

# Improving Indoor Environmental Quality for Public Health: Impediments and Policy Recommendations

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**BACKGROUND:** People in modern societies spend more than 90% of their time indoors. Hence, indoor environmental quality (IEQ) has a significant impact on public health. In this article we describe health risks associated with indoor environments, illuminate barriers to overcoming these risks, and provide policy recommendations to achieve healthier indoor environments.

**OBJECTIVES:** The weight of evidence suggests that indoor environmental contaminants pose significant public health risks, particularly among children and the poor, and the societal costs of illnesses related to indoor environments are considerable. Despite the evidence of harm to human health, poor indoor environments are generally difficult to regulate and not of sufficient concern to the general public. We discuss several reasons for this lack of concern about IEQ, focusing specifically on home environments.

**DISCUSSION:** Economics plays a large role both in political inaction and individual-level indifference. Because little effort has been made to quantify the value of the societal and individual costs of poor housing quality, as well as the benefits achievable by simple interventions, policymakers lack motivation to act on IEQ. Similarly, individual homeowners lack the incentive to remediate homes, as other problems may be more pressing than home environmental quality.

**CONCLUSIONS:** Although the problem of IEQ involves multiple stakeholders and multiple levels of governance, it is possible to establish economic incentives that would set the wheels in motion for action at all levels to achieve healthy home environments. Also important are education and information dissemination on the public health risks associated with indoor environments. These recommendations are intended for all decision makers who have an influence in developing policy to improve indoor environmental quality.

**KEY WORDS:** impediments, indoor environmental quality (IEQ), policy recommendations, public education, public health risk. *Environ Health Perspect* 115:953–957 (2007). doi:10.1289/ehp.8986 available via <http://dx.doi.org/> [Online 25 January 2007]

For many centuries doctors and public health workers have understood the role of buildings in causing or exacerbating human diseases. As early as several centuries B.C., the famous Greek “father of medicine” Hippocrates was aware of the adverse effects of polluted air in crowded cities and mines, and Biblical Israelites understood the dangers of living in damp housing. The famed 19th-century nurse Florence Nightingale was cognizant of the connection between health and the dwellings of the population. A comprehensive presentation of the history of understanding the health risks of indoor air is available by Sundell (2004).

Poor indoor environmental quality (IEQ) is an important public health risk worldwide. People in modern societies spend more than 90% of their time in indoor environments (Leech et al. 2002). Most of that time is spent in private homes; in the United States, Canada, and Germany, residence times in the home are very similar, ranging from 15.5 to 15.7 hr/day (Brasche and Bischoff 2005). Hence, indoor environmental quality in households has a significant impact on public health and well-being.

Hazards in indoor environments include biological and chemical contaminants, as well as poor ergonomics, lighting, and physical design. These hazards cause and exacerbate a

variety of adverse health effects in humans, ranging from asthma to sick building syndrome to cancer.

Indoor environments encompass homes and other residences, workplaces, transportation vehicles (including cars, trains, planes) and other diverse enclosed settings where individuals spend a portion of their day. Because of the diverse nature of these environments, this article focuses on home environments and presents the public health risks and policy impediments associated with poor IEQ in homes.

There are important barriers to developing policies to improve indoor home environments. Governments are finding it difficult to develop regulations concerning the indoor home environments because these regulations would affect the sacred privacy of individual homes. Because of a scarcity of reliable biomarkers for indoor exposure (with the notable exception of lead), hard economic numbers to indicate the impact of poor housing quality, or widespread citizens’ grassroots efforts to effect changes, there is little policy motivation to achieve healthy indoor environments. Finally, there are socioeconomic challenges. The stakeholder groups that can ensure better IEQ have little motivation to do so, whereas those who live in unhealthy homes often have few means to improve their situation. To achieve

improved indoor environmental quality, policy recommendations must include appropriate incentives for multiple stakeholders.

In this article we describe the indoor environmental risks in homes. We then discuss relevant policy issues in the United States and barriers to reducing IEQ risks, both through the marketplace and through public policy. Finally, we provide policy recommendations on how to overcome these barriers to achieve healthier home environments.

## The Public Health Risk of Poor Indoor Environmental Quality

*Hazards in home environments.* Indoor home environments are the sites of a variety of biological, chemical, and other environmental hazards. Biological hazards include infectious agents such as bacteria and viruses, molds, endotoxins, and antigens from house dust mites, rodents, cockroaches, pollen, and animal dander. The allergenic constituents of indoor air are predominantly biologic in origin. In recent years, the dramatically increasing rate of asthma in modern societies, coupled with the growing concern regarding indoor environments, has prompted a number of studies concerning exposure to airborne biologic agents and asthma [Institute of Medicine (IOM) 2000].

Chemical hazards include environmental tobacco smoke (ETS), nitrogen and sulfur oxides, ozone, particulate matter (PM), volatile organic compounds (VOCs), pesticides, formaldehyde, and plasticizers (IOM 2000). Exposures to these agents are influenced by chemicals used in building materials, furniture, and other household items; everyday practices such as heating, cooking, cleaning, and home repair; and spontaneous chemical reactions in the indoor environment.

ETS is the largest contributor to suspended PM and respirable sulfates and particles in indoor air. Passive smoking has been shown to be harmful to the health of children. During

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the first year of life, children exposed to environmental tobacco smoke have higher rates of lower respiratory illness, higher rates of middle ear effusion, and higher rates of sudden infant death syndrome. In addition, children with asthma whose parents smoke have more severe symptoms and more frequent exacerbations (IOM 2000).

A 2000 IOM report (IOM 2000) has associated environmental asthma primarily with indoor as opposed to outdoor exposures. In particular, the IOM committee found sufficient evidence of a causal relationship between asthma exacerbation and exposure to allergens from cats, cockroach, ETS, and house dust mite, and sufficient evidence of association between asthma exacerbation and exposure to allergens from dogs, mold, nitrogen oxides, and rhinovirus. Indoor dampness and mold are associated with upper respiratory tract symptoms, cough, wheeze, and asthma symptoms in sensitized asthmatic persons (IOM 2004). Cancer is also a serious risk associated with exposure to certain indoor air contaminants. ETS and radon exposure are linked with incidence of human lung cancer.

Physical hazards in indoor environments account for many acute as well as chronic injuries. Among such hazards are noise, poor ergonomic settings, and design or decoration that is likely to cause injury (Lyons et al. 2003). Through circadian and endocrine interactions, there may be adverse health effects related to lighting (Schernhammer and Schulmeister 2004). In this present article, we focus primarily on hazardous pollutants found in indoor air in homes.

Figure 1 illustrates the complexity of the relationship between the indoor structure, the hazards generated as a consequence, and the ultimate health effects in the population. Characteristics of the building structure, such

as its composition, contents, and building systems, as well as attributes of the population and activities within the building, all contribute to the health of the indoor environment. Ultimately this can lead to a variety of adverse health effects including respiratory, neurologic, dermatologic, among others, as shown in Figure 1.

**Exposure to and prevalence of hazards in home environments.** Human exposures to indoor air hazards are a function of many factors including building characteristics, lifestyles and behaviors, and availability of information and means to remediate known indoor problems. The impact of the regional climate on the types of contaminants encountered must also be considered. For example, house dust mites are common in temperate and humid regions worldwide, as are cockroaches, which are particularly a problem in urban environments and near food sources. Fungi and endotoxins are ubiquitous (IOM 2000).

