant symptoms because it may not reduce the relevant exposures (Menzies et al., 1993; Menzies et al., 1996). However, studies going beyond symptoms to direct measures of the influence of building environments on health and productivity are few.

Sick leave is an outcome that could be used to study the indoor environment. Sick leave data have been used for a variety of other purposes, such as indicators of respiratory disease among agricultural workers (Post et al., 1994), to identify ergonomic problems (Knave et al., 1991), and to evaluate health promotion programs (Golaszewski et al., 1992; Jeffery et al., 1993).

[1]*Harvard School of Public Health, Boston, Massachussets, USA, e-mail: dmilton@hohp.harvard.edu,* [2]*Polaroid Corporation, Cambridge, Massachussets, USA,* **Author to whom correspondence should be addressed.*

Sick leave has also been used to assess efficacy of influenza vaccination (Nichol et al., 1995). In general, respiratory illness accounts for a large fraction of all sick leave (Nichol et al., 1995; Bendrick, 1998; Feeney et al., 1998). Teculescu et al. (1998) recently reported that occupants of an air-conditioned building were more likely to have multiple absences from work than were persons in a naturally ventilated building in northeastern France. That study was limited, however, by the use of only two buildings, and by lack of control for ventilation rates and individual and group factors that may have confounded the relationship between building and sick leave.

Job demands, shift work and noise have all been shown to correlate with absence from work (Melamed et al., 1992; Aguirre and Foret, 1994; Lindstrom et al., 1994). Psychosocial, demographic, and work organizational factors as well as smoking also influence absence rates (Blake et al., 1988; Janes and Ames, 1992; North et al., 1993; Alexanderson et al., 1994). The influence of these various factors on absence rates makes the issue of confounding in epidemiologic studies of workplace absence particularly complex (Reidy, 1990).

Here, we report on sick leave among 3,720 hourly office, technical, and manufacturing workers in 115 different work areas, each with separate ventilation, at a large Massachusetts employer. We controlled for factors that may have influenced sick leave rates by inclusion of demographic variables in Poisson regression analyses. We also performed stratified analyses focused on office workers.

Material and Methods

As part of an evaluation of occupational and environmental health programs at Polaroid Corporation, a non-unionized manufacturing corporation in New England, we studied sick leave of hourly employees for calendar year 1994. Each timecard record contained information on duration and type of absence including sick leave, industrial accident, tardiness, vacation, family obligation, civic obligation, authorized absence, unauthorized absence and holiday for each month in 1994. Our evaluation used only sick-leave of employees not on long-term disability.

We matched absence records with information on age, gender, race, shift, job code, years of employment (seniority), and the employee's primary work area (building and floor) as recorded in the corporate database for December 1994. Job codes and titles were assigned a job type of manufacturing, trades and technical workers, or clerical office worker. Records of short-term disability (absence >5 consecutive days) included a code for the worker's medical condition. Disability codes were separated into conditions possibly exacerbated by IEQ (respiratory conditions, and headache) and all others.

There were 4,119 hourly workers. We excluded employees from the analysis of sick-leave as follows: worked outside of Massachusetts (n=215), received pregnancy leave (n=26), summer interns (n=171), incomplete demographics (n=15), payroll errors (n=8), work area with incomplete information on ventilation and humidification (n=237). Some workers met multiple exclusion criteria leaving 3,720 for analysis of total sick leave.

Because the analysis of total sick leave could be dominated by a few workers with extended sick leave, we also analyzed short-term sick leave. We computed short-term sick leave in two steps. First, we excluded workers from the computation who were scheduled to work <160 h (1 month) (n=7), were absent due to illness for 50% or more of the of the year (n=43), or received short-term disability payments at any time during the year (n=304). Several workers met multiple exclusion criteria leaving 3,364 workers for analysis of short-term sick leave. Second, for those workers included in the short-term sick leave computations, we excluded person-months with sick leave for >50% of scheduled hours. To further examine the effects of longer absences, we repeated some analyses after drawing progressively tighter restrictions on the maximum allowed absence in a month by exclusion of person-months with progressively shorter absences (exclusion of sick leave >25%, >10%, >5%, >2%, and >1% of scheduled hours).

We focused our analyses on clerical office workers to eliminate the possibility of uncontrolled confounding of sick leave by occupational factors (Melamed et al., 1992; Aguirre and Foret, 1994; Lindstrom et al., 1994), and because it is the office environment that has been the recent focus of concern about IEQ. The large number of work areas examined in this study were likely to randomize remaining occupational factors among workers in the same job categories and thus reduce potential confounding.

Each worker was assigned to one of 150 different work areas (floors) in 65 buildings based on payroll data. Fewer than 20% of the buildings were connected by an enclosed corridor with potential for air exchange between buildings. Smoking was not permitted inside any building. Humidification was the presence of devices to humidify supply air. These devices included steam, spray and finfill humidifiers. Finfill consisted of fin-like wetted media located down stream of filtration and temperature conditioning units. Both spray and finfill systems used recirculated water.

Presence of complaints was whether a formal complaint had been made to the corporate environmental health and safety office within the last 3 years (1992–1994). Complaint investigations did not result in changes in levels air supply, except for increased ventilation in one conference room. Unpleasant odor was the most frequently recorded complaint. Remediation consisted of drying and cleaning carpets or other sources of potential microbial volatile compounds, enforcement of smoking bans, and one case each of installation of local exhaust for a blue-print machine and of carbon filters in an air supply duct.

