Indoor environments contribute significantly to total human exposure to air pollutants, as people spend most of their time indoors. Indoor air quality is influenced by: penetrating outdoor air; specific indoor pollution sources; interactions between building system/construction techniques; and occupants. Some pollutants may be 2–5-fold more concentrated inside than outside buildings. Indoor pollutants may have an important biological impact even at low concentrations over long exposure periods. Indoor exposure occurs mainly at home and in schools, but also in day-care centres, social recreation settings or microenvironments, such as cars, buses, trains, subways and aeroplanes. Workplace indoor exposure is conventionally treated separately as 'occupational exposure' (see chapter 7).

The European Union (EU)-funded Towards Healthy Air in Dwellings in Europe (THADE) project showed that air pollution in dwellings is an important health problem across Europe. An EU-funded European Federation of Allergy and Airways Diseases Patients’ Associations (EFA) project, Indoor Air Pollution in Schools, pointed out that the right to breathe good air at school is largely ignored in many countries, where high levels of common indoor pollutants are frequent because of poor building construction and maintenance, poor cleaning and poor ventilation. Indoor air quality is particularly important for vulnerable subpopulations, such as children (their defence mechanisms are still evolving, and they inhale a higher volume of air per bodyweight than adults), elderly people, subjects with cardiac and respiratory diseases and those with socioeconomic deprivation.

Key points

- People spend most of their time indoors, so the quality of indoor air has major implications for health.
- Indoor air pollution can contribute to a wide spectrum of respiratory health effects, from allergic sensitisation to cancer.
- Indoor air pollution is largely the result of human activity, such as tobacco smoking, burning fuel for heat or cooking, the use of cleaning materials and solvents, and even breathing. Several pollutants may interact in a given environment.
- Natural pollutants such as allergens, dampness and mould, and radon, can also have significant health effects.
- Reflecting the complexity of indoor pollution, the most effective ways to reduce its impact are home-based, multi-component interventions.
Indoor air pollution is the eighth most important risk factor for disease, responsible for an estimated 2.7% of the global burden of disease.

Indoor pollutants and health effects

The Scientific Committee on Health and Environmental Risks (SCHER), one of the independent scientific committees managed by the Directorate-General for Health and Consumer Protection of the European Commission, reported that more than 900 different compounds have been detected in indoor air. Figure 1 shows the main indoor air pollutants and related sources. Most indoor pollutants derive from human activity (anthropogenic pollutants). Carbon dioxide (CO₂) is a product of human respiration, and elevated levels may be reached in crowded indoor environments with inadequate air exchange, thus altering indoor air quality. Allergens – mainly related to the presence of dust, damp, pets or insects, but also penetrating from outdoors – and infectious agents play an important role in indoor pollution. Indoor air pollution is the eighth most important risk factor for disease, responsible for an estimated 2.7% of the global burden of disease (4% in low-income countries). Conservative estimates show that 1.5–2 million deaths every year could be attributed to indoor air pollution, and there is consistent evidence that exposure to indoor pollutants increases the risk of several

**Figure 1 – The main indoor pollutants and their sources. CO: carbon monoxide; CO₂: carbon dioxide; NO₂: nitrogen dioxide; PAHs: polycyclic aromatic hydrocarbons; PM: particulate matter; VOCs: volatile organic compounds; HDM: house dust mite.**
respiratory/allergic symptoms or diseases. The commonest indoor risk factors with related health effects are shown in figure 2.

In indoor environments frequented by smokers, tobacco smoke is the major source of particulate matter (PM), accounting for as much as 50–90% of the total indoor PM concentration (see also chapter 8). It has, for example, been shown in Scotland and Ireland that among homes where solid fuels or gas are burned for heating and cooking, it is only in those where cigarette smoking occurs that the concentrations of fine particles with aerodynamic diameter <2.5 μm (PM2.5) are much higher than those recommended for good indoor air quality. In industrialised countries, few studies of measured indoor PM have been performed and those that do exist relate mainly to children. Positive associations of indoor PM with the risk of respiratory symptoms have been found; for example, an estimated increased incidence of nocturnal symptoms and wheezing in asthmatic children of 6–7% for each 10 μg·m⁻³ increment in indoor PM2.5. In another study, an increased prevalence of asthma in the previous year was found in schoolchildren exposed to high levels of PM2.5 in the classroom. Further research is needed to clarify whether indoor exposure to particles is associated with the severity of asthma or bronchitis in general populations, as well as with the development of respiratory diseases.

