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Changing ventilation rates in U.S. offices: Implications for health, work performance, energy, and associated economics

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ABSTRACT

This paper provides quantitative estimates of benefits and costs of providing different amounts of outdoor air ventilation in U.S. offices. For four scenarios that modify ventilation rates, we estimated changes in sick building syndrome (SBS) symptoms, work performance, short-term absence, and building energy consumption. The estimated annual economic benefits were $13 billion from increasing minimum ventilation rates (VRs) from 8 to 10 L/s per person, $38 billion from increasing minimum VRs from 8 to 15 L/s per person, and $33 billion from increasing VRs by adding outdoor air economizers for the 50% of the office floor area that currently lacks economizers. The estimated $0.04 billion in annual energy-related benefits of decreasing minimum VRs from 8 to 6.5 L/s per person are very small compared to the projected annual costs of $12 billion. Benefits of increasing minimum VRs far exceeded energy costs while adding economizers yielded health, performance, and absence benefits with energy savings.

1. Introduction

How much outdoor air ventilation should be provided to buildings? Providing more ventilation increases building energy consumption, increases the related emissions of carbon dioxide, and contributes to climate change. Modeling of the U.S. commercial building stock [1] indicates that 6.5% of all end-use energy (3.2% in offices) is for heating and cooling of mechanically-supplied outdoor air ventilation. Using the data in [1], one can estimate that an additional 3% of total end-use energy is used to heat and cool infiltration air, thus, an estimated 9.5% of end-use energy is required for ventilation. From an energy and climate change perspective, we want to reduce ventilation rates. However, providing less ventilation increases indoor concentrations of many indoor-generated air pollutants, although indoor concentrations of some outdoor air pollutants are decreased. In offices, for which the largest amount of data are available, higher VRs are associated with greater satisfaction with indoor air quality, fewer SBS symptoms, and improved work performance [2–4]. Limited research also indicates that higher VRs are associated with reduced absence rates in offices [5] and schools [6], possibly because providing more ventilation may reduce transmission of infectious respiratory illnesses [7].

Despite the long-standing debate about the correct values for minimum VRs, there have been few attempts to quantitatively compare the benefits and costs of ventilation. The minimum VRs specified in existing and most older standards for commercial buildings are based primarily on decades-old laboratory studies showing that 80% of unadapted occupants were satisfied with air quality with a VR of about 7.5 L/s per person in a situation with people as the primary indoor pollutant source [8]. The current U.S. ventilation standard for offices [9] maintains approximately this same minimum ventilation rate if the building has a default (typical) occupant density but divides the minimum ventilation requirement into two components, one a minimum rate of outdoor air supply per occupant and the second a minimum rate of outdoor air supply per unit floor area. Today, we have more information to consider when setting standards, particularly for office buildings. Accordingly, this paper provides quantitative estimates of benefits and costs of providing different amounts of outdoor air ventilation in U.S. offices. The estimates should be of value for decisions about building operation and setting of minimum ventilation rate standards.

2. Methods

Four scenarios were evaluated, each with changes in VRs in U.S. office buildings. The analysis is of hypothetical scenarios in which buildings actually have the specified minimum VRs. As a base case,

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we used a minimum VR of 8 L/s per person – just slightly below the minimum rate of 8.5 L/s per person for offices in the ASHRAE ventilation standard with the default occupant density of 5 persons per 100 m^2 of floor area [9]. In scenario 1, the minimum VR was increased to 10 L/s per person – a common minimum VR for offices in standards around the world and the minimum VR for offices in a prior version of the ASHRAE ventilation standard. In scenario 2, the minimum VR was increased to 15 L/s per person which is still considered well within the capacity of most existing heating, ventilating, and air conditioning (HVAC) systems. In scenario 3, the minimum VR is decreased to 6.5 L/s per person. In scenario 4, the minimum VR was retained at 8 L/s per person and outdoor air economizers were added to the 50% of the existing U.S. office floor space that does not have economizers (http://www.eia.doe.gov/emeu/cbecs/,May 6, 2011). An economizer is a control system that increases the VR above a minimum value when this additional amount of ventilation will reduce the energy needed for air conditioning. Economizers can substantially increase annual-average VRs. We assumed that scenarios 1 through 3 do not affect VRs during periods of economizer activation. The impacts of the scenarios on prevalence rates of SBS symptoms, work performance, short-term absence, and building energy consumption, and the associated economic impacts, were estimated. In addition, for scenario 4 the cost of adding economizers was estimated.

For the relationship of VRs in offices with prevalence rates of SBS symptoms [4], the following equation was employed:

$$RSP = \exp\left(0.00089x^2 - 0.0542x + 0.453\right) \tag{1}$$

where *RSP* is the relative SBS symptom prevalence, equal to the expected SBS symptom prevalence with a VR of *x* (in L/s per person) divided by the expected SBS symptom prevalence if the building had a VR of 10 L/s per person. This equation, based on a statistical analysis of published data from eight studies and 43 data points, indicates the average relationship for a range of SBS symptom types across a range of VRs from 5 to 35 L/s per person.