Ventilation for each floor (work area) was categorized as either ''moderate'' or ''high'' (Figure 1) based on an expert rating. This rating was made by one hygienist (M.D.W.) using his knowledge of the performance of the ventilation system, modifications made to existing buildings and systems, and the results of average end-of-day CO_2 measurements from a majority of the floors made with a continuous monitor (Metrasonics AQ502 IAQ Monitor; West Henrietta, NY, USA). We estimated ventilation rate, in cubic feet of outside air per min per person (cfmp) from available CO_2 data for representative buildings in each category using the standard conversion from CO_2 (ASHRAE, 1989). The industrial hygienist was blind to the sick leave, but was aware of the complaint status of each area.

The area occupied by each employee was estimated by subtracting the area of loading docks and warehouses from available space for each floor, then dividing by the number of employees assigned to the floor. Area data was available for 111 floors. Crowding was defined as <100 ft^2 (9.3 m^2) per employee.

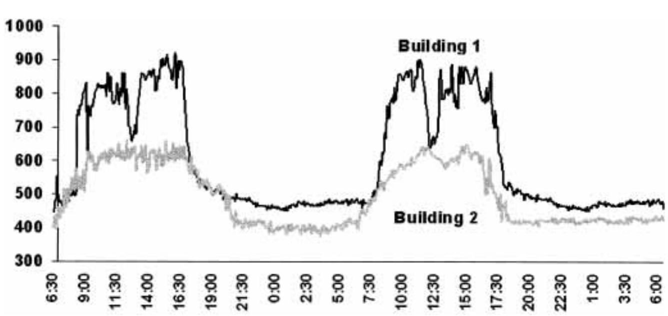

Fig. 1 Representative CO_2 measurements over two days in buildings with ventilation rated as ''moderate'' (Building 1) and ''high'' (Building 2). CO_2 concentrations were continuously monitored for two days in selected office areas to establish baseline data on adequacy of outdoor air supply rates. Building 1 has average CO_2 levels of 800–900 ppm, approximately 23–27 ft^3 (11–13 ls^{-1}) outdoor air supply per person per minute, during periods of usual occupancy. Building 2 has CO_2 levels near 600 ppm, 49 ft^3 (23 ls^{-1}) outdoor air supply per person per minute, during regular occupancy

Ventilation ratings and humidification rating data were available for 115 of the 150 floors (40 buildings), including 102 floors with area data. Air sampling data was collected for 38 floors from 1992–1994. Air sampling was performed by corporate industrial hygienists as part of routine surveys and in response to complaints. Fungal spore counts were collected using a Burkhard spore trap (Ricksmanworth, Herfordshire, UK). Air samples for culture of bacteria on trypticase soy agar and fungi on malt extract agar were collected with an Anderson N1 sampler (Grasby Anderson Inc., Atlanta, GA, USA). Fungal and bacterial samples were analyzed according to standard methods (Macher et al., 1999). Endotoxin and total airborne bacteria samples were collected on 0.4-μm pore polycarbonate membrane filters. Total bacteria were counted by the CAMNEA method (Palmgren et al., 1986). Endotoxin samples were extracted in buffer, 0.05 M potassium phosphate, 0.01% triethyamine pH 7.5, and assayed by the kinetic *Limulus* assay with resistant-parallel-line estimation method (Milton et al., 1992). Volatile organic compounds were collected on Air Quality Sciences Series 7000 TVOC tubes and analyzed by AQS (Atlanta, GA, USA).

Statistical analysis was performed using SAS (SAS Institute, Cary, NC, USA). We analyzed monthly sick leave, controlled for covariates, by Poisson regression. Robust standard errors, including compensation for overdispersion, were computed using Generalized Estimating Equations in SAS Proc Genmod (Diggle et al., 1994). Working correlation assumptions were chosen based on within person correlation of residuals from the regressions: exchangeable for analysis of total sick leave, and independent for short-term sick leave. Attributable fraction among the exposed was computed as the difference between the absence rates in the exposed and the unexposed divided by the rate in the exposed using rates adjusted for other covariates in the Poisson regression.

The cost of ventilation was estimated from the average cost of increased outdoor air supply in the buildings studied (\$3.22/cfmp per year, \$6.83/ls^{-1}). We assume that the associations observed among hourly workers would also occur among salaried workers. Therefore, the attributable cost of sick leave was estimated using the attributable days of sick leave from regression analysis and the cost of all employee compensation at Polaroid (\$40 per h) and for all full-time US workers (\$20.37 per h) (U.S. Department of Commerce, 1998).