Indoor carbon monoxide (CO) and nitrogen dioxide (NO<sub>2</sub>) exposures occur whenever high-temperature combustion occurs; indoor sources include gas stoves, space and kerosene heaters, and poorly vented furnaces and fireplaces. Roughly half of U.S. households use gas appliances, and the proportion is much higher in urban areas. About 84% of U.S. households use pesticides in the home. VOC exposure is primarily through indoor environments, with average values ranging from 2 to 84 µg/m<sup>3</sup> (IOM 2000).

In U.S. households, 27, 31, and 5% have cats, dogs, and birds, respectively. Animal dander can cause asthma and other allergic reactions. By contrast, relatively few households are exposed to allergens from farm animals such as cows, horses, or pigs. The quantities of dust mite allergen found in the air of

U.S. houses range from < 0.2 to > 100 ng/m<sup>3</sup> (IOM 2000).

Moisture and mold are prevalent problems in homes worldwide. Although indoor dampness alone is not a health hazard, it is a precursor to a variety of health hazards more common in moist environments: mold, cockroach, house dust mite, rodents, and off-gassing of chemicals in home surfaces (IOM 2004). In the United States, a questionnaire administered to the homes of 6,273 school children in six cities (Brunekreef et al. 1989) revealed that up to 58% of homeowners reported water in the basement, water damage to the building, or mold or mildew on any surface in their homes. Takaro et al. (2004) found that among 274 Seattle, Washington, homes where children with asthma resided, roughly 44% contained documented visible mold. In a survey of over 16,000 homes throughout Europe, Australia, India, New Zealand, and the United States, 22% of homeowners reported mold or mildew problems within the last year of their time at home (Zock et al. 2002).

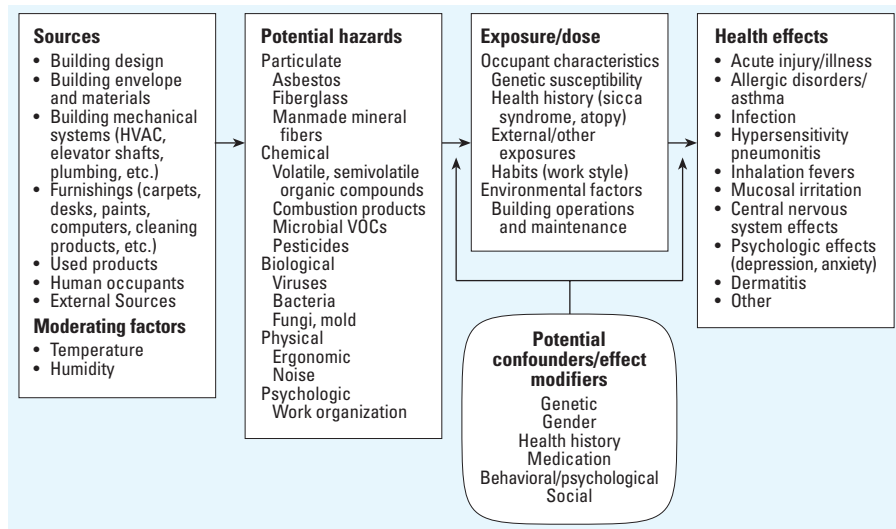
Two subpopulations particularly vulnerable to indoor contaminants are low-income persons and children. Indeed, one important barrier to preventing or reducing poor health caused by indoor dampness is poverty (IOM 2004). Census statistics indicate that the poor are more than 3 times as likely (22% vs. 7%) to have substandard-quality housing and that blacks and low-income people are more likely than the general population to be in housing that has extreme physical problems (Evans and Kantrowitz 2002). Lower socioeconomic status has been clearly linked with increased levels of asthma morbidity and mortality (IOM 2000).

Infants and children are at much higher risk of exposure to environmental stressors and toxicants because, pound for pound, they inhale twice as much air at rest, eat 3–4 times as much food, drink 4 times as much water, and have 3 times the rate of skin absorption compared with adults (Bearer 1995). The total annual cost for environmentally attributable childhood diseases in the United States from lead poisoning, asthma, and cancer alone is US\$54.9 billion (Landrigan et al. 2002). Although not all of this is due to indoor exposures, their contribution is significant.

Because indoor environmental contaminants are significant public health risks, particularly among children and the poor, both the adverse health effects and exposure levels deserve public policy attention, as the costs to society associated with illnesses related to indoor environments are considerable.

## Why Are IEQ Problems Difficult to Solve?

Despite the evidence of harm to human health, poor indoor environments are generally difficult to regulate and not of sufficient concern to



**Figure 1.** Pathway from built environment to health effects (adapted from Mitchell CS, Hodgson MJ, unpublished data).

the general public. There are several reasons for this. Economics plays a large role both in political inaction and in the indifference of individuals. Because few efforts have been made thus far to place a monetary value on the societal and individual costs of poor housing quality, as well as the monetary value of benefits achievable by simple and affordable interventions, policymakers lack a motivation to act on IEQ. Similarly, individual homeowners lack incentives to remediate homes, as other problems may be more pressing than home environmental quality.

We present a conceptual model that relates the health risks of indoor environmental hazards and modifying factors such as socioeconomic situations with the likelihood of action taken by policymakers to improve IEQ. The model, depicted in Figure 2, is based on the Health Belief Model (Becker 1974), one of the most widely used conceptual frameworks in health behavior research. The model explains why individuals respond (or do not respond) to mitigate their health risks, particularly with respect to adherence to medical regimens. We have applied this model to policy decision makers, who make decisions about whether a particular health risk is worthy of policy attention at the level of legislation, guidelines, regulations, or other forms of action. Figure 2 shows the relationship between three categories of concepts: policy perceptions, modifying factors, and likelihood of action, in which the first two influence the last. In the first section of this article, we discussed the first category: the severity of the health risk. Now we address the other categories to propose why policy action has been lacking in the area of IEQ and how action could be achieved through various recommended strategies.

**Modifying factors. Political interest and barriers.** Several political barriers exist that prevent development of interest in IEQ regulations. First, in the United States as well as most modern societies, it is very difficult to attempt to regulate private homes as opposed to public buildings such as restaurants or malls. The belief that “a man’s home is his castle” makes it difficult for a government agency to set standards on household behaviors (including product purchases, presence of animals, and cooking, heating, and cleaning habits) that affect indoor air quality.

Second, there has been insufficient political interest in the topic. By contrast, outdoor air became a concern in the United States as a result of a combination of specific incidents and a wave of grassroots action. The Cuyahoga River Fire of 1969 in Cleveland, Ohio, caused by oil and debris on the river from nearby industrial emissions, led to the establishment of “Fresh Air Funds,” charities specifically designated toward improving outdoor air quality. Outdoor air was a focus of Earth Day 1970 and the establishment of the U.S. Environmental

Protection Agency (EPA). Specifically, the Clean Air Act (1970) mentions the need to protect “shared commons.” Indoor air quality protection does not have these same motivators. Unlike outdoor air, there has been no specific “galvanizing moment.” There is no clear-cut “villain,” no public outrage, and thus no grassroots effort to effect changes in indoor environments. Housing and other indoor spaces have not been perceived to be a “shared commons,” despite that most people live in structures built by and occupied both in the present and the past by others.

Third, the nature of the regulatory framework is more complicated for indoor than for outdoor air. Outdoor air pollution has been regulated by the control of large point source polluters and motor vehicle manufacturers. IEQ, with its many contributing factors and complex interactions, is much more difficult to regulate. Further, many housing code regulations are established locally and not federally.

