Adverse Environmental Exposure and Respiratory Health in Children

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KEYWORDS
- Pollution • Household air pollution • Ambient air pollution
- Traffic-related air pollution • Children

KEY POINTS
- Pollution, especially air pollution, is a major cause of childhood morbidity and mortality.
- Due to their different physiology and the way they interact with their environment, children receive a higher relative dose of toxicants in any given environment.
- Two-way interactions exist between ambient air pollution and climate change and these contribute to adverse health outcomes for children.

INTRODUCTION
As reported in the recent Lancet Commission on Pollution and Health, pollution killed more people in 2016 than the acquired immunodeficiency syndrome, tuberculosis, and malaria combined. The burden imposed by pollution falls more on those living in low-income and middle-income countries (LMICs) and affects children more than adults. Children are more susceptible to pollution due to their different physiology. Relative to their body weight, children breathe more air (L/kg/d), drink more water (mL/kg/d), and eat more food (calories/kg/d) than do adults. They also have a higher surface area–to–body weight ratio than adults. The younger the child, the more pronounced the physiologic differences. As such, children receive a higher dose of toxicant in any polluted environment than do adults. In addition, young children are less likely to be able to detoxify xenobiotics due to immature enzyme systems. Thus, in addition to receiving a higher dose, children are more likely to suffer adverse consequences from the dose they receive.

Children interact with their environment differently from how adults do. This is related to their developmental stage. Infants and young children are likely to spend more time on the floor. The so-called hand-to-mouth behavior, which describes the
tendency for young children to put their hands, feet, and almost any object they can into their mouth, is not as common for older children or adults. The placenta does not provide a barrier to protect the developing fetus from maternal exposures, as once thought. In essence, almost anything the mother is exposed to may cross the placenta and pose a risk to the fetus. Many chemicals, especially lipophilic compounds, enter breast milk and expose the breastfeeding infant. These factors result in exposure pathways that differ between children and adults. Children’s exposure pathways are shown in Fig. 1.

Most air pollution results from incomplete combustion and consists of a mixture of particulate matter (PM) and gases. The pollution composition is influenced by many factors, including what is burnt, the temperature and efficiency of the combustion process, and the combustion source (ie, what is doing the burning).

PM generally has a carbonaceous core with various chemicals, metals, or other toxicants adsorbed to the surface. These adsorbed components generally are thought to determine the toxicity of the particles, although black carbon per se may contribute to toxicity. PM is classified by size, determined by measuring the mass median aerodynamic diameter (MMAD). Coarse particles are those with an MMAD greater that 10 μM. These particles generally do not reach the lungs, being filtered out in the nose and upper airway. Particles with MMAD less than 10 μM are referred to as PM10 and are mainstream of most air quality monitoring. Respirable particles, that is, those that easily enter the lungs, are those with MMAD less than 5 μM to 8 μM. Fine particles have an MMAD less than 2.5 μM and are referred to as PM2.5. Other particle sizes of interest are ultratine particles (MMAD <1 μM [PM1.0]) and nanoparticles (MMAD <0.1 μM [PM0.1]). The ability of particles to penetrate into the airway is determined, partly, by their size.

Air pollution also contains gases, such as carbon monoxide (CO), oxides of nitrogen (NOx), sulfur dioxide (SO2), and volatile organic compounds (VOCs). Ozone (O3) is a secondary pollutant, formed as a photoreaction between NOx and VOCs (benzene, toluene, and metal traces), in the presence of sunlight. The ability of gases to penetrate the respiratory system is influenced markedly by their solubility, with high water-

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Fig. 1. Schematic representation of pathway by which children are exposed to environmental toxicants.
soluble gases (eg, SO₂) mainly having an impact on mucous membranes in the eyes and nose, whereas gases of lower solubility (eg, NO₂) penetrate deeper into the airway tree. Surface-level O₃ is a toxic pollutant and should not be confused with stratospheric O₃, which provides protection from the sun’s UV radiation.

Epidemiologic links between air pollution and adverse health effects are strong; however, the precise mechanisms involved are not clear. The exposure pathways and mechanisms involved in adverse health effects have been reviewed recently²,⁸ and are thought to include oxidative stress (OS), a term used when oxidant stimuli overwhelm the antioxidant defenses and cause tissue damage and inflammation.