Results

Age distribution was skewed towards older workers (Table 1); 41% of the workers were 50 yrs and older,

Table 1 Demographics

	Total Absence Data		Short-term Absence Data	
Number of Workers	3,720		3,364	
Mean Age	47.0*	±9.24	46.8*	±9.22
Mean Senority	18.6*	±8.5	18.5*	±8.50
Male	2,479	66.8%	2,266	67.4%
Job type				
Office	705	19.0%	636	18.9%
Trades	1,003	27.0%	919	27.3%
Manufacturing	2,012	54.1%	1,809	53.8%
Shift				
A shift (day)	2,457	66.0%	2,185	65.0%
B shift (evening)	703	18.9%	654	19.4%
C shift (night)	392	10.5%	364	10.8%
Other or rotating	168	4.5%	161	4.8%
Ethnicity				
Native American	11	0.3%	9	0.3%
Asian	27	0.7%	22	0.7%
Hispanic	68	1.8%	59	1.8%
African American	805	21.6%	724	21.5%
Caucasian	2,809	75.5%	2,550	75.8%

Table 3 Annual Sick-Leave Rates*

	Total Absence		Short-term Absence	
	Number	Rate	Number	Rate
All employees	3,720	3.49%	3,364	1.53%
Male	2,479	3.24%	2,266	1.42%
Female	1,241	3.99%	1,098	1.75%
Office workers	705	3.57%	636	1.71%
Skilled Trades	1,003	3.09%	919	1.33%
Manufacturing workers	2,012	3.66%	1,809	1.56%
A shift (day)	2,457	4.02%	2,185	1.50%
B shift (evening)	703	2.29%	654	1.54%
C shift (night)	392	3.13%	364	1.67%
Other shift or rotating	168	1.65%	161	1.45%
Complaint Area:				
No	2,306	3.69%	2,084	1.52%
Yes	1,414	3.17%	1,280	1.54%
Ventilation:				
Moderate	665	4.87%	595	1.66%
High	3,055	3.19%	2,769	1.50%
Crowding:				
No	3,081	3.67%	2,774	1.54%
Yes†	240	2.15%	224	1.32%
Humidification:				
None	338	2.67%	307	1.31%
Some	3,382	3.57%	3,091	1.64%

* Rates are hours absent as percentage of hours scheduled. † <100 ft^2 (9.3 m^2) per employee

while 4.7% were under the age of 30 yrs, two-thirds were men, and 75% were white. Only 10% had less than 5 years seniority.

The average building system was 30 years old. The average floor had 68 employees (median=45, Table 2), and the median floor area per employee was 337 ft^2 (31.3 m^2). Ventilation was "moderate" (≈25 cfmp, 12 ls^{-1}) in areas occupied by 17.5% of workers (44 floors) and high (≈50 cfmp, 24 ls^{-1}) for the remainder. Humidification was provided to 90% of workers (98 floors, 3,382 hourly workers). Ventilation category was not associated with crowding ($\chi^2=0.35$, $p=0.56$); 23% of areas with moderate and 39% of areas with high ventilation had reported complaints ($\chi^2=3.14$, $p=0.08$). No significant elevations of airborne total bacteria counts, culturable bacteria, culturable fungi, spore counts, endotoxin, or volatile organic compounds were observed by comparison with outdoor background levels. No evidence of dissemination of endotoxin from humidifiers using recirculated water could be demonstrated by sampling both up and down stream of the units and in the supplied office areas.

Moderate ventilation and use of humidifiers were associated with greater amounts of total and short-term sick leave (Tables 3 and 4). Crowded areas tended to have lower sick leave rates. Complaint areas were not associated with increased amounts of total sick leave. However, short-term sick leave of office workers was greater in complaint areas.

Using Poisson regression, we found that the relative

Table 2 Floor occupancy

Total Workers per Floor*	All Workers				Areas With Office Workers			
	Floors	(%)	Total Workers*	(%)	Floors	(%)	Hourly Office Workers†	(%)
0–9 per floor	25	(21.7)	69	(0.8)	5	(6.0)	6	(0.9)
10–24 per floor	12	(10.4)	187	(2.3)	6	(7.2)	12	(1.7)
25–49 per floor	17	(14.8)	587	(7.1)	13	(15.7)	56	(7.9)
50–99 per floor	37	(32.2)	2677	(32.4)	36	(43.4)	363	(51.5)
100–149 per floor	10	(8.7)	1147	(13.9)	9	(10.8)	62	(8.8)
150–199 per floor	6	(5.2)	1028	(12.5)	6	(7.2)	64	(9.1)
More than 200 per floor	8	(7.0)	2558	(31.0)	8	(9.6)	142	(20.2)
totals	115		8253		83		705	

* Includes both hourly and salaried workers in occupied areas, † Total number of hourly office workers

Table 4 Office Workers Only: Annual Sick-Leave Rates*

	Total Absence		Short-term Absence	
	Number	Rate	Number	Rate
All office workers	705	3.57%	636	1.71%
Male	186	2.92%	168	1.44%
Female	519	3.81%	468	1.81%
A shift (day)	618	3.73%	556	1.72%
B shift (evening)	53	2.12%	49	1.61%
C shift (night)	23	3.88%	20	1.94%
Other shift or rotating	11	1.11%	11	1.11%
Complaint Area:				
No	459	3.77%	418	1.60%
Yes	246	3.21%	218	1.91%
Ventilation:				
Moderate	323	3.90%	299	2.00%
High	382	3.30%	337	1.45%
Crowding:				
No	545	3.65%	491	1.73%
Yes†	66	2.59%	61	1.43%
Humidification:				
None	41	2.09%	36	1.49%
Some	664	3.66%	600	1.72%

* Rates are hours absent as percentage of hours scheduled. † <100 ft^2 (9.3 m^2) per employee

risk for total sick leave (data not shown) with lower ventilation was 2.30 (95% confidence 1.54–3.44) controlled for age, gender, race/ethnicity, employment category, seniority, amount of other absences, presence of IEQ complaints, crowding and humidification. The relative risk was 1.96 (1.25–3.08) with humidification, 0.99 for complaint areas, and 0.54 (0.39–0.76) in crowded areas. The working correlation within person was 0.33. These results imply that 57% of all sick leave, or approximately 5 days per year, was attributable to lower ventilation among exposed workers. However, these results are dominated by a small number of outliers, and confounding by job type may be incompletely controlled. Therefore, we analyzed short-term sick leave of employees who did not receive disability payments during 1994, and restricted the analysis to office workers.