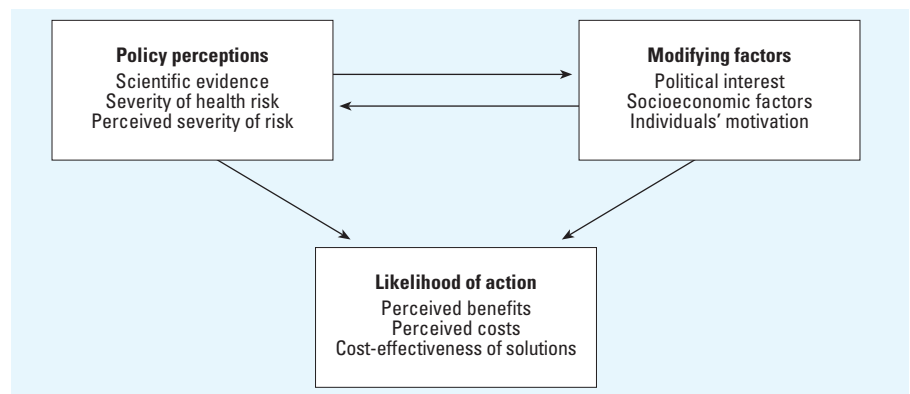
A final challenge is that scientific data are needed in most cases to establish appropriate guidelines, but finding such data for many indoor pollutants is difficult. The lack of biomarkers of exposure for many contaminants makes setting scientific standards difficult. Current science is still in its infancy in the indoor environment/healthy homes area because these questions largely have been overlooked with scant resources committed to policy-relevant research. There is also a relative lack of economic analysis regarding the impact of diseases and lost productivity associated with poor indoor home environments. Without such compelling statistics, there is no political motivation to develop new regulations on IEQ. When policies have been based on scientific findings, the substantial benefits of making such investments have become more transparent and progress adopting them as standard operating costs has been possible. But in cases where science is wanting, we often lack standards that homeowners, building managers, and governments will implement with confidence, especially for low-income housing

that often poses the greatest health risks. Thus, in both the scientific and regulatory dimensions, more information is needed to make IEQ recognized as a politically important problem, although in many cases there is sufficient knowledge to compel action.

**Socioeconomic factors.** The costs of not creating healthy houses, buildings, and communities are rarely identified or understood. These costs are real but are often overlooked or ignored because they are shifted to the health care sector of the economy, where they appear as more expensive medical care (Jacobs 2005). Consequently, investments in healthy homes are unlike other home improvements because they are not reflected in the market price of the structure. That makes health investments appear to be unwise on the part of the homeowner because unlike other home improvement or maintenance investments, they cannot be recovered when the house is sold.

Until health investments are identified in the economic value of buildings, integrating health into routine maintenance, finance, regulatory, and rehabilitation systems will continue to pose a policy challenge for all levels of government. Consequently, the health aspects of housing and indoor environments are generally an afterthought at best, and at worst appear as a burden on affordability or as an “extra” first cost.

Who should pay for healthy home and indoor environment improvements and how can housing and building market forces (both public and private) accommodate the public and environmental health improvements needed? For example, if the value of a house is too low, is additional investment to promote health even possible? How can cost shifting be prevented between the health and housing sectors of the economy? Even in the case of lead-safe housing and radon control in the United States, the value of such health investments in housing is still not routinely reflected in the market price. Without a clear financial return on their individual investments, property owners (rental and home) will be unlikely to



**Figure 2.** Pathway from perception of IEQ risk and modifying factors to likelihood of political action [adapted from Becker (1974)].



incorporate healthy home principles into their construction, rehabilitation, maintenance, and financing decisions (Jacobs 2005). One challenge is to make transparent the costs of not making homes, buildings, and schools healthy and to identify how consumers and building owners can clearly identify homes as being healthy or unhealthy.

**Individual motivation.** The third modifying factor in the model is the human dimension. How do people make decisions, and how can they be motivated to care about their indoor environments? What impediments obstruct their decision making in achieving healthier home environments? As described above, economics and information dissemination play important roles.

Clearly, income and housing affordability have important health implications. In the United States, 13% of the nation's lowest income families spend > 50% of their incomes on housing. Nearly one-third of all households in the United States spend 30% or more of their incomes on housing. As a result of widespread affordability problems, crowding is on the increase, some 2.5–3.5 million people are homeless at some point in a given year, and nearly 2 million households live in severely inadequate housing (Harvard Joint Center for Housing Studies 2004). One example of the many adverse health effects of homelessness, a study of homeless children in New York City found that 61% had not been immunized, 38% had asthma, and they had a 50% greater chance of ear infections (Redlener and Johnson 1999).

Despite the obvious benefits that could be achieved through improving indoor environmental quality, a number of barriers exist that relate to individual motivation. Two of the most significant barriers to improving health through reduced indoor dampness are economic in nature: poverty and the uneven distribution of benefits and costs. Low-income families are more likely to be living in substandard housing that has severe physical problems. These families disproportionately lack access to information about dampness-related problems and how to manage them, and even if made aware of them, they often lack the means to address such problems. The uneven distribution of benefits and costs is a barrier because stakeholders crucial to solving indoor dampness problems often lack the economic incentives to do so. They—the housing product manufacturers, builders, engineers, architects, landlords, and maintenance staff—do not usually physically live in the spaces that have been affected by the consequences of their choices. Hence, they may lack the incentive or the proper guidelines to design and maintain buildings to keep out dampness or to collaborate on improving building structures to ensure moisture prevention.

Lack of information and lack of access to information are also important problems. Often, people do not know where to turn if they experience problems with their indoor environments and which information sources they can trust. People may be unaware of the link between their indoor environments and their adverse health symptoms or diseases. Public education on IEQ is severely lacking. Indoor environments are typically not included as a topic in medical care curricula.

### Policy Recommendations to Achieve Healthy Home Environments

Just as the impediments to solving IEQ problems are both economic and information-related in nature, so are the potential solutions to overcoming these problems dealing with economic incentives and modes of communicating information. These must happen both at the levels of policymakers and broader stakeholder groups concerned with housing as well as the individual homeowners. We propose recommendations that will enable stakeholders to better understand the benefits and costs of improving home environments as well as the cost-effectiveness of various interventions. Providing economic incentives and disseminating information are key.

If health benefits from remediation of indoor environments can be translated into economic terms, political action is likely to follow. Otherwise health effects are considered an externality to housing and building policies, and are too often ignored, resulting in inefficient cost shifting. Cost-benefit analyses should be conducted on IEQ; specifically, they should contain information on the following:

- direct and indirect costs of human illness associated with poor indoor environmental quality;
- costs of interventions to achieve healthier indoor environments; and
- direct and indirect monetized benefits associated with healthier indoor environments.

An example concerns remediation of U.S. homes with lead-based paint and the impacts on children's health. Because of careful legislation, regulation, education, research, and enforcement, children's blood lead levels have decreased dramatically since the 1970s. The U.S. Department of Housing and Urban Development (HUD) and the U.S. EPA have estimated that from 2000 to 2010 the cost of reducing blood lead levels from exposure to lead-based paint will be \$2.4 billion over 10 years (HUD and U.S. EPA 2000). On the other hand, a retrospective analysis showed that annual monetized benefits, considering a 2.2–4.7 point increase in IQ per child affected, are \$110 billion–\$319 billion (Grosse et al. 2002). In short, the monetized benefits greatly exceed the costs. It will be

necessary to document, as with the case of lead remediation improving children's IQ, that the benefits of home remediation to reduce exposures to other contaminants will multiply throughout society.