A relatively recently described combustion product, environmental-persistent free radicals (EPFRs),¹¹ induces OS and may provide an important link between pollution exposure and adverse health effects.¹² Free radicals are considered to be short-lived, oxidizing whatever they contact within seconds. EPFRs persist, however, in both the environment and biological systems for prolonged periods. EPFRs are found in PM₂.⁵ generated from traffic or industrial sources.¹³,¹⁴ The effects of EPFRs in vitro may be mitigated by antioxidants, providing both information about their mechanism of action and a potential therapeutic approach.

EXPOSURE TO AIR POLLUTION INSIDE THE HOME

The term, household air pollution (HAP), refers to exposure to air toxicants inside the home. The type of toxicants and the adverse health effects, however, depend on the type and location of the housing. The exposure experienced in poor houses in low-income countries is different than those experienced in more affluent housing in high-income countries (Fig. 2). By recent convention, the term, HAP, refers to exposures seen in low-income countries, predominantly due to burning unclean, solid, or

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**Fig. 2.** HAP differs with the type and location of housing.
biomass fuels. Air pollution inside more affluent homes in higher-income countries generally is referred to in the literature as indoor air pollution (IAP).

**Household Air Pollution**

The World Health Organization (WHO) estimates that approximately 3 billion people are reliant on unclean, solid, and biomass fuels for cooking, lighting, and heating. The global distribution of the type of fuel used is not even; those in high-income countries generally use clean fuel, whereas those in LMICs make do with unclean, solid, and biomass fuels (Fig. 3). HAP is responsible for 4 million excess deaths per annum from noncommunicable disease and for 50% of pneumonia deaths in children under 5 years of age (Box 1). The global distribution of the burden of disease is uneven, with most disability-adjusted life years (DALYS) in children under 5 years of age occurring in LMICs (Fig. 4).

Although the primary exposure pathway from HAP is inhalation during the cooking process (see Fig. 1), soot and other combustion products also may contaminate food stored within the house. Fig. 5 shows a house in Central America, where food stored in the rafters to keep it away from vermin is contaminated by soot produced by burning biomass fuel for cooking on an open fire inside the house. Children living in such homes may be exposed to HAP by nutritive and non-nutritive ingestion.

Burning biomass releases PM of various sizes, a variety of gases, including CO, CO₂, methane (CH₄), VOCs, aldehyde, organic acids, and inorganic elements. Factors influencing emission composition include fire temperature—less complete combustion is likely to result in more toxic emissions,⁹ in a manner similar to cigarette smoke¹⁵; types of fuel burnt—burning crop residue results in emissions containing dioxins and furans¹⁶; moisture content of the fuel; and atmospheric conditions inside the house. Infants and young children are exposed along with their mother, especially during cooking meals. Depending on cultural practices, female children are likely to be exposed to an older age because they stay inside to help with household duties, whereas male children more likely are occupied with outdoor chores.

The adverse health consequences of HAP are vast, affecting the developing fetus, the respiratory system, the cardiovascular/circulatory system, and the brain. Anemia

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**Fig. 3.** Percentage of population with access to clean fuel and technology at the household level. (From Inheriting a Sustainable World? Atlas on Children’s Health and the Environment. Geneva: World Health Organization; 2017 with permission.)
during pregnancy and childhood is more common and more severe in those exposed to biomass emissions (Fig. 6). Although the adverse effects on other organ systems are beyond the scope of this article, the effects relevant to children’s respiratory health are summarized in Table 1.

**Indoor Air Pollution**

As defined previously, exposure to air toxicants inside modern homes in middle-income and higher-income countries generally is referred to as IAP. The sources and toxicants vary from those seen with HAP (see Fig. 1). PM, toxic gases, and VOCs are common components of IAP. In many parts of the world, tobacco smoke also is a common component of IAP. In particular, NO₂ from gas cooking and formaldehyde (HCHO) from particle board furniture, glues, and preservatives commonly are found in IAP. Incense burning, especially as part of home-based religious practices, adds to IAP, with PM and HCHO among the emissions.

