WHY WE VENTILATE

Max Sherman, Jennifer M. Logue, Phillip N. Price, and Brett C. Singer

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, California, USA

ABSTRACT

It is widely accepted that ventilation is critical for providing good indoor air quality (IAQ) in homes. However, the definition of "good" IAQ, and the most effective, energy efficient methods for delivering it are still matters of research and debate. This paper presents the results of work done at the Lawrence Berkeley National Lab to identify the air pollutants that drive the need for ventilation as part of a larger effort to develop a health-based ventilation standard. First, we present results of a hazard analysis that identified the pollutants that most commonly reach concentrations in homes that exceed health-based standards or guidelines for chronic or acute exposures. Second, we present results of an impact assessment that identified the air pollutants that cause the most harm to the U.S. population from chronic inhalation in residences. Lastly, we describe the implications of our findings for developing effective ventilation standards.

KEYWORDS

Indoor air quality; hazard analysis; residential; DALYs; ventilation

INTRODUCTION

The primary purposes of ventilation in buildings are to provide a sufficient oxygen supply for the occupants and to remove any hazardous substances or noxious odors in the indoor air. For thousands of years societies have realized the need to set or adjust ventilation for specific indoor tasks. The initial inception of residential ventilation is unknown, but likely was from neolithic times and used to remove combustion gases from indoor heating and cooking such as introducing vents for fires. According to Kuhnl-Kinel [1], ancient Egyptians noticed that stone cutters working outdoors had fewer respiratory problems, people in the Middle Ages realized that air in building could transmit disease, and in 1600 the king of England required buildings to be a certain height with tall, slim windows to facilitate the removal of smoke from heating and cooking.

Traditionally in residences the dominant form of ventilation has been natural ventilation including infiltration. In older, leakier homes infiltration from weather driven flows through cracks in the building's exterior may provide sufficient ventilation for residents. In the 1960s and 1970s home construction shifted from natural materials to new synthetic materials and new construction products; and there was increasing interest in tightening homes to conserve energy due to the energy crisis of the 1970s. The increased tightness in homes reduced ventilation that, along with synthetic materials, led to dramatic increases in residential mold related problems and potential issues with combustion spillage. There was also increasing concern about the impact of material emissions on the health of occupants as new materials were introduced.

People spend the majority of their time in residences [2], making indoor air quality an increasing concern. It has been widely recognized that the health burden of indoor air is significant [3-4]. Current ventilation standards are ostensibly set to protect the health of residents. The American Society of Heating, Refrigerating and Air Conditioning Engineer's (ASHRAE's) Standard 62.2 is the most widely accepted residential ventilation standard in the United States. ASHRAE developed Standard 62.2 "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings" to address indoor air quality (IAQ) issues (ASHRAE 2010). ASHRAE 62.2 is now required in some building codes, such as California's Title 24, and is treated as a standard of practice in many energy efficiency programs and by organizations that train and certify home performance contractors. The standard specifies an overall, residence-level outdoor air ventilation rate as a function of floor area (a surrogate for material emissions) and the number of bedrooms (a surrogate for occupant-related emissions) and requires bathroom and cooking exhaust fans. The focus of the standard generally is considered to be the overall ventilation rate. This emphasis has been based on the idea that risks indoors are driven by continuously emitted, distributed sources such as formaldehyde from furnishings and bio-effluents (including odors) from humans. The required level of whole residence mechanical ventilation was based on the best judgment of experts in the field, but was not based on any analysis of chemical pollutant concentrations or other health-specific concerns.

While whole residence ventilation has been recognized as an effective method for reducing many indoor risks, there are significant costs associated with high ventilation rates due to moving and conditioning the air. Certain human needs likely set the minimum for ventilation, based on the requirements for providing sufficient oxygen and removing CO_2. However, energy demands and associated greenhouse gas emissions can be reduced by using source control and efficient task ventilation to remove other contaminants of concern. To effectively design residential ventilation systems to maximize health while minimizing ventilation costs, we first need to specify our objectives for ventilation.