In infants and children, exposure to VOCs increases the risk of respiratory and allergic conditions such as asthma, wheezing, chronic bronchitis, reduced lung function, atopy and severity of sensitisation, rhinitis and respiratory infections.

"Pollutants
- Combustion products and ETS (CO, CO₂, NO, SO₂, PM, wood/coal smoke)
- VOCs (alkanes, formaldehyde, esters, ketones)
- Biological organisms (fungal spores, bacteria, viruses)
- Allergens (pollens, moulds, mites, cockroaches, insect, dander, feathers)
- Radon

Health effects
- Respiratory symptoms
  - Lung function reduction
  - Bronchial hyperresponsiveness
  - Asthma
  - COPD
- Upper/lower respiratory tract irritation
  - Asthma
- Respiratory infections
  - Sensitisation (specific/total IgE)
  - Respiratory allergic diseases (asthma, rhinitis)
  - Hypersensitivity pneumonitis
  - Chronic cough
  - Lung cancer

Figure 2 – The main respiratory health effects of common indoor pollutants. ETS: environmental tobacco smoke; CO: carbon monoxide; CO₂: carbon dioxide; NOₓ: nitrogen oxides; SO₂: sulfur dioxide; PM: particulate matter; VOCs: volatile organic compounds; COPD: chronic obstructive pulmonary disease."
Biomass fuels

About 50% of the world’s population (about 3 billion people) have little or no access to modern forms of energy, and use biomass fuels for cooking, heating and lighting. These are frequently burned within the households in open fires or inefficient stoves. In the rural areas of Latin America, 30–75% of households use biomass fuels for cooking, which have a dramatically high production of PM and carbon monoxide (CO). Solid fuels are still the dominant source of energy in households in rural China. In China, indoor air pollution from biomass fuels is responsible for approximately 1,000,000 premature deaths annually, compared with the 1,200,000 estimated to be caused in the country each year by outdoor PM pollution. A recent quantification of the disease burden caused by different risk factors globally indicates that in 2010, over 3.5 million deaths were attributable to household air pollution from solid fuels, representing more than 50% of the total deaths attributable to air pollution from particulate matter and ozone.

Figure 3 shows the main respiratory effects associated with biomass fuel smoke exposure. There is strong evidence of increased risk of acute lower respiratory infections in childhood (at least 2 million deaths annually in children under 5 years of age). There is also evidence of an association with the risk of developing chronic obstructive pulmonary disease (COPD), mostly for women, and with the risk of tuberculosis and asthma.

The International Agency for Research on Cancer has classified emissions from the indoor combustion of coal as a Group 1 carcinogen, i.e. a known carcinogen for humans. Indeed, there is strong evidence that women exposed to smoke from coal fires in the home have an elevated risk of lung cancer (the evidence is moderate for men) (figure 3).

Meta-analyses in low-income countries have estimated increased risks from solid fuel combustion averaging 3.5-fold for acute respiratory infections in children, 2.5-fold for chronic bronchitis in women, and 2.8-fold and 2.3-fold for COPD and chronic bronchitis in all adults, respectively.

