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Public health

Quality of indoor residential air and health

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Abstract

About 90% of our time is spent indoors where we are exposed to chemical and biological contaminants and possibly to carcinogens. These agents may influence the risk of developing nonspecific respiratory and neurologic symptoms, allergies, asthma and lung cancer. We review the sources, health effects and control strategies for several of these agents. There are conflicting data about indoor allergens. Early exposure may increase or may decrease the risk of future sensitization. Reports of indoor moulds or dampness or both are consistently associated with increased respiratory symptoms but causality has not been established. After cigarette smoking, exposure to environmental tobacco smoke and radon are the most common causes of lung cancer. Homeowners can improve the air quality in their homes, often with relatively simple measures, which should provide health benefits.

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In North America, adults spend about 87% of their time in buildings, 6% in vehicles and 7% outdoors.[1] Leech and colleagues[2] have reported that Canadians spend similar amounts of time indoors. Typically, more time is spent indoors in very hot or cold climates. As a result, personal exposure to airborne substances is more closely related to indoor rather than outdoor pollution.[3,4] We review the sources, health effects and control strategies for several of the most important sources of residential biological and chemical contaminants.

Although outdoor and indoor environments tend to be viewed as distinct entities, some outdoor pollutants enter the home. However, less air pollution enters tightly sealed homes, such as those found in colder and hotter climates where windows and doors are more regularly closed to retain conditioned air.[5] In addition, economically disadvantaged families may be more likely than others to live close to roadways and industry, have lower-quality housing and have less access to air conditioning, which may result in poor indoor air quality.[6] On days with high concentrations of particulate matter, cities with a high prevalence of air conditioner use report fewer hospital admissions for cardiovascular disease, chronic obstructive pulmonary disease and pneumonia compared with cities with lower air conditioner use.[5]

Indoor air pollutants include carcinogens and biological and chemical contaminants. The latter category can be divided into combustion products and gases released from indoor materials (off-gassing emissions). Several guidelines for exposure limits for indoor air contaminents have been developed by the Canadian government (Table 1). Overall, indoor air contaminants have largely been shown to exacerbate pre-existing conditions; however, few studies have examined causality.

Biological contaminants

Allergens

The most common indoor sources of allergens are furry pets and dust mites. Dust mite allergens can worsen pre-existing asthma.[10] Cats and cockroaches can exacerbate pre-existing asthma, and dogs and indoor fungal contamination are associated with worsening asthma.[10]

However, immune tolerance has been reported, especially with high allergen exposure.[11] Dust mite allergens have been reported to increase the risk of developing asthma.[10] Early exposure to cats or dogs has been reported to both increase and decrease the risk of allergy.[12] One cohort study that included 1300 newborns followed for up to 7 years reported no significant association between mite and cat allergens in floor dust and the development of asthma.[13] These conflicting observations make it difficult to provide clear recommendations about whether to remove pets from the home to prevent the development of allergic disease in children who have not already been sensitized.

Endotoxins

Endotoxins are lipopolysaccharide components of the outer membranes of gram-negative bacteria. Increased endotoxins or gram-negative bacteria are associated with contaminated humidifiers, lower ventilation rates, presence of cats and dogs, storage of food waste and increased amounts of settled dust.[14,15] Increased levels of endotoxins in house dust have been associated with increases in asthma symptoms and use of asthma medications and with reduced lung function in people with atopy or asthma.[16,17] Among Canadian children

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Table 1: Health Canada recommendations for indoor air quality

Contaminant	Recommendation	Year guideline was issued
Formaldehyde[7]	• 50 μg/m^3 (40 ppb) for 8 h exposure • 123 μg/m^3 (100 ppb) for 1 h exposure	2006
Mould[8]	• Control humidity and diligently repair any water damage to prevent mould growth • Thoroughly clean any visible or concealed mould growing	2007
Carbon monoxide[9]	• ≤ 11 ppm per 8 h (average) • ≤ 25 ppm per 1 h (average)	1987
Nitrogen dioxide[9]	• Short-term exposure: ≤ 480 μg/m^3 (≤ 0.25 ppm) per 1 h • Long-term exposure: ≤ 100 μg/m^3 (≤ 0.05 ppm)	1987
Ozone[9]	• ≤ 240 μg/m^3 (≤ 0.12 ppm) per 1 h	1987
Fine particulate matter (PM 2.5)[9]	• Short-term exposure: ≤ 100 μg/m^3 per 1 h • Long-term exposure: ≤ 40 μg/m^3	1987

