Indoor environments and health: moving into the 21st century*

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ABSTRACT
The quality of our indoor environments affects well-being and productivity, and risks for diverse diseases are increased by indoor air pollutants, surface contamination with toxins and microbes, and contact among people at home, at work, in transportation, and in many other public and private places. Offered here is an overview of nearly a century of research directed at understanding indoor environments and health, current research needs, and policy initiatives that need to be addressed in order to have the healthiest possible built environments. The policy context for built environments extends beyond health considerations to include energy use for air-conditioning, selection of materials for sustainability, and design for safety, security and productivity.

INDEX TERMS
Built environment; Indoor air; Indoor environments review

INTRODUCTION

The Healthy Buildings 2003 conference recognizes the relevance to health and well-being of the indoor environments where people spend most of their time. The quality of these environments affects well-being and productivity, and risks for diverse diseases are increased by indoor air pollutants, surface contamination with toxins and microbes, and contact among people in these places. These are not new problems; they have been the focus of research and of control efforts for decades. The emphasis on the built environment indicates a shift towards a more holistic approach to indoor environments and the public's health, a shift consistent with the broadening recognition of the multiple levels of environmental factors, from the personal to the global, that determine an individual's health.

There is a shift from consideration of specific problems within indoor environments, such as radon and lung cancer, to a broader view that places greater emphasis on prevention. Some specific problems of indoor environments remain quite relevant and are a current focus for research, public concern, policy development, and even litigation. The health consequences of dampness and mould are a current example, and there are always emerging issues such as phthalates, organophosphates and pyrethroid pesticides. Many of these individual topics have been reviewed in depth elsewhere (Spengler *et al.*, 2001). Offered here is an overview of nearly a century of research directed at understanding indoor environments and health, current research needs and policy initiatives in order to have the healthiest possible built environments. The policy context for built environments extends beyond health considerations to include energy use for air conditioning, selection of materials for sustainability, and design for safety, security and productivity.

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HISTORICAL PERSPECTIVE: PROBLEMS RECOGNIZED

At the start of the last century, ventilation was viewed as healthy and as decreasing risk for infection (Addington, 2001). The important early work of Constantin Yaglou, reported in the 1930s, established a paradigm for using ventilation as the way to achieve thermal and odour comfort in the built environment (Yaglou *et al.*, 1936; Yaglou and Witheridge, 1937). For the next 50 years, dilution of human odours motivated mechanical design of buildings and guided the use of often large heating, ventilating and air conditioning (HVAC) systems. In the latter part of the 20th century, as health and comfort problems associated with buildings became apparent, Ole Fanger and others pointed out that office equipment, materials and even the HVAC system itself add to the odour and contaminant load of buildings and cause discomfort to occupants (Fanger and Valbjorn, 1979). In the 21st century, concern has returned to airborne spread of infection. New analytical tools that can isolate specific strains of viruses from a room air sample or a specimen of nasal mucus can advance the understanding of the role of ventilation and health and the potential for interrupting disease transmission in indoor environments. Perhaps the most dramatic demonstration of the need for new information on this issue was the dissemination of anthrax spores in postal facilities during the 2001 bioterrorism episode.

The relevance of the built environment to health became apparent when specific pollutants in indoor air were recognized as the major contributors to total personal exposures. This recognition was broadened by such dramatic problems as mobile homes that could not be occupied because of extremely high levels of formaldehyde from building materials, the finding of homes with radon levels as high as those in underground uranium mines, and the appearance of a new clinical syndrome, often referred to as 'sick-building syndrome', that was linked to the building environment. The Japanese analogy to the problems with mobile homes in the United States has led to nationally funded research of 'toxic home syndrome.'

Some of the first measurements of indoor air pollutants were made in the 1960s (NRC, 1981). In 1965, for example, Biersteker *et al.* (1965) made measurements of nitrogen dioxide in Dutch homes, finding that this outdoor air pollutant was also present at high levels in homes with gas-fired combustion devices. Some of the initial measurements of tobacco smoke components were made in the 1970s (Hinds and First, 1975; Repace and Lowrey, 1980) and asbestos fibres were found in indoor air in public buildings and schools in the late 1970s and early 1980s (HEI, 1991). Radon had been measured in indoor air as early as the 1950s, but gained prominence as large numbers of measurements were taken in the 1970s and 1980s and homes were found with dramatically high concentrations. The problem of lead paint and lead-contaminated surface dust in inner-city homes was recognized in the 1950s and 1960s (Markowitz and Rosner, 2002).