One example of a common housing intervention that likely has unrecognized multiple health benefits is window replacement. The cost of replacing old windows with energy-efficient ones averages \$6,000 per housing unit, which is approximately equal to the increase in housing value due to fuel savings and appearance alone (Nevin 2000). But window replacement has also emerged as a way of controlling lead dust and lead paint hazards (National Center for Health Housing 2004). The health benefit of such window replacement is estimated to be over \$20,000 per housing unit (HUD 1999) due to avoided childhood lead poisoning. The health benefits associated with lead poisoning prevention, when added to the increase in home value and energy savings, clearly dwarf the expense of new windows. The economic benefits of window replacement, which includes other health improvements such as reduction of moisture and mold to reduce asthma risk, have not yet been quantified. But the common view is that the investment in new windows will only occur if the value of the property increases so that the investment can be recovered when the property is sold. Governments should consider adopting policies that uncover the health consequences of building investments (such as window replacement) rather than keeping such information hidden.

Multiple stakeholders could be given economic incentives to ensure healthy housing; for example, a reward or special recognition (such as a label) for meeting a certain level of quality. In the U.S. energy conservation arena, such means currently exist and may be expanded to cover health-related issues as well. The U.S. EPA Energy Star label is one way that consumers can determine if windows, appliances, and other products meet government standards for energy conservation (U.S. EPA 2007a). This is a voluntary program that manufacturers can choose to join if their products meet certain standards. In a similar vein, homes and rental spaces could be awarded a particular label for meeting a certain quality of indoor environment. Landlords also could be given awards and public recognition for providing rental spaces with good IEQ. Systems are emerging that could accomplish this, such as U.S. EPA's Energy Star Plus Indoor Air and the Enterprise Foundation's Green Communities program (U.S. EPA 2007b).

In addition to adopting policies that promote such investments, local governments should develop and implement hazard identification and remediation protocols. Although more research is needed to standardize such

protocols, one effort to build local capacity is a joint collaboration among HUD, the Centers for Disease Control and Prevention, U.S. EPA, the National Center for Healthy Housing, and a network of training providers to establish the Healthy Homes Training Center and network.

For both Energy Star and Healthy Homes, it is clear that public education and information dissemination are key to achieving healthy home environments. People must understand the health benefits associated with healthy houses in order to have the incentives to purchase them. The questions are “Who should communicate to the public?” and “How can we persuade people to make effective behavioral changes?”

Several pilot studies have shown that educational efforts carried out by community health workers and nurses, in combination with environmental interventions in the home, are effective in changing the indoor environment and motivating behavior change in ways that promote healthier home environments (Carter et al. 2001; Krieger et al. 2005; Morgan et al. 2004). In the successful educational interventions, the strategies taught to home dwellers were usually simple and feasible: cleaning and vacuuming more frequently with HEPA-filter vacuums, increasing fresh air ventilation in the home, putting covers on pillows and mattresses, and noticing and taking steps to prevent excess moisture. Krieger et al. (2005) found that the educational intervention combined with the cost of providing basic cleaning and bedding materials to families was cost-effective, as these measures led to a decrease in the number of hospital visits for children with asthma compared with a case-control study. The cost-effectiveness of other types of home environmental interventions is discussed in Wu and Takaro (2007). On the other hand, there is a need for more studies on the effectiveness of interventions that focus on building operations and maintenance by building owners/operators,

how to take proper care of their homes. Unfortunately, some low-quality homes are virtually impossible to cost-effectively remediate, and the regulatory and legal remedies available to compel these improvements are often lacking. The result in both of these situations is suboptimal human health conditions.

Although the problem involves multiple stakeholders and multiple levels of governance, it is possible to establish economic, social, and other incentives that would initiate action at all levels. Individuals must view their long-term health as an important investment when making decisions to purchase and maintain a home, even if this factor is not necessarily reflected in the price of the home. Regulatory decision makers also need comprehensive economic analyses on the costs associated with poor indoor environments and the benefits of healthy ones in order to gain the political means to effect broad changes in IEQ. Ultimately, the housing market and housing providers must include health-related investments in market prices and the costs of doing business to stimulate further investment and action.

Education and information dissemination on the public health risks associated with indoor environments are essential. Policy-makers must be well informed of such risks in order to make useful public health decisions. Similarly, individuals must understand both the health consequences of poor indoor environmental quality, and some simple and feasible interventions to improve IEQ. Public health education conducted by community health workers has been found to be cost-effective regarding behavioral changes in the home and resulting health benefits.

Indeed, policy changes at multiple levels are needed to achieve healthy indoor environments. It is quite certain that the benefits of such investments, measured in terms of improved human health and productivity, significantly outweigh the costs.

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## Discussion

There is now sufficient evidence from a risk assessment standpoint that home environments contain multiple health hazards that deserve public policy attention. However, the problem of IEQ involves multiple stakeholders who lack both the motivation and the proper information necessary to make changes. The combination of inaction at both the individual and societal levels makes healthy indoor environments difficult to achieve. Even if regulatory decision makers, architects, and engineers could be convinced to provide high-quality homes to all, indoor environments could still be poor if the building dwellers did not know

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## Current State of the Science: Health Effects and Indoor Environmental Quality

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Our understanding of the relationship between human health and the indoor environment continues to evolve. Previous research on health and indoor environments has tended to concentrate on discrete pollutant sources and exposures and on specific disease processes. Recently, efforts have been made to characterize more fully the complex interactions between the health of occupants and the interior spaces they inhabit. In this article we review recent advances in source characterization, exposure assessment, health effects associated with indoor exposures, and intervention research related to indoor environments. Advances in source characterization include a better understanding of how chemicals are transported and processed within spaces and the role that other factors such as lighting and building design may play in determining health. Efforts are under way to improve our ability to measure exposures, but this remains a challenge, particularly for biological agents. Researchers are also examining the effects of multiple exposures as well as the effects of exposures on vulnerable populations such as children and the elderly. In addition, a number of investigators are also studying the effects of modifying building design, materials, and operations on occupant health. Identification of research priorities should include input from building designers, operators, and the public health community. *Key words:* allergens, chemistry, exposure, fungi, humans, indoor air pollution, intervention, review. *Environ Health Perspect* 115:958–964 (2007). doi:10.1289/ehp.8987 available via <http://dx.doi.org/> [Online 25 January 2007]

Our understanding of health effects related to the indoor environment has evolved over the past decade. In the past, discussions of indoor environmental quality (IEQ) focused on indoor air constituents (primarily particles, bioaerosols, and chemicals), and comfort factors (temperature, air flow, and humidity) (Samet et al. 1998). More recently, we have begun to look at the relationship between the built environment and humans as a complex interplay between building occupants (who they are and what they do) and an array of physical, chemical, biological, and design factors. This evolution in understanding has profound implications for the design and operation of buildings, how the buildings are used, and the prevention and management of health problems that occur in building occupants.