Poisson regression of short-term sick leave among office workers gave a relative risk of 1.5 for work in moderate ventilation areas. Inclusion of data on humidified areas and control for humidification, complaints, and crowding did not change the estimates. Because power to examine humidification was low, we dropped 36 workers in unhumidified areas from the analyses. In the final analysis of ventilation and complaints, we controlled for age, gender hours of non-illness absence, and crowding (Table 5). Additional factors examined and eliminated as not significant and not confounding the associations of interest included shift worked, ethnicity, and seniority. Interactions of ventilation with complaint area and with crowding were not significant. The relative risk of 1.53 for sick leave implied that 35% of short-term sick leave was attributable to lower ventilation among exposed workers, or 1.2 to 1.9 days of increased sick leave per person per year, depending on age and gender.

We further examined whether outliers, person-months with large amounts of sick leave, dominated the results for short-term sick leave among office workers by performing repeated analyses that included only person-months with progressively smaller amounts of sick leave (Tables 6 and 7). The effects of ventilation and complaints were robust to these exclusions – and the overdispersed variance of the Poisson regression decreased as the subjects became more homogeneous in their sick leave experience.

An economic analysis, assuming that the association we have observed is causal (Table 8), shows that the additional cost of delivering outdoor air to workers would be more than offset by the savings from reduced sick leave, particularly in the highly paid corporate environment studied. If we assume that the 93.5 million full-time workers in the US are being provided the currently recommended ventilation rates, then the estimated lost productivity would be $22.8 billion, and $15.3 billion in net savings per year could be obtained.

Table 5 Office Workers: Poisson Regression of Monthly Short-term Sick-Leave*

Parameter	Estimate	Std Err	Z	Pr>|Z|	Rate Ratio		
					Estimate	95% Confidence Limits	
INTERCEPT	−4.538	0.153	−29.64	0			
Age ≥50	−0.221	0.105	−2.12	0.0341			
Female	0.250	0.140	1.79	0.0734			
Hours Non-Illness Absence	0.015	0.004	3.68	0.0002			
Complaint Area	0.421	0.132	3.18	0.0015	1.52	1.18	1.97
Lower Ventilation	0.428	0.115	3.71	0.0002	1.53	1.22	1.92
$\sqrt{\phi}$	5.243	–	–	–			

* Short-term absence excluded data from workers who received short-term disability payments anytime during the year, or were absent due to illness ≥50% of the year. Office workers in areas without humidification (36) were excluded. Poisson regression of monthly absence was performed using generalized estimating equations to obtain empirical estimates of variance from independent working correlation assumptions. Variance corrected for overdispersion (ϕ)

Table 6 Office Workers Without Disability: Monthly Mean Short-Term Sick-Leave

Exclusions*	Ventilation Category	Person-Months	Complaint Area	
			No	Yes
None	Moderate	3152	1.96%	2.48%
	High	3943	1.16%	1.77%
Months with <80 Scheduled Hours	Moderate	3143	1.97%	2.49%
	High	3934	1.15%	1.77%
Months with Sick-Leave >50%	Moderate	3136	1.89%	1.88%
	High	3926	1.06%	1.60%
Months with Sick-Leave >25%	Moderate	3118	1.69%	1.71%
	High	3908	0.96%	1.40%
Months with Sick-Leave >10%	Moderate	2977	1.02%	1.08%
	High	3787	0.61%	0.77%
Months with Sick-Leave >5%	Moderate	2793	0.52%	0.59%
	High	3624	0.28%	0.41%
Months with Sick-Leave >2%	Moderate	2473	0.018%	0.242%
	High	3352	0.010%	0.009%
Months with Sick-Leave >1%	Moderate	2448	0.0016%	0.0027%
	High	3334	0.0008%	0.0006%

* Exclusions are cumulative from the top to the bottom of the table, thus the person months in each analysis and the amount of sick-leave decrease progressively

Table 7 Poisson Regression-Based Estimates of Attributable Short-Term Sick-Leave Among Office Workers*

Exclusions†		$\sqrt{\phi}$	Attributable Fraction Exposed		
			Estimate	95% Confidence Limits	
None (All Person-Months)	Complaint Area	5.24	34.3%	14.9%	49.3%
	Lower Ventilation		34.8%	18.3%	48.0%
Months with <80 Scheduled Hours	Complaint Area	5.25	34.3%	14.9%	49.3%
	Lower Ventilation		34.9%	18.3%	48.0%
Months with Sick-Leave >50%	Complaint Area	4.53	27.3%	11.7%	40.2%
	Lower Ventilation		33.7%	21.0%	44.3%
Months with Sick-Leave >25%	Complaint Area	4.03	27.4%	12.4%	39.9%
	Lower Ventilation		34.2%	22.1%	44.5%
Months with Sick-Leave >10%	Complaint Area	3.12	21.8%	5.6%	35.3%
	Lower Ventilation		34.9%	22.5%	45.4%
Months with Sick-Leave >5%	Complaint Area	2.60	31.0%	13.3%	45.2%
	Lower Ventilation		40.3%	26.9%	51.2%
Months with Sick-Leave >2%	Complaint Area	1.71	8.7%	−108.5%	60.0%
	Lower Ventilation		51.3%	−6.8%	77.8%
Months with Sick-Leave >1%	Complaint Area	1.18	32.5%	−272.6%	87.8%
	Lower Ventilation		58.3%	−174.8%	93.7%