The extent to which pollutants from external sources, such as industry or traffic, contribute to IAP is not well characterized. Certainly, children in La Plata, Argentina, living near major petrochemical production facilities were exposed to higher levels of VOCs inside their home. On first principles, it would be expected that penetration

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**Box 1**

**Extracts from the World Health Organization fact sheet on household air pollution**

*HAP and health: WHO fact sheet*

- Approximately 3 billion people cook on open fires/stoves burning kerosene, biomass, or coal
- 4 million excess deaths annually attributable to HAP from noncommunicable diseases (stroke, cardiovascular disease, chronic obstructive pulmonary disease, lung cancer) or childhood pneumonia
- Approximately 50% of pneumonia deaths attributable to HAP


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**Fig. 4.** Global distribution of DALYs in children under 5 years of age attributable to HAP. (*From* World Health Organization. *Inheriting a Sustainable World? Atlas on Children’s Health and the Environment.* Geneva: World Health Organization; 2017, with permission.)
of outdoor pollutants into homes to be greater in summer and where windows are regularly open and lower in winter and where air conditioners are used.27

The exposure pathways, mechanisms involved, and adverse health consequences of IAP are qualitatively similar to those associated with HAP. There is more literature examining associations between IAP and asthma inception and exacerbation than with HAP.2,8,27,30 Exposure to tobacco smoke inside the home increases the rate of allergic sensitization31 and the risk and severity of childhood asthma.32,33 The literature relating IAP to wheeze and adverse respiratory outcomes in children is inconsistent, with not all studies finding strong associations.34 Some of this may relate to the individual child’s antioxidant defense capacity because those with null mutations in

Fig. 5. Contamination of food stored in the rafters by soot from burning biomass fuel for cooking on an open fire. (Courtesy of Professor F. Diaz Barriga, MA, PhD, San Luis Potosi, Mexico.)

Fig. 6. Schematic representation of the organs systems adversely affected by exposure to biomass emission in HAP.
<table>
<thead>
<tr>
<th>Exposure Period</th>
<th>Proposed Mechanisms</th>
<th>Intermediator Effect</th>
<th>Health Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fetal development</td>
<td>Maternal inflammation OS Epigenetic changes Direct particulate damage</td>
<td>Poor placental function Reduced lung growth Delayed immune maturation</td>
<td>Low birthweight/IUGR Low lung function at birth Increased infection risk/pneumonia Lifelong increased risk of COPD, lung cancer</td>
</tr>
<tr>
<td>Infancy</td>
<td>Direct particulate damage Systemic inflammation OS DNA damage Epigenetic changes</td>
<td>Anemia Poor lung growth Delayed immune maturation</td>
<td>Respiratory infections/pneumonia Lifelong increased risk of COPD, lung cancer</td>
</tr>
<tr>
<td>Childhood</td>
<td>Direct particulate damage Systemic inflammation OS DNA damage Epigenetic changes</td>
<td>Anemia Reduced lung function Delayed immune maturation</td>
<td>Respiratory infections/pneumonia Lifelong increased risk of COPD, lung cancer</td>
</tr>
</tbody>
</table>

Abbreviations: COPD, chronic obstructive pulmonary disease; IUGR, intrauterine growth restriction.
Refs. 1,2,8,17–26

Fig. 7. Sources contributing to ambient air pollution.
### Table 2
Air quality standards: guidelines of allowable exposure to criteria air pollutants set by the US Environmental Protection Agency and the World Health Organization