<table>
<thead>
<tr>
<th>Evidence</th>
<th>ALRI (children &lt;5 years)</th>
<th>COPD (women)</th>
<th>Lung cancer (coal) (women)</th>
<th>COPD (men)</th>
<th>Lung cancer (coal) (men)</th>
<th>Lung cancer (biomass) (women)</th>
<th>Asthma (all)</th>
<th>Tuberculosis (all)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>2.3 (1.9–2.7)</td>
<td>3.2 (2.3–4.8)</td>
<td>1.9 (1.1–3.5)</td>
<td>1.8 (1.0–3.2)</td>
<td>1.5 (1.0–2.5)</td>
<td>1.5 (1.0–2.1)</td>
<td>1.2 (1.0–1.5)</td>
<td>1.5 (1.0–2.4)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Moderate II</td>
<td></td>
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</tr>
</tbody>
</table>

Figure 3 – The major respiratory health effects associated with exposure to biomass and solid fuel smoke. ALRI: acute lower respiratory infection; COPD: chronic obstructive pulmonary disease; CI: confidence interval. Reproduced and modified from Torres-Duque et al., 2008.
Nitrogen dioxide

Indoor nitrogen dioxide (NO₂) is generated mainly by gas-fuelled cooking and heating appliances. The results of longitudinal studies on the asthmatic population (mainly children), or those at risk of developing asthma, indicate positive associations between NO₂ concentration and respiratory symptoms, including wheezing, breathing difficulty, chest tightness, shortness of breath and cough. Adverse health effects in the general population are less evident. A recent study indicated that exposure to outdoor, but not indoor, NO₂ during the first year of life increases the risk of persistent cough. Conflicting results could in part be explained by the difficulty of determining the amount of exposure, as this can fluctuate depending mainly on the season or the use of specific NO₂ sources (i.e., peak concentrations occur during cooking or heating activities).

Volatile organic compounds

Exposure to volatile organic compounds (VOCs) may be related to a spectrum of illnesses ranging from mild (irritations) to very severe (cancer). Even the levels of exposure commonly found at the general population level are relevant. In infants and children, exposure to VOCs increases the risk of respiratory and allergic conditions such as asthma, wheezing, chronic bronchitis, reduced lung function, atopy and severity of sensitisation, rhinitis and respiratory infections. A recent meta-analysis estimated an average increase of 17% in the risk of asthma in children for each 10 μg·m⁻³ increase in formaldehyde concentration. In a national representative cross-sectional survey in France, high concentrations of VOCs in homes were associated with an increasing prevalence of asthma and rhinitis in adults.

The highest estimated risks between VOCs and health effects are: an approximately 8-fold increase for formaldehyde exposure with chronic bronchitis; 11- and 8-fold increases, respectively, for aromatic and aliphatic chemicals with increased specific immunoglobulin (IgE) to milk; a 3.4-fold increase for plastics/plasticisers with persistent wheezing; and a 5.6-fold increase for painting with respiratory infections. The estimated increased risk for a diagnosis of asthma ranges from 1.2 to 2.9. Many of the effects observed in children have also been shown in adults. Exposure to VOCs generated by cleaning is a risk factor for asthma and it has been suggested that VOCs produced by microorganisms such as moulds (mVOCs) may contribute to asthma. At the population level, positive associations have been found between the exposure to mVOCs and nocturnal breathlessness, asthma, and chronic bronchitis-like symptoms. However, the role played by mVOCs is still controversial, due to their low specificity in relation to fungi and their very low concentrations in indoor air.
Phthalates also merit specific mention. These are semi-volatile organic compounds derived from the organic chemical compound phthalic acid. The main indoor sources of phthalate esters are plasticised polyvinyl chloride (PVC) materials, used in floor and wall coverings, shower curtains, adhesives, synthetic leather, toys, cosmetics and many other consumer products. There has been considerable concern about phthalates in relation to reproduction and human development; some recent studies have identified associations between phthalates in indoor dust and allergic respiratory symptoms. There is a need for large-scale epidemiological studies in different populations and housing conditions to investigate the respiratory effects of exposure to phthalates in homes.