### Source Characterization

Outdoor air pollution is a dynamic system in which the physical and chemical processes affecting the accumulation of pollutants in the atmosphere are constantly changing, largely driven by complex meteorology and photochemistry. In contrast, the usual approach of modeling indoor air pollution considers only pollution source strength and dilution by air exchange, thus treating the indoor environment as a static box in which physical and chemical transformations of

indoor air pollutants are absent or negligible. This misconception produces conservative estimates for primary indoor air pollutant concentrations and ignores the secondary pollutants. In-depth studies of indoor air have shown that the concentration of agents in indoor air is a function of outdoor concentration, indoor source strength, removal and deposition rate within the structure, indoor mixing, and chemical reaction. In the following sections, we use real-world examples to illustrate the dynamic nature of these processes and to discuss the implication of this dynamic environment in assessing exposures and health effects associated with indoor air pollution.

**Indoor production.** The generation of pollutants within the indoor environment may come from primary and secondary sources. Primary sources include fuel combustion for cooking, heating, and lighting; tobacco smoking; bioeffluents from humans and animals; floor and wall coverings; synthetic paints, glues, polishes, and waxes; pesticides; and building products. Another source is the release of gases from solvents used indoors or from water that is used daily for showers, bathing, cooking, and from drinking fountains. Such sources are important for by-products (e.g., chloroform) of chlorination-based water disinfection and radon (McKone and Knezovich 1991; Xu and Weisel 2005). Because of the use of many types

of synthetic materials in our daily lives, concentrations of many volatile organic compounds (VOCs) are consistently higher indoors than outdoors in residences and offices in developed countries. For some VOCs such as limonene, indoor levels up to 10 times those outdoors are common, even in locations with significant outdoor air pollution sources, such as petrochemical plants (Ott and Roberts 1998; Weisel et al. 2005). Secondary sources refer to indoor chemistry that transforms a set of indoor pollutants, emitted from primary sources or transported from outdoors, to a new set of indoor pollutants, as discussed below.

**Outdoor-to-indoor transport.** Pollutants of outdoor origin, including those present in the outdoor air and those released from soil sources, can be transported indoors via building openings and cracks (Garbesi et al. 1999; Nazaroff 2004). Attempts have been made to estimate the fraction of measured indoor concentration contributed by outdoor air due to the outdoor-to-indoor transport process (Ott et al. 2000; Thatcher and Layton 1995). One such study, the Exposures of Adult Urban Populations in Europe Study (EXPOLIS), compared concentrations of ambient particulate matter  $\leq 2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ), its 16 elemental constituents and black carbon, 30 VOCs, and carbon monoxide (CO) among urban adult populations in seven European cities. The study examined exposures in workplaces, residential outdoor and indoor air, and separated workday and leisure time (Jantunen et al. 1998). EXPOLIS data from Helsinki, Finland, showed the infiltration factor (the

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proportion of outdoor PM found indoors) for PM<sub>2.5</sub> averaged 0.64 for residential structures, 0.47 for workplaces, and 0.35 for a subsample of office buildings constructed after 1990 (Hänninen et al. 2004b, 2005). In another study, the Relationship of Outdoor, Indoor, and Person Air (RIOPA), fractions of measured indoor concentration contributed by outdoor air for PM<sub>2.5</sub> and each of 24 VOCs including 10 aldehydes and ketones were estimated for 310 residences located in three U.S. cities (Weisel et al. 2005). The median fractions of measured indoor concentration contributed by outdoor air for compounds with dominant indoor sources were less than 50%, for example, 13% for *d*-limonene (a common cleaning solvent), 20% for chloroform (a by-product of drinking water disinfection), 31% for  $\alpha$ -pinene and 20% for  $\beta$ -pinene (ingredients of synthetic paints), and 19% for formaldehyde (released from building/furnishing materials). For the compounds with sole or dominant outdoor sources (e.g., methyl *tert* butyl ether, carbon tetrachloride, and trichloroethylene), the fractions were about 100%, as expected. The fractions for PM<sub>2.5</sub> had a median of 56%, 25th percentile of 46%, and 75th percentile of 93% across the RIOPA homes (Meng et al. 2005; Weisel et al. 2005).

Significant interhome variability in fractions of measured indoor concentrations contributed by outdoor air has been observed for PM<sub>2.5</sub> and most of the VOCs in the RIOPA study. This finding has important implications for air pollution epidemiologic studies using concentrations measured at outdoor locations. Numerous exposure studies have shown poor correlations between personal exposure or residential indoor concentration and outdoor concentrations, indicating the observed associations between adverse health effects and PM concentrations measured at fixed outdoor sites do not necessarily represent the exposure–response relationships (Adgate et al. 2004; Clayton et al. 1993). Although attempts have been made to differentiate PM of outdoor origin from PM of indoor origin, analyses have been complicated because the fraction of indoor species contributed by outdoor air depends not only on outdoor concentration but also on home-specific parameters including air exchange rate [AER; typically expressed as air exchanges per hour (ach)], indoor generation rate, removal rate, and house volume (Meng et al. 2005; Thomas et al. 1993; Wallace et al. 1991).

Outdoor-to-indoor transport of very reactive chemical species has often been considered unimportant. An example is ground-level ozone (O<sub>3</sub>) that is formed via photochemical reactions and has elevated concentration in polluted atmospheres during photochemical smog episodes. O<sub>3</sub>, like PM, is regulated in the United States as a criteria pollutant.

Because of its high reactivity, only a fraction of O<sub>3</sub> can penetrate a building envelope. This fraction had been considered insignificant to cause any exposure concerns until 1989 when Weschler et al. (1989) showed that indoor exposure to O<sub>3</sub> can easily surpass outdoor exposure. Under moderate AERs (~ 0.5 ach), indoor O<sub>3</sub> concentrations may be 20–30% of corresponding outdoor concentrations. Under high AERs (> 1 ach), indoor O<sub>3</sub> levels can be 50–70% of outdoor levels. In a study carried out in six homes located in suburban New Jersey, indoor O<sub>3</sub> concentrations were 22–66% of outdoor levels during afternoon hours (Zhang et al. 1994). In summer time, 50% of the schools measured in Mexico City had indoor O<sub>3</sub> levels > 113 ppb (Gold et al. 1996). It is reasonably conservative to state that indoor O<sub>3</sub> levels > 20 ppb are common when outdoor O<sub>3</sub> concentrations are elevated. O<sub>3</sub> concentration at 20 ppb may not be sufficient to cause health concerns due to direct O<sub>3</sub> exposure, but this O<sub>3</sub> level can be sufficient to drive a complex set of indoor chemical reactions. When O<sub>3</sub> generators (so-called air purifiers) are used at O<sub>3</sub> generation rates of tens to thousands of milligrams per hour, indoor O<sub>3</sub> concentrations can be in the parts per million levels in a room with typical volume and AER.

Particle sources include both indoor home and residential sources, although recent research has shown that indoor (workplace and residential) contributions to total exposures may be underestimated compared with outdoor sources such as traffic (BeruBe et al. 2004; Koistinen et al. 2004). This appears to depend on the character of the particle; combustion-derived particles may be due more to outdoor sources, whereas other particles (for example, soil-derived particles) may be related to resuspension of particles during a host of indoor activities (Ferro et al. 2004; Larson et al. 2004). Recent experiments have shown that a wide range of indoor activities can result in considerable generation of PM (Afshari et al. 2005). Models of indoor PM exposure have been developed to account for both indoor and outdoor sources, as well as mixing, transport, and removal (Georgopoulos et al. 2005; Nazaroff 2004).