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>US Environmental Protection Agency</th>
<th>World Health Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Comment</strong></td>
<td><strong>Averaging Time</strong></td>
</tr>
<tr>
<td>CO</td>
<td>9 ppm 8-h mean (1(^{st}))</td>
<td>35 ppm 1-h mean (1(^{st}))</td>
</tr>
<tr>
<td>PM(_{10})</td>
<td>150 (\mu g/m^3) 24-h mean (1(^{st}) + 2(^{nd}))</td>
<td>20 (\mu g/m^3) annual mean</td>
</tr>
<tr>
<td>PM(_{2.5})</td>
<td>12 (\mu g/m^3) annual mean (1(^{st}))</td>
<td>35 (\mu g/m^3) 24-h mean **</td>
</tr>
<tr>
<td>PM(_{2.5})</td>
<td>15 (\mu g/m^3) annual mean (2(^{nd}))</td>
<td></td>
</tr>
<tr>
<td>O(_3)</td>
<td>70 ppb 8-h mean (1(^{st}) + 2(^{nd}))</td>
<td>100 (\mu g/m^3) 8-h mean</td>
</tr>
<tr>
<td>NO(_2)</td>
<td>53 ppb annual mean (1(^{st}) + 2(^{nd}))</td>
<td>100 ppb 1-h mean (1(^{st})) **</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>500 ppb 3-hourly mean (2(^{nd}))</td>
<td>75 ppb (1(^{st})) ***</td>
</tr>
</tbody>
</table>

**Abbreviations:** 1\(^{st}\), primary standards provide public health protection, including protecting the health of “sensitive” populations, such as asthmatics, children, and the elderly; 2\(^{nd}\), secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings; ppb, parts per billion by volume; ppm, parts per million by volume.


glutathione-S-transferase enzymes are more susceptible to pollution exposure.\textsuperscript{35} These data are consistent with the notion that induction of OS stress is an important mechanism mediating the adverse health effects of IAP.

**EXPOSURE TO AIR POLLUTION OUTSIDE THE HOME**

Multiple sources contribute to outdoor air pollution. As for HAP and IAP, most ambient air pollution comes from incomplete combustion of fossil fuels. Natural sources, however, also may contribute to ambient air pollution (Fig. 7).

By legislation, the US Environmental Protection Agency (EPA) monitors 6 key pollutants in ambient air: lead, PM, CO, NO\textsubscript{2}, SO\textsubscript{2}, and O\textsubscript{3}. These criteria pollutants have national air quality standards set by legislation that define allowable concentrations in ambient air. The WHO and many countries also set allowable exposure levels, with little consistency. Table 2 shows allowable exposures to criteria pollutants set by the WHO and the EPA.

The global distribution of air pollution is not even, with higher exposures in mega cities in LMICs. Fig. 8 shows the global distribution of PM\textsubscript{2.5}, with substantially higher levels seen in South Asia and Southeast Asia.

Air pollution exposure has negative impacts on respiratory health. Traffic-related air pollution (TRAP) exposure during childhood is associated with an increased risk of respiratory infections of greater severity\textsuperscript{2,36}; lower lung function and reduced lung growth\textsuperscript{37,38}; and wheezing illnesses, incident asthma, and asthma exacerbations.\textsuperscript{30,39} Accumulating evidence suggests that TRAP exposure induces OS in humans. Children exposed to high levels of TRAP in Mexico City had increased levels of malondialdehyde, an OS-induced product of lipid peroxidation, in exhaled breath condensates.\textsuperscript{39} Subjects with null or reduced function mutations in antioxidant defense genes, such as GSTP1, showed increased susceptibility to TRAP exposure,\textsuperscript{40} and asthma was more likely in children with TRAP exposure if they showed increased expression of the redox-sensitive transcription factor, NFE2L2 (NRF2) gene.\textsuperscript{41}

Acute exposure to TRAP increases respiratory symptoms in children on the day of exposure and with lags of 1 day or 2 days.\textsuperscript{42} Increased TRAP levels are associated

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*Fig. 8. Global distribution of PM\textsubscript{2.5} in urban locations. (From Inheriting a Sustainable World? Atlas on Children’s Health and the Environment. Geneva: World Health Organization; 2017 with permission.)*
with an increase in school absences for respiratory illnesses, with a peak occurring 5 days after increased O$_3$ exposure. Sexual dimorphism may occur in TRAP responsiveness, with girls more sensitive in some but not all studies. Socioeconomic status also influences the outcomes of TRAP exposure, although not always in a consistent direction. Children with asthma generally are more sensitive to TRAP, with increased symptoms, asthma exacerbations, and declines in lung function. Exposure to petrochemical-related VOCs may be dangerous especially for asthmatics.