Note: ppb = parts per billion, ppm = parts per million.

followed from birth to 2 years, a doubling of the indoor air endotoxin concentration was associated with an increase of 0.32 episodes of illness each year ($p = 0.0003$).[18]

Despite these adverse effects, early exposure to endotoxins may reduce future allergies and asthma.[19] Endotoxins induce production of interleukin-12 and interferon-γ, which may decrease expression of Th2 lymphocytes that help mediate atopy and asthma.[20] Consistent with this is the observation that children who grow up on farms, where endotoxin exposure is higher than in urban areas, have lower rates of atopy.[19,21]

Building-related dampness and mould

Apart from floods, there are 4 major sources of mould growth in residences: leaks in building fabric, condensation, unattended plumbing leaks and household mould (e.g., mould growth on kitchen and bathroom surfaces, hidden food spills, garbages, defrost pans).[22] A large number of cross-sectional and case–control studies from several countries have found an association between mould or dampness in the home and health complaints.[8] A recent meta-analysis of the health effects associated with dampness and mould reported pooled odds ratios (OR) of 1.70 (95% confidence interval [CI] 1.44–2.00) for upper respiratory symptoms, 1.67 (95% CI 1.49–1.86) for cough, 1.50 (95% CI 1.38–1.64) for wheeze and 1.56 (95% CI 1.30–1.86) for current asthma.[23]

If home dampness or mould is causal, it could account for 30%–50% of respiratory symptoms. Most studies have not objectively measured mould growth or health outcomes. Home dampness may be a proxy for mould growth; however, dampness may also be a marker for dust mites, endotoxins and reduced ventilation, which could increase concentrations of indoor pollutants. A causal relation is biologically plausible given that indoor fungi produce allergens, irritants and toxins. The US Institute of Medicine's Committee on Damp Indoor Spaces and Health concluded that there was sufficient evidence of an association between dampness and health outcomes; however, causality had not been established.[24]

Chemical contaminants

Combustion products

Environmental tobacco smoke

The 2006 US Surgeon General's report is one of the most recent comprehensive reviews of the adverse health effects of environmental tobacco smoke.[25] This report states that environmental tobacco smoke is a cause of premature mortality. Living with a smoker is associated with an estimated 20%–30% increased risk of lung cancer. Environmental tobacco smoke is also associated with a 25%–35% increased risk of coronary artery disease. Among children, environmental tobacco smoke has been reported to increase the risk of childhood cough and wheeze, admission to hospital for respiratory illness and sudden infant death syndrome. Environmental tobacco smoke also slows lung growth.[25]

Coal and biomass fuels

Coal, wood and plant residues are commonly used for cooking and heating in rural areas of developing countries, such as China.[26] The combustion products of these solid fuels include carbon monoxide, nitrogen dioxide, particulates and polycyclic hydrocarbons. Some coal is very high in sulfur and may contain toxic metals such as lead and chromium. Use of coal is associated with an increased risk of lung cancer (OR 2.65, 95% CI 1.6–4.1) and childhood asthma (OR 2.3, 95% CI 1.5–3.5).[26]

Carbon monoxide

Indoor sources of carbon monoxide include vehicle exhaust from attached garages, gas stoves, furnaces, woodstoves, fireplaces and cigarettes. In California between 1979 and 1988, there were 270 deaths caused by accidental carbon monoxide poisoning from nonvehicular sources.[27] Liu and colleagues[28] reported that deaths were more common in winter and among men, black people and the elderly. Unvented combustion

heaters and charcoal fuel were common sources of carbon monoxide.[28] A 2005 report to the California legislature suggested that there are thousands of symptomatic but nonfatal cases each year in California. Symptoms of carbon monoxide poisoning, such as headache, nausea and fatigue, may be mistaken for the flu.[27]