The health- and risk-relevant concept of total personal exposure to pollutants was introduced in the 1970s and provided a framework for integrating and interpreting pollutant measurements taken indoors and outdoors (NRC, 1991). In the 1980s, the US Environmental Protection Agency's Total Exposure Assessment Methodology (TEAM) Study used this model for comprehensive assessment of the contributions of indoor and outdoor exposures to total personal exposure for selected volatile organic chemicals, such as benzene (Wallace, 1987). This study yielded the then startling conclusion that indoor pollution sources are generally a far more significant contributor to total personal exposure for toxic volatile organic compounds than are releases by some industrial sources into outdoor air. The Harvard Six-Cities Study, known as a landmark investigation of outdoor air pollution, also proved to be an invaluable research platform for understanding residential indoor air pollution and its strong contributions to total personal exposures for a number of pollutants, including particles, sulphates, and nitrogen oxides (Speizer *et al.*, 1980; Dockery *et al.*, 1993; Ware *et al.*, 1984).

SOME PROBLEMS SOLVED

The measurement of indoor air pollutants was often followed by research directed at their health effects. Epidemiological studies of cross-sectional and cohort design focused on the risks of exposures at home and a more limited number considered workplace exposures, particularly to tobacco smoke. Case–control studies, and a few cohort studies, of second-hand smoke exposure and lung cancer risk in never smokers were carried out. The risks of cancer associated with asbestos and radon were estimated by extrapolating risks from studies of workers (HEI, 1981; NRC, 1988) but ecological and case–control studies of indoor radon and lung cancer in the general population were also initiated as early as the late 1970s (NRC, 1998). Studies of infants and children addressed adverse respiratory effects of nitrogen dioxide, second-hand tobacco smoke exposure, and biological agents, particularly indoor allergens. The earliest of these studies date to the late 1960s and research over the ensuing decades has provided convincing evidence for adverse effects of second-hand smoke, radon, and some biological agents. The evidence remains mixed for some other indoor pollutants: volatile organic compounds and nitrogen dioxide, for example.

For involuntary smoking, research on adverse effects on respiratory health of children began in the late 1960s; the first studies on involuntary smoking and lung cancer were published in 1981 (Hirayama, 1981; Trichopoulos *et al.*, 1981). The possibility of preventing exposure through elimination of smoking indoors was always clear and as the epidemiologic evidence mounted, increasing numbers of municipalities and states implemented policies to reduce or ban smoking in public places and workplaces. By 1986, the US Surgeon General and the National Research Council had concluded that involuntary smoking causes lung cancer and adverse effects on the respiratory health of children (US DHHS, 1986; NRC, 1986); the list continues to expand, now including coronary heart disease as well. With these causal conclusions, the debate over tobacco use shifted from the rights of an individual to use a product to the right of the public to breathe clean indoor air. Increasingly stringent control measures have resulted with broad impact; the majority of workplaces are now smoke-free in the United States, as are almost all commercial air flights, and levels of cotinine, the tobacco smoke biomarker, have declined sharply in the United States in recent years (CDC, 2003). Reducing involuntary smoking in the home is a remaining challenge, one that can be addressed primarily through education. Unfortunately, passive smoking remains a worldwide problem, particularly for women and children (Samet and Yang, 2001).

Indoor radon, labelled as ‘the colourless, odourless killer’, gained notoriety in the United States in the early 1980s, after media reports of a Pennsylvania home with such high levels that the nuclear power plant worker who lived there triggered the radiation monitoring system at the plant as he arrived at work. In the subsequent 20 years, the risks posed by indoor radon became clear (Samet and Eradze, 2000). A pooled analysis of data from 11 cohort studies of underground miners was carried out to estimate the risks of indoor radon, with complementary evidence gained from case–control studies of lung cancer in the general population (Lubin *et al.*, 1994; NRC, 1998). Elegant experimental models, involving irradiation of single cells with single alpha particles, provide results consistent with a linear non-threshold relationship between typical concentrations of indoor radon and lung cancer risk (Zhou *et al.*, 2000, 2001). The source of most indoor radon, soil gas, is well characterized and radon concentrations can be measured cheaply and with reasonable accuracy. In spite of the abundant scientific evidence supporting strategies for radon control, including measuring and mitigating home with high levels and building radon-resistant homes, the voluntary initiatives of the Environmental Protection Agency have had limited acceptance by the public (US EPA, 1992a,b; Cole, 1993). Since the mid-1980s, the Agency reports that 18 million US homes have been tested and 50 000 homes mitigated (Gregory and Jalbert, 2001). The voluntary approach is strengthened where radon testing is a standard requirement in purchase and sales agreements for homes.