For the relationship of VRs in offices with office work performance [3], the following equation was employed

$$RMP_{VR} = \exp\left(\left(-76.38_x^{-1} - 0.78xLn(x) + 3.87x - y_0/1000\right)\right) \tag{2}$$

where RWP_{VR} is the relative work performance as affected by VR, x is the VR in L/s per person and y_0 is calculated as follows

$$y_0 = -76.38X_R^{-1} - 0.78X_RLn(X_R) + 3.87X_R \tag{3}$$

where X_R is a reference value of VR. Equation (2) applies for VRs of 6.5–47 L/s per person. This equation is based on statistical analysis of research data from nine studies and 26 data points. Equations (1)–(3) are illustrated graphically at www.iaqscience.lbl.gov (May 6, 2011). It is important to note that the studies analyzed by Seppänen et al. (2006) to derive equations (2) and (3) involved only call center work and work tasks for which speed and accuracy could be readily quantified. In actual practice, the effects of ventilation rate on work performance may vary substantially with type of work, with indoor pollutant sources, and with other factors that affect indoor air quality. In most of the studies analyzed by Seppänen et al. the occupant density was high.

The findings of a study in 40 buildings [5] were employed to estimate the relationship of office VR with short-term absence. This study found that the adjusted relative risk (RR) for short-term absence at 24 versus 12 L/s per person was 0.66. We used an exponential model to predict the RR associated with other changes in VR

$$RR = 0.66^{(x/12)} \tag{4}$$

where *x* is the change in VR in L/s per person. These estimates have higher uncertainty than those described above because of the reliance on the results of a single study; however, supportive findings are available from a study of VRs and absence in classrooms [6] and there is a body of evidence [7] indicating that lower VRs may increase respiratory infections, which are a major cause of absence. The calculations extrapolate with equation (4) to lower VRs than encountered in the original study. This extrapolation may cause an underestimation of the impacts of VR on absence because we expect the benefits of increased VR to be larger in buildings with initially low values of VR.

To estimate changes in numbers of workers experiencing SBS symptoms, values of RSP were multiplied by the estimated SBS symptom prevalence rate at the base case VR of 8 L/s per person, and by the office worker population. We started with the average prevalence (16.8%) of weekly eye, nasal, headache, and tiredness/fatigue symptoms [10] from a survey of 100 U.S office buildings, as these were the types of symptoms considered for derivation of equation (1). The geometric mean VR in the survey was 18.3 L/s per person, thus SBS symptom prevalence will be higher in our base case with 8 L/s per person. With equation (1), an average SBS symptom prevalence of 23% was projected at 8 L/s per person. Similarly, to calculate changes in days of short-term absence, we also required an estimate of the base case rate of short term absence at a VR of 8 L/s per person. We conservatively used the reported short term absence rate of 2% at a VR of 12 L/s per person [5] which translates to 4.8 days per year assuming 240 work days.

For the analyses of scenarios 1 through 3, the fraction of time that economizers in existing buildings increase VRs was needed, because we assume these scenarios have no impact on VRs when economizers are activated. For analyses of scenario 4, we required information on the VRs in office buildings when economizers are activated in order to apply equations (1–4). We employed a widely used building energy simulation program (EnergyPlus) and modeled prototype small, medium, and large office buildings with and without economizers. Ventilation rates sometimes increased above the minimum rate in buildings with economizers, and the VR was fixed at the minimum rate in buildings without economizers. The “enthalpy” economizer control option was selected because enthalpy-controlled economizers are less likely to cause indoor humidity problems in humid climates. The prototype buildings have been designed to be representative of the office building stock [11]. Modeling was performed for five representative U.S. climates (Baltimore, Chicago, Houston, Los Angeles, and Minneapolis). This modeling yielded hourly VRs in buildings of each size with and without economizers. For each climate and building size, annual geometric mean VRs were calculated for use in equations (1–4). The EnergyPlus analyses also yielded estimates of building energy use in buildings with and without economizers. Outputs from modeling of scenario 4 were weighted to account for the variability of existing economizer installation as a function of building size and climate as determined from the national database (http://www.eia.doe.gov/emeu/cbecs/,May6,2011). These calculations indicated that, on average in the 50% of office building floor area with economizers, the economizers increase VRs above a 8 L/s per person base rate 60% of the time; therefore, in the full stock of office buildings economizers increase VRs 30% of the time. Thus, for the full stock of office buildings, the VR changes associated with scenarios 1 through 3 were assumed to occur 70% of the time on average (100% of the time in the 50% of buildings without economizers and 40% of the time in the 50% of buildings with economizers).

Costs reported for prior years were updated to 2008 by adjusting for the consumer price index (CPI) for medical care costs, and the general CPI for other costs. Costs of SBS symptoms were based on estimates of the associated health care costs (annual-average