This paper presents a summary of the ongoing work at the Lawrence Berkeley National Laboratory to develop a health-based ventilation standard. This work focuses on non-biological indoor air pollutants. Ventilation affects moisture in the indoor environment, and moisture affects mold development. However, ventilation is not an effective method of controlling whole residence moisture loads (although it is effective in bathrooms) because many locations have higher outdoor than indoor humidity. First we discuss a hazard assessment of indoor pollutants that identified the air pollutants in residences that exceed health-based standards and guidelines. Second, we present the results of a study that determined the relative importance of different pollutants to health. Lastly, we discuss the impact of these results on ventilation standards.

HAZARD ASSEMENT OF INDOOR POLLUTANTS

The initial step in this broad effort was to conduct a hazard assessment of non-biological air pollutants – e.g. including chemical gases and particles – in residences [5]. The analysis compiled data from published studies reporting measurements of air pollutants in residences. That literature review identified 86 articles that were relevant to acute and chronic exposure in residences and considered a broad collection of contaminants measured indoors regardless of pollutant source. The contaminants included some emitted purely from indoor sources, some that enter predominantly from outdoors, and some having both indoor and outdoor sources.

Summary results were compiled and used to calculate representative mid-range and upper-bound concentrations relevant to chronic exposures for over 300 pollutants and peak concentrations relevant to acute exposures for a few pollutants. For over 100 pollutants, measured concentrations were compared to available chronic and acute health-hazard standards and guidelines from the U.S. Environmental Protection Agency (USEPA), California Office of Environmental Health Hazard Assessment (OEHHA), the U.S. Occupational Safety and Health Administration (OSHA), the Agency for Toxic Substances and Disease Registry (ATSDR), and the World Health Organization. Fifteen diverse pollutants were identified as potential chronic or acute health hazards for many homes. A subset of pollutants were identified as priority chemical pollutants based on the prevalence of the pollutant in homes and the quality of available measurements in homes. Table 1 lists the identified priority hazards.

Priority Pollutants for Chronic Exposure	Potential Acute Exposure Concerns
Acetaldehyde	Acrolein
Acrolein	Chloroform
Benzene	Carbon Monoxide
Butadiene, 1,3-	Formaldehyde
Dichlorobenzene,1,4-	NO_2
Formaldehyde	
Naphthalene	
NO_2	
$PM_{2.5}$	

Table 1. Pollutants that potentially pose an adverse indoor health risks.

The hazard assessment narrowed the list of hundreds of chemicals to a much smaller group of pollutants of concern. But this approach considered only disease incidence for cancer standards and disease potential for non-cancer standards; it did not consider disease severity. Prioritizing mitigation efforts among residential indoor air pollutants, and comparing their cumulative health damage to other environmental hazards requires a consistent and comparative metric that accounts for both disease incidence and the severity or costs of the health endpoints. This need motivated development of an impact assessment methodology for indoor air pollutant inhalation.

HEALTH DAMAGE OF CHRONIC INDOOR AIR EXPOSURE

We synthesized disease incidence and health damage models to develop a methodology for quantifying indoor air quality and then applied the methodology to calculate the population average health damage due to chronic inhalation of non-biological air pollutants in U.S. residences [6]. We first analyzed published data to calculate mean exposure concentrations and then estimated age-dependent inhalation air intake over the course of a year. We used disease incidence and disease damage models to predict the pollutant-specific and total health damage in Disability Adjusted Life Years and to identify the pollutants that dominate impacts on human health.

Determining Annual Population Health Damage

To determine the annual population health damage we compared estimates of current air pollutant intake in U.S. homes (using measurement based estimates of population-averaged, residential chronic exposure concentrations) to the theoretical case of a home with no indoor pollutant sources and no pollutants infiltrating from outdoors, i.e. with homes having no pollutants in the indoor air. Population intake via other micro-environments was held constant as a baseline for which inhalation in residences adds an increment of harm.

The Disability Adjusted Life Year (DALY) metric is a powerful tool for quantifying and inter-comparing the damages from health endpoints that can result from specific pollutant intake [7]. DALYs quantify overall disease damage including both mortality and morbidity. DALYs are the equivalent years of life lost to illness or disease and include years lost to premature death (YLL) and equivalent life years lost to reduced health or disability (YLD).

$$DALY = YLL + YLD \quad (1)$$

The years of reduced health are weighted from 0 to 1, based on the severity of disease, to calculate equivalent years lost. For example, a 5 year illness that reduces quality of life to 4/5 that of a healthy year is valued at 1 DALY lost.