Asbestos, another inhaled carcinogen, was widely used in the United States through the 1970s as an insulating material in public and commercial buildings; it has also been used to insulate piping in residences and there is a potential for exposures in homes if the asbestos-containing material is friable. Concern about asbestos indoors first followed the recognition that insulating materials in many schools contained asbestos and some of the first measurements in schools indicated the possibility of unsafe levels in air. Under the Asbestos Hazard Emergency Response Act (AHERA, 1986), school systems had the option of either removing the asbestos or of maintaining it in place. Initially, asbestos-containing material was removed from many schools at substantial expense but this approach was re-evaluated as further measurements were obtained and options for managing asbestos-containing materials in commercial buildings were considered. A risk assessment carried out by the Health Effects Institute proved pivotal in pushing control towards in-place management (HEI, 1991). Concerns about asbestos indoors may arise again after it becomes widely known that tremolite asbestos fibres, from the Libby Montana mine, are in Zonolite insulation used in millions of homes, businesses and schools (Bowker, 2003).

Nitrogen dioxide, one of the first pollutants measured indoors, can adversely affect the lung at high concentrations and consequently when it was found to be emitted by such ubiquitous appliances as gas stoves, epidemiological studies were initiated on its effects on the respiratory health of children and adults (Samet and Utell, 1990; Samet and Basu, 1999). The findings of these studies have not provided consistent evidence for adverse effects of nitrogen dioxide and levels in homes have declined as stoves with electronic ignition have replaced older stoves with gas pilot lights and cooking patterns in the United States have moved towards increasing use of microwaves and less cooking generally. Some higher level exposures persist, however. Gas stoves are still used for supplemental heating, particularly by those in public housing who are often not sub-metered for gas use. Also, quite high levels of nitrogen dioxide have been measured in poorly ventilated indoor ice rinks that are resurfaced with machines powered by gasoline or diesel engines (Brauer and Spengler, 1994).

The biological agents have proved challenging; they are myriad and cause disease through infectious and non-infectious mechanisms. Nonetheless, we have sufficient evidence to prevent the disease caused by some specific agents. The transmission of *Legionella* species through inadequately maintained cooling equipment for HVAC systems and building water systems is well recognized and building-related (Barry, 2001) (as well as cruise ship) epidemics of *Legionella* infection can be avoided through proper cleaning and maintenance. Numerous indoor allergens have been measured and some linked to exacerbation and possibly causation of allergic diseases, including asthma. Control measures can reduce exposures to some of the agents, e.g. cockroach and mite antigens, but substantial benefits to health have not been readily shown, in part because of the difficulties of maintaining reduced levels (Burge, 2002).

APPROACHING THE PROBLEMS REMAINING TO BE SOLVED

The single most pervasive and harmful indoor air problem worldwide is the oldest—smoke from fires. Domestic cooking and heating with biomass fuels of wood, crop residues, dried animal dung or with charcoal and coal can produce substantial concentrations of particles, carbon monoxide and polycyclic aromatic hydrocarbon indoors. The World Health Organization's 2002 report (WHO, 2002) on global burden of disease considered the almost daily exposures of billions of people, primarily women and young children, as the eighth leading cause of disability adjusted life years (DALYs) lost, accounting for nearly 3% of the world's total burden of disease. For over two decades we have known that improving stove efficiency, providing working flue vents, or improving fuel quality, e.g. switching to propane or liquefied petroleum gas (LPG), could dramatically reduce acute respiratory infections, chronic lung and heart disease, and blindness.

Many of the recognized indoor air quality problems facing developed countries are avoidable. If achieving a healthy indoor environment were a specific design criterion for buildings, many of the recurring problems of mould, pest allergens, radon, organic compounds, nitrogen dioxide and carbon monoxide could be controlled. Tobacco smoking indoors has been reduced by restriction and bans but achieving effective control in the home remains a challenge; educational strategies are needed, particularly for protecting those at greatest risk, such as infants and children with asthma. Attention should be focused on particularly critical building environments; schools are one obvious example as children spend substantial time in them but ventilation and maintenance may be inadequate.