Nitrogen dioxide

Nitrogen dioxide is an airway irritant that is emitted mainly during the combustion of fossil fuels. The indoor sources of nitrogen dioxide include combustion appliances such as gas or oil furnaces and stoves.[29] Nitrogen dioxide may move from the outdoors to indoors; however, if from an outdoor source, it will be at a lower concentration in the home than if it were from an indoor source. Whether chronic exposure to low concentrations of nitrogen dioxide from indoor sources increases the risk of respiratory illnesses is unclear. In a cohort study that included over 1500 children aged 7–11 years at enrolment, long-term exposure to indoor nitrogen dioxide at concentrations greater than 38 μg/m^3 was associated with a significantly increased risk of respiratory symptoms.[30] However, 2 cohort studies that followed 1205 infants for 18 months after birth[31] and 1611 infants for 12 months after birth[32] did not find an effect of indoor nitrogen dioxide on the incidence of lower respiratory illness. Reasons for these conflicting findings are unknown, but perhaps older children are more susceptible than younger children to nitrogen dioxide. Older children are more likely to exhibit atopy and asthma, which may modify the response to nitrogen dioxide. This is shown by the observation that short-term inhalation of high concentrations of nitrogen dioxide increases bronchial responsiveness to inhaled allergens in sensitized asthmatics.[33]

Off-gassing emissions

Off-gassing emissions (gases released from indoor materials) include formaldehyde and volatile organic compounds (e.g., aliphatic and aromatic hydrocarbons) released from materials such as wood-based products, paints, floor finishes, glues, consumer products and freshly dry-cleaned clothing. Emissions are highest from new materials and recently applied paints and finishes. These products decay over time, explaining why concentrations of formaldehyde and volatile organic compounds are usually higher in newer homes than in older homes.[34]

Formaldehyde

At room temperature, formaldehyde is a gas. It is also available in an aqueous solution as formalin. It is an airway irritant and a possible carcinogen. In indoor environments, formaldehyde is mainly produced by off-gassing from wood-based products assembled using urea-formaldehyde resins (plywood, particle board, medium-density fibreboard). Other sources include cigarette smoke, certain paints, varnishes and floor finishes.[35]

A study of 96 homes in Québec City, Quebec, between January and April 2005 reported formaldehyde concentrations between 9.6 to 90.0 μg/m^3 (mean 29.5 μg/m^3).[36] Greater concentrations of formaldehyde were associated with lower fresh air exchange and with painting, varnishing and acquiring new wooden or melamine furniture in the previous 12 months.[36] Levels of formaldehyde in mobile homes, which generally have a high proportion of pressed wood products that contain urea–formaldehyde resin, tend to be even higher than the concentrations in homes with urea-formaldehyde foam insulation.[37] Formaldehyde concentrations in homes are inversely correlated with the air change rate.[36]

Acute effects such as eye, nose and throat irritation have been observed following controlled exposures to concentrations of at least 1230 μg/m^3.[38] However, in people with asthma and allergic sensitization to the dust mite *Dermatophagoides pteronyssinus*, inhalation of 100 μ/m^3 formaldehyde for 30 minutes caused a significant increase in bronchial responsiveness to the mite.[39] Associations between residential or school exposure to formaldehyde and respiratory symptoms has been reported in observational epidemiologic studies.[40,41] In a study that included 298 children and 613 adults in Tucson, Arizona, Kryzanowski and colleagues[40] reported that physician-diagnosed asthma and bronchitis, but not respiratory symptoms, were associated with increasing concentrations of formaldehyde. A 22% decrease in peak flow was estimated to occur for each 60 part per billion increase in home formaldehyde concentrations.[40] Formaldehyde was declared a toxic substance by the 1999 Canadian Environmental Protection Act.[7]

Volatile organic compounds

The World Health Organization defines an organic compound as volatile if it has a melting point below room temperature and a boiling point between 50–100 °C and 240–260 °C.[42] The United States Environmental Protection Agency has a regulatory definition: a volatile organic compound is a carbon-containing compound that participates in atmospheric photochemical reactions.[42]

Cigarette smoke, recently dry-cleaned clothes and room deodorizers are major sources of volatile organic compounds.[43] Wallace reported that exhaled benzene was 10 times higher for smokers than nonsmokers.[44] Gasoline vapours have been found in homes with attached garages.[5] Age of building materials is also an important determinant of the rate of off-gassing. Exposure is much higher from wet paint and new carpets compared with dry paint and old carpets.[45–47] The type and quantity of volatile organic compounds in the material, the surface area of the material and the depth of the volatile organic compounds within the material also affects exposure.[48] In contrast, ventilation and air conditioning tend to reduce indoor volatile organic compounds.[49] In general, indoor concentrations are higher than outdoor concentrations, and concentrations in winter are greater than in summer.[50]