Several authors have determined the DALYs lost per incidence of specific diseases using the preeminent work of Murray and Lopez [7-11]. Multiplying a disease incidence rate by a "damage factor" yields a rate of lost DALYs per disease incidence.

$$DALYs = \frac{\partial Damage}{\partial Disease\ incidence} * Disease\ Incidence \quad (2)$$

Damage rates multilplied by available disease incidence statistics , integrated over all diseases of interest, are often used to determine the total burden of disease in a community. This method was used by the World Health Organization to determine the disease damage for 192 countries [11].

Our analysis used the compilation of measured concentration data to calculate total DALYs lost due to inhalation of air pollutants in residences. We approached this using three different methods. The first method was for criteria pollutants, which are more extensively studied and have a larger body of available epidemiological studies. We aggregated the available Concentration-Response (C-R) functions in the literature to determine disease incidence as a function of a change in airborne concentrations. For each health outcome for each criteria pollutant we multiplied the change in disease occurrence rate by the damage factor for that disease. This level of epidemiological data was not available for the majority of remaining pollutants. The second method that we used was primarily for air toxics or hazardous air pollutants which have limited epidemiological data, but extensive data from toxicological studies. This method used the work of Huijbregts et al. [7] to calculate the health damage associated with the intake of non-criteria pollutants. Huijbregts et al. [7] determined cancer and non-cancer mass intake-based damage factors by synthesizing disease damage factors and animal toxicology based disease incidence rates. This method is much more uncertain than using C-R functions which is reflected by significantly larger uncertainties. The third method was used for pollutants that had already had been significantly studied and had available literature studies apportioning specific disease rates to exposure. This applied to radon and secondhand tobacco smoke (SHS). The population average DALYs lost due to radon, acute carbon monoxide (CO) and SHS were determined based on estimates of disease incidence by multiplying them by the damage factors for those diseases.

Figure 1 shows the damage in DALYs per year per 100,000 people from exposure to the 15 pollutants with the highest central estimate of damage. The whiskers indicate the aggregate uncertainty (95th percentile confidence interval) in the disease incidence and disease damage factors. Figure 1 shows the clear result of our analysis: on a population average, the most harmful pollutants in residential indoor air are $PM_{2.5}$, SHS, formaldehyde, acrolein, radon and ozone. The hazards of SHS and radon are more widely recognized and focused in a smaller fraction of homes. By contrast, $PM_{2.5}$, acrolein, and formaldehyde are present at substantial levels in most homes yet there may be less widespread recognition of these hazards. Formaldehyde is primarily emitted from materials throughout the home. Acrolein is primarily emitted from materials and cooking [12]. $PM_{2.5}$ concentrations indoors, unlike acrolein and formaldehyde, are due to both indoor and outdoor sources and outdoor concentrations may exceed indoors in many locations [4].