* Controlled for age, gender, hours of non-illness absence, and crowding. † Exclusions are cumulative from the top to the bottom of the table

Table 8 Potential Economic Benefits of Increased Ventilation

Outcome	Annual Cost (Saving) per 100 Corporate Employees	Annual Cost (Savings) per 100 Full-time US Workers (1997 Dollars)
Ventilation Costs		
2500cfm/100 workers×$3.22/cfm/year*	$8,050	$8,050
Sick Leave Costs		
Sick leave avoided (150 days per 100 workers)†	($48,000)	($24,444)
Net Savings	($39,950)	($16,394)

* An increase of 25 cfmp (11.8 ls^{-1}) priced at the average cost of increased outdoor air supply in the buildings studied
† Costs of sick leave were estimated at $20.37 per hour for full-time workers, on the basis 1997 data on the employer cost per hour for all full-time workers in the U.S. (U.S. Department of Commerce, 1998)

Discussion

In this evaluation of sick leave among employees of a large Massachusetts manufacturer, we found a consistent association of increased sick leave with lower levels of outdoor air supply. Humidifier use and IEQ complaints were also associated with increased sick leave. The large number of work areas (115 floors, 83 floors for office workers) with independent ventilation spread over 40 buildings occupied by a single employer, the a relatively homogeneous workforce, and control for possible confounding in the analysis leaves little likelihood that these results are due to chance or selection bias. The time card data that we used, primarily designed for pay roll purposes, identifies where workers receive their checks or submit time cards. We are aware that these data may not always accurately reflect actual work area – this error in measurement probably affected small numbers and would bias the results toward the null. However, given that this analysis was part of an observational health surveillance program, and given that exposure assessment relied on expert judgement and limited CO_2 data, confirmation of these findings by prospective, and preferably experimental, studies using detailed continuous ventilation measurements is needed.

There are two likely mechanisms for a causal association of ventilation and humidification with illness-related absence: irritant and allergic reactions, or increased respiratory illness due to either airborne spread of infection or an increase in susceptibility. If irritant and allergic reactions were the explanation for these findings, we would expect complaints associated with ventilation and humidification to be on the causal pathway leading from these environmental factors to increased sick leave. Then, controlling for complaints would reduce the association of the environmental factors with sick leave. However, we found that complaint areas were not associated with lower ventilation, and that controlling for complaints did not affect the observed association of ventilation with sick leave. The absence of an association of complaints with ventilation in these buildings, given the relatively high level of ventilation we observed, is consistent with earlier reports (Mendell, 1993; Menzies et al., 1993). However, our measure of complaints, corporate industrial hygiene records, would not have been sensitive to small symptom gradients. Thus, a possible explanation for the association of humidification with increased absence is that humidification may have promoted increased bioaerosol exposures with concomitant increase in non-specific building related symptoms – even though bioaerosol monitoring was unable to demonstrate increased levels of airborne fungi or endotoxin in humidified areas. Our findings of an association of humidification with increased absence is in agreement with the findings of Preller et al. (1990) and in contrast with those of Green among school children (1974, 1985).

The apparent reduction in sick leave rates associated with increased ventilation or absence of humidification (35%) is similar to the reduction in sick leave observed during the flu season with influenza vaccination of a healthy working population (36–43%) (Nichol et al., 1995). Airborne transmission of respiratory infection may be an important factor determining the relationship of building ventilation with health and productivity. Experimental human exposures suggest that airborne transmission of rhinovirus (Dick et al., 1987), adenovirus (Couch et al., 1969), and coxsackievirus (Couch et al., 1970) is a potential, and for some agents a common, route of infection. Airborne transmission of influenza has long been recognized (Riley, 1974). Studies of military recruits in the early 1980s, and of troops stationed in the Persian Gulf demonstrated an increased risk of febrile respiratory illness among soldiers housed with lower levels of ventilation with outdoor air (Brundage et al., 1988; Richards et al., 1993). These military studies suggest that the airborne route accounted for transmission of a significant number of common colds, especially those from adenoviruses, and influenza (Klontz et al., 1989). However, some of these data are also compatible with an effect mediated through increased susceptibility rather than increased transmission. Recent reports suggest that building architecture and ventilation have important impacts on transmission of colds and influenza outside military barracks in confined residential populations (Warshauer et al., 1989; Drinka et al., 1996).