**IMPACT OF CLIMATE CHANGE ON CHILDREN’S RESPIRATORY HEALTH**

The link between air pollution and climate change is intricate and obvious. Air pollution increases atmospheric CO$_2$, which, in turn, induces global warming and climate change (Fig. 9). Global warming and climate change increase air pollution, although

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**Box 2**

Extracts from World Health Organization climate change and health

*Climate change and health: WHO fact sheet*

Climate change adversely affects the social and environmental determinant of disease

Approximately 50,000 excess deaths per year expected (2030–2050) from malnutrition, malaria, diarrhea, and heat stress

Direct costs to health—$2–$4 billion per year by 2030

Countries with weak health infrastructure worse affected

Reducing greenhouse gas emissions can improve health outcomes

<table>
<thead>
<tr>
<th>Climate Change Impact</th>
<th>Pathway</th>
<th>Adverse Effect on Children's Respiratory Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased ambient temperature</td>
<td>Urban heat island effects, Heat waves, Increased temperature variability, Altered plant distribution, longer growing seasons and increased pollen production, Crop failure and food insecurity</td>
<td>Heat stress, Electrolyte disturbance in cystic fibrosis, Increased allergic sensitization, Increased allergic rhinitis and asthma exacerbations</td>
</tr>
<tr>
<td>Decreased air quality</td>
<td>Higher PM, Increased surface level O$_3$, Air stagnation, Rising CO$_2$</td>
<td>Reduced fetal growth and birthweight, Lower lung function and lung function growth, Altered lung growth and increased bronchial responsiveness, Increased incident asthma and asthma exacerbations, Increased hospitalization for respiratory illnesses, Increased pulmonary infection with serous pathogens in cystic fibrosis</td>
</tr>
<tr>
<td>Rising CO$_2$</td>
<td>Altered plant distribution, longer growing seasons and increased pollen production</td>
<td>Increased allergic rhinitis and asthma exacerbations</td>
</tr>
<tr>
<td>Altered rainfall distribution</td>
<td>Altered distribution of disease vectors, Crop failure and food insecurity, Water insecurity</td>
<td>Altered distribution of vector-borne disease, Malnutrition, stunting, and increased susceptibility to respiratory infections</td>
</tr>
<tr>
<td>Ocean warming/sea level rise</td>
<td>Severe weather events, Drought, floods, cyclones, bushfires, Crop failure and food insecurity, Water insecurity, Population displacement</td>
<td>Increased respiratory infections, asthma exacerbations, emergency department presentations, and hospitalization for respiratory illnesses, Increased non–tuberculosis mycobacterium infection, Increased chemical exposure, Malnutrition, stunting, and increased susceptibility to respiratory infections, Adverse mental health outcomes</td>
</tr>
</tbody>
</table>
the precise effect anticipated varies with geographic location. \(^49\) Modeling predicts marked deterioration in air quality over the rest of the twenty-first century, with increases in PM, \(^49\) increases in surface-level \(\text{O}_3\), \(^50\) changes in relative humidity, \(^49\) and air stagnation. \(^61,52\)

The WHO predicts an additional 250,000 deaths per year between 2030 and 2050 due to malnutrition, malaria, diarrheal diseases, and heat stress directly attributable to climate change, with direct health costs of between $2 billion to $4 billion per year by 2030 (Box 2).

The potential impacts of climate change on respiratory health of children are shown in Table 14.3. Mechanisms include adverse effects on fetal growth and birthweight; increasing lifelong risk of acute and chronic respiratory disease \(^53–56\); low lung function at birth and decreased lung function growth \(^19,20\); and increased risk of respiratory infection, including pneumonia, under 5 years of age. \(^48,57\) Climate change–induced increases in surface level \(\text{O}_3\) \(^58,59\) and in wildfire smoke \(^60\) are predicted to increase health care utilization and hospitalization for asthma and acute respiratory illnesses in children (Table 3).

Climate change does represent an opportunity for physicians and gives them a responsibility to act. The American College of Physicians has produced a position paper urging all physician to act \(^61\) and recommends that physicians engage in environmentally sustainable practices that reduce carbon emissions; support efforts to mitigate and adapt to effects of climate change; and educate the public, their colleagues, and lawmakers about the human health risks of climate change, especially respiratory health.

**DISCLOSURE**

The author has nothing to disclose.

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