**Indoor-to-outdoor transport.** Ventilation is the primary factor affecting indoor-to-outdoor transport of indoor generated pollutants. Ventilation is necessary to reduce concentrations of pollutants generated indoors, but it is also necessary to reduce the time available for chemical reactions among indoor pollutants. One reason offered to support the conventional view of indoor chemistry being insignificant is that chemical reactions among indoor pollutants are too slow to complete with air exchange processes. Although this may be true when the AER is high, a variety of chemical reactions can take place at AERs

typical of today's residences and offices. Since the late 1970s, the airtight design of buildings, driven mainly by energy conservation, has resulted in reduced AERs. Based on approximately 4,590 measurements of residential AERs conducted across the United States, Pandian et al. (1998) reported that the mean, median, and SDs of AERs were 0.55, 0.42, and 0.47 ach, respectively, for the northeastern region, and 0.71, 0.62, and 0.56 ach for the southeastern region of the United States. AERs of this magnitude are undesirable for removing air pollutants that originate indoors and are low enough for certain chemical reactions to occur.

**Indoor chemistry.** Pollutants can be removed from indoor air through both physical and chemical processes. Physical processes that can result in pollutant removal (in addition to transport outdoors) include phase change, adsorption or absorption, or dissolving in water or organic films. Recently there has been considerable research interest in removal of pollutants through chemical reactions.

"Indoor chemistry" has been defined as reactions involving indoor pollutants, occurring either in the gas phase or on surfaces (Weschler et al. 2006). For a chemical reaction to influence the indoor environment, the rate of the reaction must be sufficient to compete with AERs. These chemical reaction processes represent sinks for the reactants (primary indoor pollutants) and sources of new reaction products (secondary indoor pollutants). The products may predominate in the air or on the surface. Removal does not necessarily occur in a simple linear fashion; for example, semi-volatile organic compounds can undergo an initial removal followed by a secondary increase due to resuspension of the compounds adsorbed on particles (Liou 2006).

Both gas-phase reactions and surface reactions that can occur under typical indoor conditions have been identified. The most extensively studied gas-phase reactions are oxidation reactions involving O<sub>3</sub> and free radicals. O<sub>3</sub> drives most indoor oxidation chemistry because it can react at meaningful rates with nitric oxide, nitrogen dioxide, and unsaturated organic compounds (e.g., terpenes, terpenoids, sesquiterpenes, unsaturated fatty acids) to yield reactive intermediates, the hydroxyl radical (OH), the nitrate radical (NO<sub>3</sub>) and oxygenated organic compounds (Weschler and Shields 1996). Reactions of O<sub>3</sub> with NO<sub>2</sub>, in the absence of sunlight, form the NO<sub>3</sub> radical that further reacts with VOCs, leading to the formation of indoor nitric acid. The NO<sub>3</sub> radical can also react with NO<sub>2</sub> to form dinitrogen pentoxide (N<sub>2</sub>O<sub>5</sub>) that undergoes hydrolysis, another pathway of nitric acid formation (Weschler et al. 1992). When O<sub>3</sub> and NO<sub>2</sub> are present simultaneously, indoor NO<sub>3</sub> may be the dominant indoor oxidant that

effectively reacts with nearly all indoor VOCs. The role of indoor  $\text{NO}_3$  chemistry in transforming indoor air pollutants remains to be evaluated.

Several terpenes, especially *d*-limonene and  $\alpha$ -pinene, are present at substantially higher concentrations indoors compared those with outdoors. These terpenes react readily with  $\text{O}_3$  under typical or realistic indoor conditions to initiate a series of complex chemical reactions, for example, at an  $\text{O}_3$  concentration of 20 ppb, the rate constant for  $\text{O}_3$  reaction with *d*-limonene and  $\alpha$ -pinene is approximately 0.36 ach and approximately 0.15 ach (Fan et al. 2003). Products of these reactions are found in both the gas and particle phases. Gas-phase-stable products include aldehydes, carboxylic acids, potentially allergenic peroxides and hydroperoxides (Fan et al. 2003). In one experiment where  $\text{O}_3$  (~41 ppb) was mixed with a VOC mixture comprising 23 commonly found VOCs, the resulting peak concentration of ultrafine and fine particles was approximately  $100 \mu\text{g}/\text{m}^3$  (Fan et al. 2005). Although attempts have been made to chemically identify the resulting particles, the majority of the particle mass could not be explained by the compounds identified thus far (Fan et al. 2003). It will be even more challenging to identify the short-lived, highly reactive, thermally labile or highly oxidized species that are formed in this complex reaction system. Unstable products of the ozone-terpene reactions include reactive intermediates and the hydroxyl radical. Hydroxyl radicals resulting from these indoor reactions can reach levels higher than typical nighttime outdoor concentrations, and thus react with other indoor VOCs with which ozone reacts too slowly to be of any practical significance (Weschler and Shields 1996).

The formation of particles via  $\text{O}_3$ -driven indoor chemistry has two implications. First, in an analysis of indoor particles measured in residences located in several United States cities, 25% of indoor  $\text{PM}_{2.5}$  could not be explained with known sources (Wallace 1996). Indoor chemistry was not considered in the analysis, which might explain at least part of the unknown sources. Second, because  $\text{O}_3$  and fine particles are co-generated outdoors during photochemical episodes, indoor particles resulting from indoor  $\text{O}_3$ /VOC reactions can vary coincidentally with the variations of outdoor summertime fine particles. This will certainly complicate the effort to separate PM of outdoor origin from PM of indoor origin. It should also be noted that source characterization may vary significantly, depending on the size of the particles (Koistinen et al. 2004).

A second type of indoor chemistry involves surface reactions. Outdoor aerosol surfaces play an important role in atmospheric chemistry. The importance of surface reactions indoors is

easily recognized, given that surface-to-volume ratios indoors are much larger than outdoors (roughly 3 vs.  $0.01 \text{ m}^2/\text{m}^3$ ). Indeed, indoor surfaces may be ideal for substance sorption and for water condensation. Surface water film can react with indoor  $\text{NO}_2$ , a major product of natural gas combustion, to form nitrous acid (HONO) and nitric acid ( $\text{HNO}_3$ ). The resulting nitrous acid is released into the air as gas-phase HONO, whereas nitric acid remains on surfaces as an  $\text{HNO}_3\text{-H}_2\text{O}$  complex (Dubowski et al. 2004). The latter yields possible acidic, oxidizing, and nitrating surface films on interior walls.  $\text{O}_3$  reacts with unsaturated VOCs contained in surface coatings at a faster rate than when it reacts with the same compounds in the gas phase (Reiss et al. 1995).

Indoor surfaces, including building materials, wall cavities, ducts, skin, clothing, dust, and airborne particles are very diverse and are a determining factor of indoor surface chemistry. They affect HONO formation via surface- $\text{NO}_2$  chemistry (Wainman et al. 2001). Complex physical and chemical processes involving surfaces include sorption, redox reactions, acid-base chemistry and hydrolysis (Nazaroff and Singer 2004). For example, dipthalate esters (plasticizers contained in polyvinyl chloride flooring materials) can undergo hydrolysis to form alcohols and monoesters. Aldehydes are emitted, at concentrations exceeding their odor thresholds, when  $\text{O}_3$  interacts with carpets (Morrison and Nazaroff 2002).

Building materials contain a large number of reactive constituents that can be released into the indoor air along with secondary products, including terpenoids, aliphatic aldehydes, phthalates, phenol, mono- and dicarboxylic acids, diisocyanates, and various photoinitiators. Photoinitiators, contained in ultraviolet curable coatings, can undergo decomposition to generate free radicals, and some (e.g., benzaldehyde and cyclohexanone) are precursors of odorous products (Salthammer et al. 2002). In a study conducted in German houses constructed with wooden studs treated with pentachlorophenol (PCP), it was found that over time PCP had been transformed to tetrachloroanisole, a compound of highly undesirable odor (Gunschera et al. 2004).