The impact of airborne transmission, and thus of ventilation, on common respiratory infection rates in offices and other non-residential environments, especially schools, is more controversial (Gwaltney, 1990). We are aware of only one recent study that addresses the risk of colds in relation to the office environment (Jaakkola and Heinonen, 1993). That study suggested an increased risk of colds for workers sharing offices with other people. Whether this increased risk developed because of direct contact, short-range large droplet aerosols, or inhalation of droplet nuclei as in true airborne infections such as tuberculosis (Nardell et al., 1991) is not known. The lack of confounding by crowding in this report may imply airborne transmission, or merely that crowding was minimal (only 7% of all workers, and 11% of office workers had <100 ft^2 per person). An extensive study of office workers at a large insurance company in the 1960s (Gwaltney et al., 1966 al., 1968; Hendley et al., 1969) suggested that working adults were responsible for introducing 32% of the colds into families. However, demonstration that the infections were acquired at work and of transmission among office workers was not possible due to statistical power constraints with technology of the day. Thus, the impact of air recirculation on the transmission of respiratory disease in the indoor work environment is unknown, but may be large (Wells et al., 1942; Riley, 1979).

The analysis of total absence data found an association of humidification with increased sick-leave rates. Experimental data show that survival of common respiratory pathogens is affected by relative humidity (RH). Rhinoviruses have improved survival with increased (RH) (Karim et al., 1985). *Chlamydia pneumoniae* aerosols also show improved survival at high RH (Theunissen et al., 1993). Conversely, coronavirus may have reduced survival at mid to high RH (Ijaz et al., 1985). However, since rhinovirus is a more common cause of the common cold, it is likely that the net effect of increased RH in buildings would be to promote airborne transmission.

Drying of mucous membranes may affect host susceptibility to infection. However, there is little evidence to support the concept that low RH promotes susceptibility to respiratory infections. Viral respiratory illnesses follow a seasonal pattern around the globe, even in tropical climates with little variation in RH. School opening may be a major factor determining the timing of many respiratory infections (Johnston et al., 1996).

If airborne spread of respiratory infections is an important cause of sick leave, then alternatives to ventilation may be effective for the control of this problem. In particular, upper room ultraviolet (UV) radiation may be an effective and relatively inexpensive means for controlling the airborne spread of tuberculosis (Nardell et al., 1991), and has been suggested as an approach to the control of the epidemic spread of viral infections (Wells et al., 1942; Riley and Nardell, 1989).

The workers whose sick leave we examined are employees of a large corporation and as such, although somewhat older and more highly paid than the general population, are likely to be reasonably representative of workers in U.S. industry. The results of this health and safety evaluation should therefore be generalizable to other working adults. The lower ventilation rates in this study were at or above the currently recommended levels for offices (ASHRAE, 1989). Assuming that the association we observed is a causal one, our economic analysis suggests that lost productivity attributable to ventilation at currently recommended levels, compared with approximately double that amount, accounts for over $240 of lost productivity per worker per year, or $22.8 billion per year for full-time US workers. We used short-term sick leave as our measure of productivity impact, and assumed that most workers receive the recommended amounts of outdoor air supply. We did not consider impacts of ventilation on productivity other than via sick leave, although recent experimental studies demonstrate that tasks such as typing speed are adversely affected by poor air quality (Wargocki et al., 1999). Thus, even though our cost estimates may be conservative, these data suggest that the impact of ventilation on productivity and health care costs may be greater than recent estimates (Fisk and Rosenfeld, 1997). Additional studies, including experimental interventions are needed to confirm these associations, identify the underlying mechanisms, and to examine whether alternatives to increased outdoor air supply have a significant impact on sick leave.

Acknowledgements

The authors thank Drs. Joel Schwartz, Sally Thurston, and Mathew Wand for statistical consultation, Dr. Warren Kantrowitz for sponsoring this detailed review of environmental health and safety programs, and Mr. Roger Borghesani for energy utilization data from Polaroid's buildings.

The authors (D.K.M., P.M.G.) of this publication were partially supported by Training Grant No. T42/CCT110421 and Grant No. 1R01OH03694 from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health, the National Institute of Environmental Health Sciences Occupational and Environmental Center Grant 2P30 ES00002, and National Institute of Standards and Technology Contract No. 43NANB814490. The contents are solely the responsibility of the author and do not necessarily represent the official views of the supporting federal agencies.

References

Aguirre, A. and Foret, J. (1994) "Irregularity of working hours in railway workers and types of complaints", *International Archives of Occupational and Environmental Health*, **65**, 367–371.

Alexanderson, K., Leijon, M., Akerlind, I., Rydh, H. and Bjurulf, P. (1994) "Epidemiology of sickness absence in a Swedish county in 1985, 1986 and 1987. A three year longitudinal study with focus on gender, age and occupation", *Scandinavian Journal of the Society of Medicine*, **22**, 27–34.

ASHRAE (1989) *Ventilation for acceptable indoor air quality*, Atlanta, GA, American Society of Heating, Refrigeration, and Air Conditioning Engineers (Standard 62–1989).

Bendrick, G. A. (1998) "Seasonal variation of grounding rates among B-52H aircrew", *Military Medicine,* **163**, 692–694.

Blake, G.H., Abell, T.D. and Stanley, W.G. (1988) "Cigarette smoking and upper respiratory infection among recruits in basic combat training", *Annals of Internal Medicine,* **109**, 198–202.

Brundage, J.F., Scott, R.M., Lednar, W.M., Smith, D.W. and Miller, R.N. (1988) "Building-associated risk of febrile acute respiratory diseases in Army trainees", *Journal of the American Medical Association,* **259**, 2108–2112.

Couch, R.B., Douglas, R.G., Jr., Lindgren, K.M., Gerone, P.J. and Knight, V. (1970) "Airborne transmission of respiratory infection with coxsackievirus A type 21", *American Journal of Epidemiology,* **91**, 78–86.