One lesson that has been learned repeatedly is the need to approach the built environment with multidisciplinary teams, whether for research, design and problem-solving, or for planning for the future. There is far too much isolation of the involved professions, who include public health and medical scientists and researchers, architects, engineers, city planners, building managers, and others, and there is insufficient engagement with the needs of the population itself. The Healthy Buildings and Indoor Air & Climate conference series, along with interdisciplinary meetings to address indoor air quality issues, have been impressed with the immediate recognition among the participants of the necessity for interdisciplinary interactions on such issues as sick-building syndrome, air cleaning, and the level of optimal humidity (ATS, 1988; ALA/ATS, 1997). Over the last several decades, the profession of indoor air quality specialist has developed and there are private firms providing indoor air quality services that include problem-solving and management. Since 1978, the *Indoor Air* conferences have offered an international venue for scientific exchange among the many disciplinary experts concerned with the built environment. Some of the critical topics have been addressed by committees of the National Research Council, the Institute of Medicine, and other organizations (IOM, 1993, 2000; NRC, 1998).

With an ever growing research base available, the scientific evidence on indoor air should inform the process of designing and maintaining buildings. All too often, well-intended inclusion of indoor air quality as a consideration is reduced to a simple checklist of general items to be avoided and to compliance with ventilation codes. This approach reflects a 'dumbing down' of the complex ways in which humans interact with the environment. A more comprehensive rethinking is needed on the physiological, sociological, ergonomic, and psychological characteristics of the built environment that affect health and well-being. Many building codes and design criteria are not soundly based in their consequences for human performance (e.g. lighting requirements). Ventilation requirements for buildings have been assessed, along with those for temperature and humidity more on the basis of meeting comfort criteria than with an orientation towards health or even productivity. Remarkably, there has never been a comprehensive study on the role of ventilation and health and comfort in homes. The current guidelines of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, 1989) recommend a minimum air exchange rate of 0.35 h^{-1} for homes, which is the lowest among developed countries. However, associations of homebuilders have resisted attempts to specify mechanical means to achieve this recommended exchange rate or to have higher exchange rates for homes, even though the majority of time is spent in homes.

New issues related to the built environment will inevitably emerge. On the current shortlist of chemicals likely to be of concern are several synthetic organic compounds: poly-chlorinated biphenyls in building materials; phthalates in polyvinyl chloride materials used in flooring, wall coverings, cables, foam and other building, consumer and personal care products; polybrominated diphenyl esters, which are fire retardants used in many products including computers; pesticide residues including the recently introduced family of pyrethroids; and cleaning agents such as those with phenol among other potentially sensitizing compounds (Rudel *et al.*, 2003).

The current concern about intentionally introduced viruses as acts of bioterrorism or surprise infectious agents, such as SARS, will advance research on the role of building ventilation and air disinfection in the transmission of pathogenic organisms. As more multi-disciplinary research on health and buildings is carried out, the effects of interior design, materials, lighting and air quality on stress and performance should become better understood. Studies of workforce health complaints related to the building environments have been methodologically complicated by the non-specificity of most complaints and separating causal effects of engineering and design factors from job stress, personal stress, and perception of unsatisfactory indoor environmental conditions is often impossible. A recently published research agenda for indoor environments and worker health emphasized building-related asthma and allergic diseases in addition to communicable respiratory infections and non-specific building-related symptoms (Mendell *et al.*, 2002).

While research continues, for some problems the public, the lawmakers, and the lawyers will not await more certainty from scientific investigations. For example, state and federal legislation on toxic mould has been proposed. Many individuals, building owners, and insurance companies have been affected by the consequences of water damage and moulds and there is uncertainty as to health risks and control approaches. Effective policy approaches are urgently needed for the problem of indoor moulds and moisture. The current situation is reminiscent of the past tumultuous debates and litigation around asbestos in buildings. In the 1980s and early 1990s expensive removal of asbestos-containing material was the first course of action regardless of whether the presence of that material actually exposed occupants to asbestos fibres. Currently, insurance companies are attempting to write policies excluding mould liability or simply refusing to insure in states where mould claims are widespread. This situation needs resolution through science-based policies and perhaps legislation, but the needed research has yet to be carried out.

The Healthy Building and Indoor Air & Climate conference series have done much to advance the field of indoor air quality and building sciences worldwide. Despite National Resource Council report in 1981 (NRC, 1981), only recently has the subject of health and the built environment been more widely recognized in the United States. Research needs on indoor environments are featured prominently by the US National Institute of Occupational Health & Safety (http://www.cdc.gov/niosh/homepage.html) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (http://www.ashrae.org/). The US National Institute for Environmental Health Sciences (http://www.niehs.nih.gov/) organized a workshop on the 'Built Environment—Healthy Communities, Healthy Homes and Healthy People' in July 2002 (http://www.niehs.nih.gov/translat/BE-final.pdf). Now the *American Journal of Public Health* is publishing two special issues of research articles on the health and built environment (September 2003 and April 2004).

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