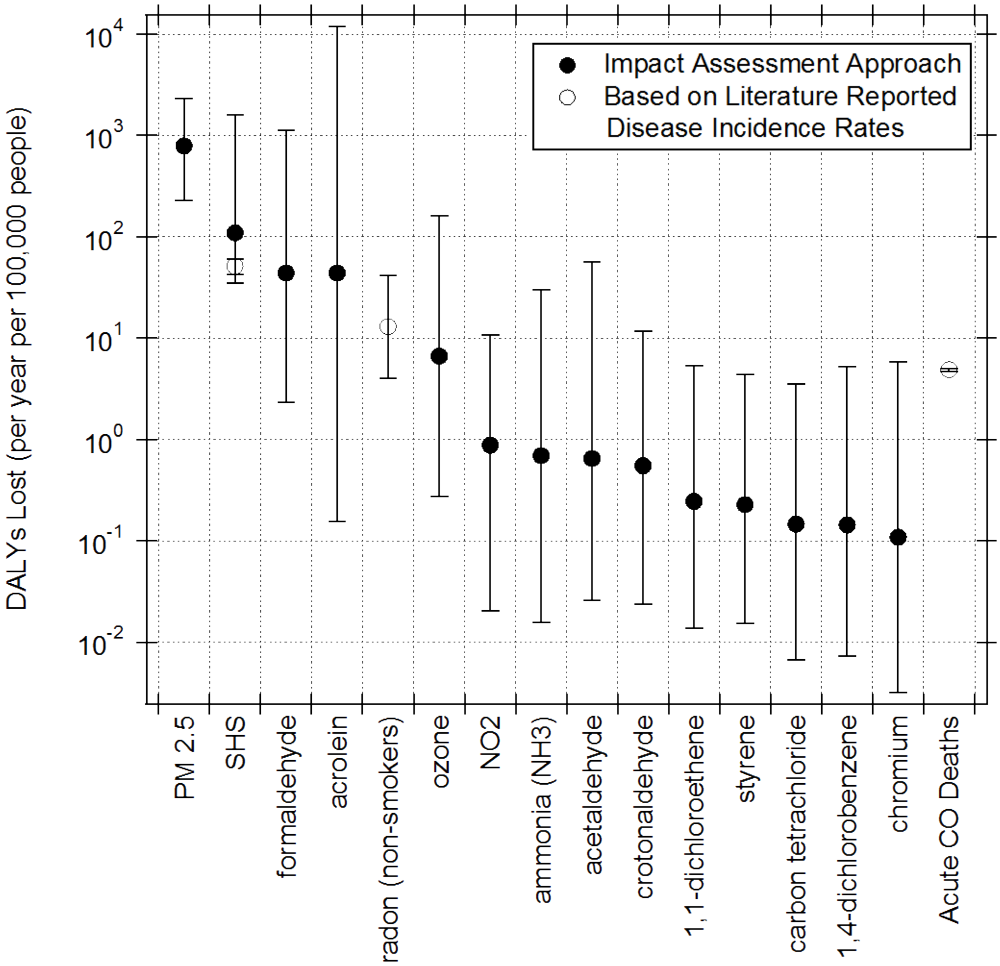

Figure 1. Estimated population averaged annual cost, in DALYs, of chronic air pollutant inhalation in U.S. residences; results for the 15 pollutants with highest mean damage estimates.

To explore possible variations in the health impact rankings of pollutants across homes, we used a Monte Carlo approach to calculate the total chronic health damage from exposure to all pollutants included in our analysis, except radon and SHS. For each model run, we sampled with replacement from the distribution of estimated damage for each pollutant and calculated an estimate of total health damage for the home. We assumed independent variability of all pollutants. This was repeated for a sufficient number of homes to yield a stable mean and standard deviation for the total health damage. We assumed that individual pollutant damages vary independently. This approach did not explicity account for any synergistic or antagonistic interactions of pollutant health effects. The resulting distribution of total health damage and the characteristics of each set of individual pollutant contributions to the total health damages were analyzed. For 80% of the sample sets (calculated damages for individual homes), $PM_{2.5}$ was the largest contributor. For 16% of the sample sets acrolein was the dominant contributor and for 4% of the sample sets it was formaldehyde. The dominant contributor was a compound other than these three in less than 0.25% of the sample sets. For 90% of the sample sets, acrolein, formaldehyde, and $PM_{2.5}$ contributed more than 80% of the total health damage. This reinforces the finding that these three pollutants account for the majority of chronic health from intake of air pollutants in non-smoking homes. We estimate that the current indoor air quality related heath damage to the U.S. population from all sources, excluding SHS and radon, is in the range of 4-11 mili-DALY/p/yr (mili-DALYs per person per year). This indicates that the damage attributable to indoor air is, comparatively, somewhere between the health effects of road traffic accidents (4 mili-DALY/p/yr) and all-cause heart disease (11 mili-DALY/p/yr) in the U.S. The compounds that dominate that total are $PM_{2.5}$, acrolein, and formaldehyde.