Couch, R.B., Knight, V., Douglas, R.G., Jr. and Black, S.H.B. (1969) "The minimal infectious dose of adenovirus type 4; the case for natural transmission by viral aerosol", *Transactions of the American Climatological Association,* **80**, 205–211.

Dick, E.C., Jennings, L.C., Mink, K.A., Wartgow, C.D. and Inhorn, S.L. (1987) "Aerosol transmission of rhinovirus colds", *Journal of Infectious Disease,* **156**, 442–448.

Diggle, P., Liang, K.-Y. and Zeger, S.L. (1994) *Analysis of longitudinal data*, Oxford, Oxford University Press.

Drinka, P.J., Krause, P., Schilling, M., Miller, B.A., Shult, P. and Gravenstein, S. (1996) "Report of an outbreak: nursing home architecture and influenza-A attack rates", *Journal of the American Geriatric Society,* **44**, 910–913.

Feeney, A., North, F., Head, J., Canner, R. and Marmot, M. (1998) "Socioeconomic and sex differentials in reason for sickness absence from the Whitehall II Study", *Occupational and Environmental Medicine,* **55**, 91–98.

Fisk, W.J. and Rosenfeld, A.H. (1997) "Estimates Of Improved Productivity and Health From Better Indoor Environments", *Indoor Air,* **7**, 158–172.

Golaszewski, T., Snow, D., Lynch, W., Yen, L. and Solomita, D. (1992) "A benefit-to-cost analysis of a work-site health promotion program", *Journal of Occupational Medicine,* **34**, 1164–1172.

Green, G.H. (1974) "The effect of indoor relative humidity on absenteeism and colds in schools", *ASHRAE Transactions,* **80**, 131–141.

Green, G.H. (1985) "Indoor relative humidities in winter and the related absenteeism", *ASHRAE Transactions,* **91**, 643–653.

Gwaltney, J.M., Jr., Hendley, J.O., Simon, G. and Jordan, W.S., Jr. (1966) "Rhinovirus infections in an industrial population. I. The occurrence of illness", *New England Journal of Medicine,* **275**, 1261–1268.

Gwaltney, J.M., Jr., Hendley, J.O., Simon, G. and Jordan, W.S., Jr. (1968) "Rhinovirus infections in an industrial population. 3. Number and prevalence of serotypes", *American Journal of Epidemiology,* **87**, 158–166.

Gwaltney, J., Jr. (1990), "The common cold", *Principles and Practice of Infectious Diseases*, In: Mandell, G., Douglas, R., Jr. and Bennett, J. (eds), New York, Churchill Livingstone.

Hendley, J.O., Gwaltney, J.M., Jr. and Jordan, W.S., Jr. (1969) "Rhinovirus infections in an industrial population. IV. Infections within families of employees during two fall peaks of respiratory illness", *American Journal of Epidemiology,* **89**, 184–196.

Ijaz, M.K., Brunner, A.H., Sattar, S.A., Nair, R.C. and Johnson-Lussenburg, C.M. (1985) "Survival characteristics of airborne human coronavirus 229E", *Journal of General Virology,* **66**, 2743–2748.

Jaakkola, J. and Heinonen, O. (1993) "Shared office space and the risk of the common cold", *European Journal of Epidemiology,* **11**, 213–216.

Janes, C.R. and Ames, G.M. (1992) "Ethnographic explanations for the clustering of attendance, injury, and health problems in a heavy machinery assembly plant", *Journal of Occupational Medicine,* **34**, 993–1003.

Jeffery, R.W., Forster, J.L., Dunn, B.V., French, S.A., McGovern, P.G. and Lando, H.A. (1993) "Effects of work-site health promotion on illness-related absenteeism", *Journal of Occupational Medicine,* **35**, 1142–1146.

Johnston, S.L., Pattemore, P.K., Sanderson, G., Smith, S., Campbell, M.J., Josephs, L.K., Cunningham, A., Robinson, B.S., Myint, S.H., Ward, M.E., Tyrrell, D.A. and Holgate, S.T. (1996) "The relationship between upper respiratory infections and hospital admissions for asthma: a time-trend analysis", *American Journal of Respiratory and Critical Care Medicine,* **154**, 654–660.

Karim, Y.G., Ijaz, M.K., Sattar, S.A. and Johnson-Lussenburg, C.M. (1985) "Effect of relative humidity on the airborne survival of rhinovirus-14", *Canadian Journal of Microbiology,* **31**, 1058–1061.

Klontz, K.C., Hynes, N.A., Gunn, R.A., Wilder, M.H., Harmon, M.W. and Kendal, A.P. (1989) "An outbreak of influenza A/Taiwan/1/86 (H1N1) infections at a naval base and its association with airplane travel", *American Journal of Epidemiology,* **129**, 341–348.

Knave, B., Paulsson, H., Floderus, B., Gronkvist, L., Haggstrom, T., Jungeteg, G., Nilsson, H., Voss, M. and Wennberg, A. (1991) "Incidence of work-related disorders and absenteeism as tools in the implementation of work environment improvements: the Sweden Post strategy", *Ergonomics,* **34**, 841–848.

Lindstrom, I., Ohlund, C. and Nachemson, A. (1994) "Validity of patient reporting and predictive value of industrial physical work demands", *Spine,* **19**, 888–893.