**Radon**

In the early 1920s, in eastern Europe, miners working in mines with high levels of radon were found to have an elevated risk of lung cancer, suggesting a causal relationship. Subsequent studies on miners, including never-smokers, showed a strong association of radon exposure with lung cancer risk. The natural occurrence of radon in indoor environments, including homes, is therefore a public health concern. Numerous studies have shown that radon represents a risk at any level of exposure, irrespective of smoking. After cigarette smoking, radon is the second main cause of lung cancer in the general population with no occupational exposure, and it is a well-established cause of lung cancer in never-smokers. Indoor radon significantly increases the relative risk of lung cancer – probably in a linear dose–response relationship with no threshold – by 8–16% for every 100 Bq·m⁻³ increment in its concentration. In the USA, 2100–2900 cases of lung cancer in never-smokers each year are attributable to radon exposure, while in the UK, about 1100 deaths each year from lung cancer are related to radon. A pooled analysis of studies in North America showed that the risk of lung cancer increased by 10% for each concentration increment of 100 Bq·m⁻³ of residential radon; a similar result was found in a meta-analysis in Europe (a risk increase of 10.6% per 100 Bq·m⁻³).

**Allergens**

The exposure–response relationship between indoor allergens and respiratory/allergic conditions is complex, depending on several factors, such as genetic susceptibility or gene–environment interaction. The reported results are conflicting, with several studies reporting respiratory effects of indoor allergen exposure, including allergic sensitisation and the development of asthma.

Endotoxins are derived from the cell wall of Gram-negative bacteria and are ubiquitous in the environment. High exposure to endotoxins is significantly associated with the risk of COPD and COPD-like symptoms, as well as with bronchial hyperresponsiveness and wheezing. However, other studies have found that early or high exposure to cat allergens or dampness-related allergens have a protective effect against asthma/wheeze/atopy. This protective effect has been discussed extensively, and further studies are needed to better understand possible interactions with the immune system. A pooled analysis using a large database of European birth cohort studies (22 000 children) indicates that pet ownership in early life does not appear to either increase or reduce the risk of asthma or allergic rhinitis symptoms in children aged 6–10 years. However, a recent study found that asthmatic children sensitised and exposed to low levels of common household allergens, including mould, dust, cat and dog allergens, have an increased risk of illness.
Dampness/mould

Dampness is present in 10–50% of houses. Moulds are a source of allergens, mVOCs and mycotoxins. Meta-analyses show associations of dampness/mould with increases of approximately 30–50% in respiratory and asthma-related health outcomes, including current asthma, ever-diagnosed asthma, upper respiratory tract symptoms, cough, wheezing and the development of asthma. According to the World Health Organization (WHO), dampness-related factors are also associated with dyspnoea, respiratory infections, bronchitis and allergic rhinitis. Positive associations, although not always statistically significant, have been found in children/infants or young adults between fungal concentration (expressed by culture colony counts) and risk of allergic sensitisation and asthma. Significant associations have also been found between exposure to moulds and respiratory symptoms or doctor-diagnosed asthma, regardless of atopy.

Some studies have found increased risks of wheezing and allergic sensitisation in relation to high exposure to ergosterol [a mould marker], whereas others found no such association. Other epidemiological studies have evaluated mould exposure based on β-glucans (components of the bacterial cell wall) or mycotoxins (fungal products). Exposure to β-glucans did not affect respiratory/allergic disorders, whereas there is insufficient evidence to implicate mycotoxins in mould-related respiratory effects. Recently, a new method has been developed to measure fungal DNA as a mould marker in dust/air. The main advantage of using DNA is the possibility of also identifying dead or dormant organisms. Significant positive associations have been reported between the quantity of DNA of certain fungi and wheezing, nocturnal dry cough, persistent cough, daytime breathlessness or a diagnosis of asthma.

Combined effects

Many studies have focused on the respiratory risks of exposure to a single pollutant. However, combined exposure to two or more agents is common. Indeed, indoor environments always contain complex mixtures of substances from different sources, which may jointly contribute to the toxic effects. There is evidence, mostly from in vitro or animal studies, of an interaction between air pollutants and allergens in the development of respiratory allergic diseases. In one human study addressing such interactions, a significant association between respiratory symptoms – consistent with asthma exacerbation – and PM was noted only in asthmatic children who owned a dog. Another study found that in mild asthmatics, exposure to a typical home concentration of NO₂ enhanced the decrease in airflow associated with inhaled allergen. In a recent study of children at high risk of asthma,
co-exposure to dog allergen and NO₂, or to dog allergen and environmental tobacco smoke, appeared to increase the risk of asthma.