Small clinically controlled studies have demonstrated bronchoconstriction from insecticides that contain pyrethrin and perfumes.[51,52] In a study that included 88 adults, 50% of whom had asthma symptoms, Norback and colleagues[53] found that respiratory symptoms were related to residential formaldehyde and volatile organic concentrations. Bronchial reactivity was related to limonene, a volatile terpene found in citrus fruits and often added to cleaning products. Wieslander and colleagues sampled 562 people in Uppsala, Sweden, in 1990 and found that asthma symptoms and bronchial hyper-

reactivity were associated with both wood and kitchen painting in the previous 12 months.[54] They report that total volatile organic compounds were 100 mg/m^3 higher in homes that had been recently painted.[54]

The use of aerosol cleaning products has been associated with an increased incidence of asthma symptoms over an average follow-up period of 9 years. Among 3503 people in 10 European countries who used aerosolized products for glass cleaning, air freshening and furniture polishing, the relative risk was 1.49 (95% CI 1.12–1.99) for asthma symptoms or medication use and 1.39 (95% CI 1.06–1.80) for wheeze. There was a dose–response relation between the weekly frequency of using cleaning sprays and relative risk of asthma. Airways responsiveness, measured by methacholine bronchial challenge, was not associated with cleaning sprays. The use of nonaerosol products was not associated with asthma.[55]

Plastic compounds

Jaakkola and colleagues performed an age-matched case–control study within the Oslo birth cohort that included 3754 children.[56] The clinical diagnosis of bronchial obstruction was more common among children living in homes with polyvinyl chloride than in homes with wood flooring (OR 1.89, 95% CI 1.1–3.1). Bronchial obstruction was also more common among children in homes with textile wallpaper than with painted walls (OR 1.6, 95% CI 1.0–2.5). In a second case–control study by this group, which included a cohort of 2568 children born between 1984 and 1989 in Espoo, Finland,[57] the authors report that plastic wall materials were associated with increased risk of asthma (OR 1.5, 95% CI 0.4–6.7). There was also increased risk of wheeze, cough and phlegm (OR 3.4, 2.4 and 2.8 respectively). One explanation is that one major component of polyvinyl chloride is the plasticizer di-(2-ethylhexyl) phthalate and its hydrolysis product mono-(2-ethylhexyl) phthalate, which, in rats, induces bronchial hyperreactivity.[58] The Third National Health and Nutrition Examination Survey, which included 240 adults, reported that increased levels of monobutyl phthalate were associated with decreased pulmonary function in men but not women.[59] For a change from the 25th to the 75th percentile in monobutyl phthalate level among men, 1-second forced expiratory volume decreased by 112 mL (standard error 51, $p = 0.03$).[59]

Carcinogens

Radon

The US Environmental Protection Agency estimates that residential radon causes about 21 000 deaths because of lung cancer annually in the United States.[60] Lung cancer typically develops 5–25 years after exposure. Radon, a radioactive gas, comes from the natural decay of uranium in soil. It enters the home through cracks and holes in the foundation and accumulates. Well water and building materials are not common sources. The average outdoor level of radon is about 0.4 pCi/L or 37 Bq/m^3. A study by the US Environmental Protection Agency that included homes in 50 states reported a mean indoor air radon concentration of 46 Bq/m^3, ranging between 54 Bq/m^3 in single-family homes to 24 Bq/m^3 in multifamily homes.[61] The level of radon on the first floor of a home may be less than half of the level in the basement.[62]

A Canadian survey performed between 1977 and 1980 that included 14 000 homes reported a range of mean radon levels from 5.2 Bq/m^3 to 57 Bq/m^3. Of the included homes, 1 in 1000 homes had a radon level in excess of 800 Bq/m^3.[37] Based on a meta-analysis of 7 case–control studies in North America, the odds of developing lung cancer increased with residential radon exposure. The estimated OR for lung cancer 5–30 years after exposure was 1.11 (95% CI 1.00–1.28) at 100 Bq/m^3. These results were not influenced by sex, education, or smoking.[63] The upper radon exposure limit in the guidelines published by Health Canada is 200 Bq/m.^{3}