Indoor oxidation chemistry is largely driven by  $\text{O}_3$  reactions with unsaturated VOCs and perhaps with  $\text{NO}_2$  as well. Given that ozone levels have been rising in many areas, that indoor use of unsaturated VOCs (e.g., terpenes) has been on the rise, and that AERs have been decreasing, indoor oxidation chemistry has likely increased over the past several decades.

## Exposure Assessment

Much remains to be learned about exposure assessment in indoor environments. Part of the challenge is to account for the relative contributions of both indoor and outdoor

exposures. This has important implications, as indoor and outdoor exposures are often regulated very differently. Studies suggest that although indoor environmental measurements provide a better estimate of personal exposure than outdoor monitoring of VOCs, neither indoor nor outdoor environmental sampling (together or individually) is a good predictor of personal exposures (assessed by personal sampling and blood VOC concentrations) (Sexton et al. 2004, 2005).

Exposure assessment for biological agents is even more challenging than for particulate and chemical exposures. New and more accurate identification methods to identify molds are under development. Currently, polymerase chain reaction (PCR) methods are used in which the target DNA from building material is used as a template. In quantitative PCR (qPCR), quantitative data on the presence of viable and dead molds can be obtained—information that is not possible to obtain with the present culture methods (Cruz and Stetzenbach 2004; Meklin et al. 2004). These new methods are not yet fully developed and need to be evaluated (Keswani et al. 2005; McDevitt et al. 2004; Vesper et al. 2004). Even if fungal and mold species can be identified more accurately in the environment, there are as yet no reliable markers of human exposure or dose for these and other biological agents; some efforts are under way to assess exposure using chemical markers or immunologic markers (Schmechel 2006; Sebastian et al. 2005).

## Health Effects

In this section we review recent findings on specific agents and mixtures of pollutants. Some of the most significant advances have been made in our understanding of the mechanism of inflammation, and its role in mediating the responses to a wide variety of environmental stressors.

**Particulate matter.** Particulate air pollution has long been linked to both acute and chronic health effects, including asthma (e.g., mineral and organic dusts), cardiac disease (e.g., tobacco smoke and ambient air  $\text{PM}_{2.5}$ ), and other conditions (Pope et al. 1991; Viegi et al. 2004). Recent attention has focused on the ability of PM to potentiate the effects of common allergens, promoting IgE production (Karol 2002). Fine particles have been shown to decrease the forced expiratory volume in 1 sec ( $\text{FEV}_1$ ) in asthmatic schoolchildren (Delfino et al. 2004). Although particles have been shown to increase cardiovascular mortality, the specific mechanisms by which this occurs have yet to be clarified. Recent investigations have focused on possible effects on heart rate variability (Magari et al. 2002; Pope et al. 1999). PM, especially products of combustion, has also been linked to the development of cancer, although the



exact relationship is still under active investigation (Vineis and Husgafvel-Pursiainen 2005).

Most studies of PM have focused on ambient (outdoor) exposures and their relationship to hospital admissions and mortality. The contribution and significance of indoor particulate matter, which may differ substantially in composition from outdoor particulates, have yet to be fully explored (Bell et al. 2004; Morris 2001). Few studies have described the attributable risk of adverse health effects from indoor sources of particles, but some are attempting to quantify the relative contributions of indoor and outdoor particulate matter (and other toxins) in greater detail, to aid risk and exposure models (Weisel et al. 2005).

**Chemicals.** Chemicals of interest in the built environment include volatile and semi-volatile organic compounds, pesticides, and some chemicals produced during combustion (carbon monoxide, nitrogen oxides). Initially, interest in chemicals in indoor environments focused primarily on irritant and toxic properties of individual chemicals such as volatile organic compounds (VOCs) and combustion products. Concerns were also raised about the potential for chronic health effects (primarily cancer) related to exposures to organic compounds. There is interest also in the health effects from plastics and plasticizers. Chemical constituents of plastics have been found in household dust, and studies suggest these plasticizers may be related to allergic diseases in children (Bornehag et al. 2004b, 2005; Oie et al. 1997). Chemical processing inside structures also contributes to adverse health effects from indoor chemicals (Weschler 2004).

The relationship between irritation, stress, and perceived health effects of VOC exposures has gained increased attention. In one recent study, controlled exposures to VOCs, with and without ozone, did not significantly affect health effects compared with performance of a stress-inducing task (Fiedler et al. 2005).

The relationship of VOCs to asthma, particularly in children, remains controversial. A population-based case-control study of asthmatic and nonasthmatic children (ages 6 months to 3 years) in Australia found that the adjusted odds ratios for asthma increased with increasing concentrations of VOCs (particularly benzene, toluene, ethylbenzene, and xylene) (Rumchev et al. 2004). By contrast, a study in the United Kingdom found that VOC exposure (except formaldehyde) was not associated with an increased risk of wheezing illness, whereas dampness was significantly associated with wheezing illness (Venn et al. 2003). Several factors could account for inconsistencies between observational and interventional studies of home exposures to VOCs and asthma risk, including confounding, small effect levels, or chronicity of exposure (Dales and Raizenne 2004).

Polybrominated diphenyl ethers commonly used in flame retardants in consumer products can concentrate in house dust, and thus are potentially available for ingestion by occupants (Gevao et al. 2006). Similar results have been obtained for a variety of chemicals used in consumer products, indicating the importance of examining not only building components but also furnishings and contents of the indoor environment as sources of exposure (Marklund et al. 2003).

**Biological agents. Animal antigens.** Allergy to indoor agents can cause frequent and severe health problems, especially in children. Animal allergens are found commonly indoors, even where animals are not present. For example, assessment of cat, dog, and mite allergens in settled dust in schools and daycare centers in Oslo, Norway, revealed most samples contained detectable amounts of cat and dog allergens. Allergens were detected in mattress and floor dust in daycare centers and in curtain and floor dust in schools. The levels of cat and dog allergens in school floor dust were associated with the number of pupils with animals at home. By contrast, < 1% of the samples had measurable levels of mite allergen Der p 1. Endotoxin levels were also assessed. Levels of endotoxin tended to be higher in dust from floors (1.4 ng/m<sup>2</sup>) compared with that from mattresses (0.9 ng/m<sup>2</sup>). Mattresses in daycare centers are reservoirs of cat and dog allergens and should be cleaned frequently (Instanes et al. 2005).

In most communities, avoiding cats in the home would not decrease the prevalence of sensitization to cats because cat allergen is distributed in schools, other public buildings, and homes without a cat. Evidence that children or adults who make a modified T-helper 2 response (IgG and IgG4 antibody without IgE) are not at increased risk of asthma supports the role of IgE in asthma (Erwin et al. 2005).

**Biological hazards associated with damp indoor environments.** There is a large and growing literature on the health effects of biological agents typically found in damp indoor environments (Bornehag et al. 2001, 2004a). An Institute of Medicine (IOM) committee concluded there was sufficient evidence of association of damp indoor spaces with various upper and lower respiratory tract symptoms in adults and children. Molds and other specific biological agents were associated with a number of conditions including hypersensitivity pneumonitis in susceptible persons. The committee noted that in many cases and for many conditions, evidence is still insufficient to conclude that such an association exists (IOM Committee on Damp Indoor Spaces and Health 2004).