IMPLICATIONS FOR VENTILATION STANDARDS

Ventilation standards have the potential to significantly improve indoor air quality (IAQ) in the vast majority of homes. Identifying the pollutants that drive the risks will allow us to make suggestions for modifying the current ventilation standards and identify areas where further research is needed. This section describes how two particular elements of ventilation standards can improve IAQ: overall air exchange rate and localized exhaust ventilation.

Current ventilation standards focus primarily on providing the right amount of overall ventilation for a home based on the idea that the main drivers for pollutant concentrations are furnishings and occupants themselves. A reasonable lower bound for the overall ventilation rate would likely be the airflow needed to control for body odor [13]. Additional air flow is needed to control concentrations of pollutants that have diffuse emission sources in residences. Our analysis indicated that material emissions of acrolein and formaldehyde are the main pollutants that need to be controlled with an overall ventilation rate and the rate should be set at levels that would provide safe indoor concentrations of these pollutants.

There is insufficient material emission data currently to set a ventilation rate based on acrolein, however an appropriate ventilation rate for formaldehyde has been suggested based on California health standards of 0.3 air changes per hour for existing homes and 0.5 for new homes [14]. There are two main concerns with providing ventilation at these levels: 1) the cost of conditioning the extra airflow and 2) bringing in outdoor pollutants.

One way of reducing the needed overall ventilation for a home, and the associated energy and cost penalty, would be source control. Currently in the U.S. there is not sufficient information to estimate the benefits of source reduction by simulating the replacement of specific materials or applying specific existing standards or guidelines for material emissions [15]. Developing these databases could aid in the reduction of material loading of formaldehyde and acrolein. Implementing standards that reduced material loading in homes would reduce the required ventilation rate and save energy.

Increasing air flow through the home can increase the rate at which outdoor pollutants are brought indoors. Our study identified $PM_{2.5}$ as the most important pollutant for health in residential environments. While indoor sources such as combustion and chemistry significantly impact indoor $PM_{2.5}$ concentrations, a significant fraction of homes may have higher concentrations outdoors than indoors indicating that more ventilation may actually increase health risks [4]. Providing ventilation air via filtered supply or filtered balanced ventilation using heat/enthalpy recovery ventilators is one potential solution. Another option is to filter the indoor air independent of the ventilation system to reduce indoor $PM_{2.5}$ concentrations. Including measures to reduce indoor particle concentrations in ventilation standards could greatly improve IAQ from a health perspective.

Our analysis indicates that removing pollutants near their point of release using effective localized exhaust ventilation is key to maintaining good IAQ. The two main types of localized exhaust in ventilation standards are kitchen and bath ventilation. Effective kitchen ventilation is needed to mitigate acute pollutant events resulting from combustion based cooking appliances and food preparation activities. Task ventilation can also significantly mitigate chronic exposures by removing pollutants at their source. ASHRAE 62.2 requires a kitchen exhaust fan that is above the cooktop and provides at least 100 cubic feet per minute (roughly 50 m^3 h^{-1}) of airflow while producing 3 sones or less of noise. The standard doesn't specify a minimum pollutant capture efficiency or sound limits at higher flow rates. Requiring a high pollutant capture efficiency and potentially requiring automatic fan use when the range is operated could significantly improve indoor air quality. Four out of five of the identified acute contaminats of concern (except chloroform) are emitted by combustion or cooking. It is critically important to make sure that there is effective ventilation for all indoor combustion. Research is needed to determine if the health benefit of adding a commissioning requirement to ventilation standards is worth the cost.

Effective bath fans are also critical for providing good indoor IAQ. Bath fans remove bio-effluence, moisture and pollutants generated in bathroom activities such as personal care product use and showering. Showering has been shown to elevate concentration of chloroform above acute thresholds[16]. Bathroom exhaust flow rate requirements should be designed to keep chloroform levels below acute thresholds. Further research is needed to determine which episodic activities in bathrooms may lead to acute exposures.

CONCLUSION

The main air pollutants of concern for regulators setting residential ventilation standards are formaldehyde, acrolein, and $PM_{2.5}$. This implies that whole-residence ventilation rates should be based on controlling formaldehyde and acrolein. Filtration of incoming or house air to remove $PM_{2.5}$ would substantially improve indoor air quality.