Macher, J., Milton, D. K., Burge, H. A. and Morey, P. (eds) (1999) *Bioaerosols: Assessment and Control*, Cincinnati, American Conference of Governmental Industrial Hygienists.

Melamed, S., Luz, J. and Green, M.S. (1992) "Noise exposure, noise annoyance and their relation to psychological distress, accident and sickness absence among blue-collar workers – the Cordis Study", *Israeli Journal of Medical Science,* **28**, 629–635.

Mendell, M.J. (1993) "Non-specific symptoms in office workers – a review and summary of the epidemiologic literature", *Indoor Air,* **3**, 227–236.

Menzies, D., Tamblyn, R.M., Nunes, F., Hanley, J. and Tamblyn, R.T. (1996) "Exposure to varying levels of contaminants and symptoms among workers in two office buildings", *American Journal of Public Health,* **86**, 1629–1633.

Menzies, R., Tamblyn, R., Farant, J.P., Hanley, J., Nunes, F. and Tamblyn, R. (1993) "The effect of varying levels of outdoor-air supply on the symptoms of sick building syndrome", *New England Journal of Medicine,* **328**, 821–827.

Milton, D.K., Feldman, H.A., Neuberg, D.S., Bruckner, R.J. and Greaves, I.A. (1992) "Environmental endotoxin measurement: the kinetic Limulus assay with resistant-parallel-line estimation", *Environmental Research,* **57**, 212–230.

Nardell, E.A., Keegan, J., Cheney, S.A. and Etkind, S.C. (1991) "Airborne infection. Theoretical limits of protection achievable by building ventilation", *American Reviews of Respiratory Disease,* **144**, 302–306.

Nichol, K.L., Lind, A., Margolis, K.L., Murdoch, M., McFadden, R., Hauge, M., Magnan, S. and Drake, M. (1995) "The effectiveness of vaccination against influenza in healthy, working adults", *New England Journal of Medicine,* **333**, 889–893.

North, F., Syme, S.L., Feeney, A., Head, J., Shipley, M.J. and Marmot, M.G. (1993) "Explaining socioeconomic differences in sickness absence: the Whitehall II Study", *British Medical Journal,* **306**, 361–366.

Palmgren, U., Strom, G., Blomquist, G. and Malmberg, P. (1986) "Collection of airborne micro-organisms on Nuclepore filters, estimation and analysis – CAMNEA method", *Journal of Applied Bacteriology*, **61**, 401–406.

Post, W.K., Burdorf, A. and Bruggeling, T.G. (1994) "Relations between respiratory symptoms and sickness among workers in the animal feed industry", *Occupational and Environmental Medicine*, **51**, 440–446.

Preller, L., Zweers, T., Brunekreef, B. and Boleij, J.S.M. (1990) "Sick leave due to work-related health complaints among office workers in the Netherlands". In: *Proceedings of Indoor Air '90*, Toronto, pp. 227–230.

Reidy, A. (1990) "Questioning the status quo: sickness absence research so far claims more than it should!", *Social Science of Medicine*, **31**, 421–432.

Richards, A.L., Hyams, K.C., Watts, D.M., Rozmajzl, P.J., Woody, J.N. and Merrell, B.R. (1993) "Respiratory disease among military personnel in Saudi Arabia during Operation Desert Shield", *American Journal of Public Health*, **83**, 1326–1329.

Riley, R.L. (1974) "Airborne infection", *American Journal of Medicine*, **57**, 466–475.

Riley, R.L. (1979) "Indoor spread of respiratory infection by recirculation of air", *Bulletin of Physiopatholological Respiration (Nancy)*, **15**, 699–705.

Riley, R.L. and Nardell, E.A. (1989) "Clearing the air. The theory and application of ultraviolet air disinfection", *American Review of Respiratory Disease*, **139**, 1286–1294.

Teculescu, D.B., Sauleau, E.A., Massin, N., Bohadana, A.B., Buhler, O., Benamghar, L. and Mur, J.M. (1998) "Sick-building symptoms in office workers in northeastern France: a pilot study", *International Archives of Occupational and Environmental Health*, **71**, 353–356.

Theunissen, H.J., Lemmens-den Toom, N.A., Burggraaf, A., Stolz, E. and Michel, M.F. (1993) "Influence of temperature and relative humidity on the survival of Chlamydia pneumoniae in aerosols", *Applied Environmental Microbiology*, **59**, 2589–2593.

U.S. Department of Commerce (1998) *Statistical Abstract of the United States*, Washington, D.C., Bureau of the Census, http://www.census.gov/prod/3/98pubs/98statab/sasec13.pdf.

Wargocki, P., Wyon, D.P., Baik, Y.K., Clausen, G. and Fanger, P.O. (1999) "Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads", *Indoor Air*, **9**, 165–179.

Warshauer, D.M., Dick, E.C., Mandel, A.D., Flynn, T.C. and Jerde, R.S. (1989) "Rhinovirus infections in an isolated antarctic station. Transmission of the viruses and susceptibility of the population", *American Journal of Epidemiology*, **129**, 319–340.

Wells, W., Wells, M. and Wilder, T. (1942) "The environmental control of epidemic contagion I. An epidemiologic study of radiant disinfection of air in day schools", *American Journal of Hygiene*, **35**, 97–121.