In a large Indian study (about 100 000 women and 57 000 men, aged 20–49 years), living in a household using biomass for cooking and solid fuels showed a significantly higher risk of asthma in women, whereas tobacco smoking was associated with higher asthma prevalence in both sexes. The combined effects of biomass and solid-fuel use and tobacco smoke on the risk of asthma were higher in women. The combination of VOCs and allergens may also be of importance.

**Indoor air quality in schools**

Indoor air quality in schools has received particular attention in recent years, as children spend a large proportion of their indoor time at school. Indoor air pollution in schools is a combined effect of physical, chemical and biological factors, and depends on the level of environmental ventilation. The internal air within schools is often of poor quality. Schools are often poorly ventilated (as demonstrated by elevated CO₂ levels) and several pollutants have been found in classrooms, such as bacteria, moulds, VOCs and PM. Associations have been reported among the concentrations of pollutants and the onset of health problems in schoolchildren, mainly respiratory/allergic symptoms and diseases.

Direct comparison of studies is seldom possible because of different methodologies. However, two multicentre European studies using the same standardised procedure have provided data from different countries. Figure 4 shows the average 1-day indoor PM10 concentration, as measured inside the classrooms in the EU-funded Health Effects of School Environment (HESE) study and the School Environment And Respiratory Health of Children (SEARCH) study, promoted by the Regional Environmental Centre for Central and Eastern Europe (REC) [search.rec.org/search1/documents.html].

**Interventions**

Various intervention studies aimed at improving air quality have been performed. These include: a wood stove-exchange programme, which results in an overall reduction in
indoor PM$_{2.5}$ concentrations; nonpolluting home heating, which reduces the level of NO$_2$; education programmes that aim to decrease exposure to indoor allergens; displacement ventilation that may reduce CO$_2$, formaldehyde and viable bacteria; and electrostatic air cleaners to reduce the concentration of particles of all sizes. Evaluations of the effects of interventions that aim to reduce indoor exposure should take into account the impact on health in terms of dose–response relationships.

In summary, home-based, multi-trigger, multi-component interventions with an environmental focus are effective in improving the overall quality of life and productivity of children and adolescents with asthma. Allergen-reducing interventions (i.e. installation of mechanical ventilation and heat recovery systems) result in a significant decline in asthma symptoms, such as breathlessness during exercise, wheezing, and coughing during the day and night. In addition, the installation of non-polluting heating in the homes of children with asthma significantly reduces symptoms of asthma, days off school, healthcare utilisation and visits to a pharmacist. Education and remediation to reduce exposure to both indoor allergens and environmental tobacco smoke at home reduce asthma-associated morbidity in urban children with atopic asthma.

The effectiveness of interventions in adults is uncertain, as only a small number of studies have been performed and with inconsistent results. However, one experimental study in adults suggested that office workers with airway symptoms may benefit from installation of local air cleaners. In general, increasing ventilation above currently adopted standards and guidelines is likely to improve respiratory health. Programmes and public health initiatives to reduce exposure to indoor air pollution particularly need to be adopted in low- or middle-income countries. In developing countries, use of a chimney woodstove instead of a traditional indoor open fire significantly reduces CO exposure and the risk of all respiratory symptoms.

**Conclusion**

The adverse health effects of indoor air pollution exposure have been demonstrated in many epidemiological and experimental studies. Policies aimed at improving health quality both in public and private indoor settings are required in order to achieve relevant public health benefits.
Further reading

**Indoor air pollution and health effects**

**Indoor air quality in schools**

**Biomass**
Nitrogen dioxide

Volatile organic compounds

Moulds/dampness

Radon

Pet allergen

Combined effects

Prevention and intervention