Effective task ventilation is critical for controlling acute exposures in residences. All combustion in homes should be effectively vented and cooking exhaust systems should be required to meet minimum pollutant capture efficiency standards.

The identification of formaldehyde, acrolein and $PM_{2.5}$ as the highest priority pollutants for chronic exposure opens opportunities to improve energy efficiency through consideration of control measures complementary to ventilation.

ACKNOWLEDGEMENTS

Funding was provided by the U.S. Dept. of Energy Building Technologies Program, Office of Energy Efficiency and Renewable Energy under DOE Contract No. DE-AC02-05CH11231; by the U.S. Dept. of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070, by the U.S. Environmental Protection Agency Office of Air and Radiation through Interagency Agreement DW-89-92322201-0 and by the California Energy Commission through Contract 500-08-061.

REFERENCES

[1] Kuhnl-Kinel, J. *The History of Ventilation and Air Conditioning: Is CERN up to date with the latest technological developments?* in *Proceedings of the Third ST Workshop-CERN*. 200. Chamonix, France: European Organization for Nuclear Research (CERN).

[2] Klepeis, N.E., et al., *The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants.* Journal of Exposure Analysis and Environmental Epidemiology, 2001. **11**(3): p. 231-252.

[3] Edwards, R.D., et al., *VOC concentrations measured in personal samples and residential indoor, outdoor and workplace microenvironments in EXPOLIS-Helsinki Finland.* Atmospheric Environment, 2001. **35**: p. 4531-4543.

[4] Weisel, C.P., et al., *Relationships of Indoor, Outdoor, and Personal Air (RIOPA) Part I. Collection Methods*. 2005, Health Effects Institute, Mickely Leland National Urban Air Toxics Research Center and Descriptive Analysis.

[5] Logue, J.M., et al., *Hazard assessment of chemical air contaminants measured in residences.* Indoor Air, 2011. **21**(2): p. 92-109.

[6] Logue, J.M., et al., *Chronic Health Damage of Residential Indoor Air.* Submitted to Environmental Health Perspectives, 2011.

[7] Huijbregts, M.A.J., et al., *Human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment.* Integrated Environmental Assessment and Management, 2005. **1**(3): p. 181-244.

[8] Lvovsky, K., et al., *Environmental costs of fossil fuels: a rapid assessment method with application to six cities*. 2000, The World Bank Environment Department: Washington, D.C.

[9] Murray, C.L. and A.D. Lopez, *The global buden of disease: a comprehensive assessment of rmortality and disability from diseasees, injuries, and risk factors in 1990 and projected to 2020.* Global Burden of Disease and Injury Series. Vol. 1. 1996, Cambridge, MA: Harvard University. 990.

[10] Murray, C.L. and A.D. Lopez, *Global health statistics: A compendium of incidence, prevalence, and mortality estimates for over 200 conditions*, in *Global burden of disease and injury series*. 1996, Harvard University: Cambridge, MA. p. 906.

[11] WHO, *Global Health Risks: Mortality and burden of disease attributable to selected major risks*. 2009, World Health Organization: Geneva, Switzerland.

[12] Seaman, V.Y., D.H. Bennett, and T.M. Cahill, *Origin, occurrence, and source emission rate of acrolein in residential indoor air.* Environmental Science & Technology, 2007. **41**: p. 6940-6946.

[13] Cain, W.S., et al., *Ventilation requirements in buildings: I. Control of occupancy odor and tobacco smoke odor.* Atmospheric Environment, 1983. **17**(6): p. 1183-1197.

[14] Sherman, M.H. and A.T. Hodgson, *Formaldehyde as a basis for residential ventilation rates.* Indoor Air, 2004. **14**(1): p. 2-8.

[15] Willem, H. and B.C. Singer, *Chemical Emissions of Residential Materials and Products: Review of Available Information*. 2010, Lawrence Berkeley National Laboratory: Berkeley, CA. p. 48.

[16] Kerger, B.D., C.E. Schmidt, and D.J. Paustenbach, *Assessment of airborne exposure to trihalomethanes from tap water in residential showers and baths.* Risk Analysis, 2000. **20**(5): p. 637-651.