The clinical effects of human exposure to mold spores were studied in sensitive subjects who had previously experienced potentially

building-related symptoms at work. A highly controlled dose of fungal material was aerosolized directly from wet building materials. In a double-blinded study, eight sensitive school employees were exposed to *Penicillium chrysogenum* or *Trichoderma harzianum* spores for 6 min on 3 separate days. A statistically significant rise in symptoms from mucous membranes was assessed. This short-term exposure to high concentrations of two different molds induced no more reactions than exposure to placebo. Long-term experimental exposure studies on larger number of subjects would be needed to rule out an effect of mold exposure (Meyer et al. 2005).

One area in which the IOM panel felt evidence was insufficient to conclude whether an association or causal relationship concerned molds and a number of systemic conditions alleged to be related to mycotoxins (Fischer and Dott 2003). Molds can produce toxic metabolites known as mycotoxins. Over 400 mycotoxins have been described, most produced by species occurring on food. Many of the molds found indoors are similar to those on food and thus are also considered potential mycotoxin producers. It is important to note that mycotoxin production depends both on the growth conditions and the substrate, and therefore only a limited number of species are known to produce toxic compounds when grown on building or in house materials (Nielsen et al. 2002). The most well-known species is *Stachybotrys chartarum* but there has been considerable controversy regarding the toxic potential of *S. chartarum*. Care is essential when dealing with fungal problems caused by *Stachybotrys* or related fungi. Although the species *S. chartarum* is well known, there about 17 other different species of *Stachybotrys* and the related *Memmoniella* (Jarvis 2003; Jong and David 1976).

Research on the chemistry of *Stachybotrys* toxins is progressing to identify the chemical properties of species occurring in indoor environments. An excellent review of the toxins of *S. chartarum* describes a variety of secondary metabolites including trichothecenes, triprenylated phenols, and a new class of diterpenoids called "atranones" produced by the fungus (Jarvis 2003). Two chemotypes were found in *Stachybotrys*. The very toxic macrocyclic trichothecenes were detected in one-third of the isolates; less toxic, simple trichothecenes and a new class of atranones were found in the remaining two-thirds of the isolates. Atranones also possess significant biological activity (Miller J.D., personal communication). Species of *Chaetomium* and *Aspergillus vesicolor* are also potential toxin producers.

The clinical effects of mycotoxins have been alleged to include respiratory, neurologic, immunologic, dermatologic, gastrointestinal, and irritant effects, among others (Kuhn and

Ghannoum 2003; Laumbach and Kipen 2005). Despite the absence of validated markers of exposure, efforts have been made to understand the relationship between mold exposures and chronic nonallergic health effects. There have also been trials of empiric therapies for treating mold-exposed individuals, including patients treated with cholestyramine (Shoemaker and House 2005). There remains a lack of consensus regarding the systemic effects of mold exposures (Terr 2004). One of the limiting factors in this research is reliable, validated markers of exposure to either molds or the putative mycotoxins.

In addition to intact molds and fungi, (1 $\rightarrow$ 3)- $\beta$ -D-glucans are nonallergenic structural cell wall components of most fungi that have been suspected of playing a causal role in the development of respiratory symptoms associated with indoor fungal exposure. Current epidemiologic data do not permit conclusions to be drawn regarding the presence (or absence) of such an association between exposure and specific adverse health effects or which specific immunologic mechanisms underlie the presumed health effects (Douwes 2005).

Other biological hazards associated with indoor environments include bacteria, viruses, and other organisms. Although the association of *Legionella* with building water systems is well known, humidification systems carry risks for development of a variety of organisms capable of causing acute inflammatory responses as well as infection (Koschel et al. 2005). In addition, the design and operation of heating, ventilation, and air conditioning systems (HVACs) may have significant impact on the distribution of and subsequent exposures to aerosolized infectious agents (Li et al. 2005a, 2005b).

**Interactions and multiple exposures.** Investigators have begun to measure multiple pollutants present within the same environment, including particles, combustion products, photochemical smog products, and allergens (Breyse et al. 2005; Hänninen et al. 2004a). This is partly because health effects are often related to multiple exposures and because many experimental interventions affect more than one exposure and agent. Important interactions also occur between exposures to pollutants and other hazards such as infectious agents. Exposures to O<sub>3</sub> and NO<sub>2</sub> have been shown to increase airway epithelial cell cytokine production (Spannhake et al. 2002). Studies have also demonstrated interactions between particles and other contaminants such as O<sub>3</sub> that can potentiate the health effects of the two concomitant exposures (D'Amato et al. 2005; Harkema and Wagner 2005; Mar et al. 2005; Molhave et al. 2005). These findings suggest the possibility of additional benefits to interventions that reduce cumulative

exposures to several pollutants compared with interventions focusing on only one exposure.

## Building Design and Health

There is growing interest in examining the interaction of building design and health (Cummins and Jackson 2001). Physical and design characteristics of built structures (lighting, heating, ergonomics, noise, design) may create additional exposures that might contribute to health and comfort. Some of these factors may also play a role in chronic health effects. For example, evidence indicates that suppression of melatonin by nocturnal artificial lighting may play a role in breast and colon cancer development (Pauley 2004; Stevens 2005).

Research in office buildings, which has tended to focus on health and productivity, is now moving beyond indoor air to issues such as office design and acoustics (De Croon et al. 2005). There is a growing literature on school design and injury prevention, with more recent research on physical activity, obesity, and the implications of school design for the development of chronic diseases in later life (Sallis and Glanz 2006), but there is limited literature on student achievement (Sexton et al. 2000). Finally, studies of residential building design have examined a range of health outcomes related to building design, notably injury, but also mental health and other outcomes (Bonney et al. 2003; Weich et al. 2002).

## Intervention Studies

A number of investigators are now examining the effectiveness of environmental modification and education in reducing asthma severity. Examples include the use of air filters (Francis et al. 2003; Kilburn et al. 2003), pest management (McConnell et al. 2003), and education coupled with environmental modification (Krieger et al. 2002; Morgan et al. 2004; Tobias et al. 2004). Most of the interventions focus on control of more than one exposure, and have a relatively short duration.

Another study showed that use of ultra-violet germicidal irradiation within the HVAC system could reduce irritation symptoms in office workers (Menzie et al. 2003). This study was a crossover design in which subjects were blinded as to whether the intervention was in effect, and it used both symptom reporting and objective measures as outcomes. Although it did not examine all potential limitations and side effects of the intervention, it provides a useful example of the kinds of studies that may be needed to evaluate intervention strategies.

## Conclusion

It is increasingly apparent that indoor environments are unique and contain significant exposures that can affect the health of occupants. The exposures are the result of complex

interactions between the structure, building systems, furnishings, the outdoor environment, and the building occupants and their activities. As people spend more time indoors, the opportunities increase for significant health effects resulting from these exposures. So too does the need for research into the circumstances that make exposures more likely and the effectiveness of interventions to reduce the exposures. Interventions may involve difficult tradeoffs such as increased ventilation versus the need for energy efficiency. In addition, more research is needed on the interactions of multiple exposures, and the risks to certain populations (such as children, the elderly, or socioeconomically disadvantaged populations). Identification of research priorities should include input from building designers, operators, and the public health community. Research on interventions should examine a range of outcomes and potential tradeoffs and confounders, and does not necessarily need to await the identification of specific causal agents. Research is also needed on better measures of dose, particularly for biological agents.

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