Asbestos

Occupational exposure to asbestos causes lung cancer, mesothelioma and lung fibrosis.[64] Asbestos is a fibrous mineral found in rock formations that has been widely used in home construction materials, such as floor and ceiling tiles, insulating board and pipe covers. A 2004 Canadian provincial government report stated that Canadian homes built over 20 years ago may have asbestos in the coverings of furnaces, ducts, pipes and flooring.[65] Health Canada reports that if the asbestos fibres are enclosed or tightly bound in a compound, there is no significant health risk.[66] If the asbestos material is more than slightly damaged or fragmented, or if home renovations that might disturb the material are planned, a professional should perform the repairs or renovations. Homeowners who are planning to remodel their homes should first find out whether asbestos-containing materials are present.[67]

The health professional's role

When to suspect poor indoor air quality

Allergic diseases such as rhinitis and asthma may be exacerbated by indoor allergens and irritants. Otitis media and respiratory infections are more frequent among children exposed to environmental tobacco smoke. Headaches may be a sign of carbon monoxide poisoning.

How to screen for potential exposures

Obtaining a short patient history is an important first step. Ask about the presence of furry or feathered pets; if there is a smoker in the home; if there is visible water damage, mould growth or mouldy smells; what heating sources are used; if there has been furnace maintenance; whether the patient or someone else in the home uses scented products; and which hobbies the patient participates in. Carpets, drapes and soft furnishings are reservoirs for fungi, dust mites, endotoxins, and pet and pest allergens. Generally, it is not possible to accurately predict the presence of elevated radon concentrations.

When to suggest a home inspection

If there is a suspicion of water leakage or mould growth, a building inspector could be called to examine the home. Air sampling is not generally recommended for fungi. A heating contractor should regularly inspect the furnace and check for

gas leaks and carbon monoxide even in the absence of a suspected problem. Commercial companies can address concerns about radon and asbestos and provide remediation if necessary.

Improving indoor air quality

Allergens

If furry and feathered pets cannot be kept outside, they should be restricted to less inhabited parts of the home. After removal of a cat from the home, allergen levels fall over the next several months.[68] Washing cats and dogs reduces allergen levels for a few days.[69] If carpets, drapes and soft furnishings cannot be removed, frequent vacuuming with a HEPA (high-efficiency particulate air) filter or a central vacuum is recommended. Washing bedding materials in warm water can remove allergens. In a review of measures that can be taken to avoid allergens, Eggleston reported that completely encasing the mattress and pillows with coverings that are made of allergen-impermeable materials reduced allergen concentrations by about 89%.[70] Although allergen concentrations can be effectively reduced, the size of the resulting health benefits are unknown.[31–33] At this time, avoiding allergens is recommended for people with allergies.

Chemical contaminants

Trichloroethylenes can be reduced several-fold by not bringing recently dry-cleaned clothes into the house for a few days. Room deodorizers, perfumes and strong chemicals can be avoided. Automobiles should not be left running in attached garages. Emissions from fuel containers, lawn mowers and other yard tools can be avoided by storing them in a location that is not attached to the home. Solid hardwood furniture and flooring generally have less volatile emissions than particleboard, medium-density fibreboard, plywood and oriented strand board. Increasing home ventilation can effectively reduce the concentrations of volatile organic compounds.

Combustion products

Exposure to combustion products in the home should be avoided. Smoke alarms and carbon monoxide detectors provide early detection. Remediable sources of fine particulate and gaseous air pollution include cigarettes, candles, incense, and backdrafting or leaking woodstoves and fireplaces and furnaces. Living further away from heavy traffic is associated with reduced indoor exposure to combustion products. Indeed, nitric oxide falls to background levels by about 200 m from the roadway.[71]

Additional information about improving indoor air quality can be obtained from Health Canada (www.hc-sc.gc.ca/ewh-semt/air/in/index_e.html) and the Canada Mortgage and Housing Corporation (www.cmhc-schl.gc.ca/en/co/co_001.cfm).

Conclusion

Although allergen exposure causes symptoms in sensitized people, additional research about host and environmental characteristics is needed to determine if allergen exposure increases or decreases the risk of allergic disease in people who have not been previously sensitized. Fungus causes many diseases in clinical situations, and mould contamination of the home is associated with illness; however, causality has not been universally accepted. Cigarette smoke and high levels of carbon monoxide are accepted causes of illness, but the evidence for nitrogen dioxide is less certain. After smoking, inhalation of second-hand smoke and radon appear to be the most common cause of lung cancer.

Housing structure and function along with lifestyle decisions determine indoor air quality, which in turn influences health. Future research to improve our understanding of the health effects of indoor air quality has the potential to improve the health of our population.

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