



Review article

Adverse health effects of outdoor air pollutants

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Abstract

Much research on the health effects of outdoor air pollution has been published in the last decade. The goal of this review is to concisely summarize a wide range of the recent research on health effects of many types of outdoor air pollution. A review of the health effects of major outdoor air pollutants including particulates, carbon monoxide, sulfur and nitrogen oxides, acid gases, metals, volatile organics, solvents, pesticides, radiation and bioaerosols is presented. Numerous studies have linked atmospheric pollutants to many types of health problems of many body systems including the respiratory, cardiovascular, immunological, hematological, neurological and reproductive/ developmental systems. Some studies have found increases in respiratory and cardiovascular problems at outdoor pollutant levels well below standards set by such agencies as the US EPA and WHO. Air pollution is associated with large increases in medical expenses, morbidity and is estimated to cause about 800,000 annual premature deaths worldwide [Cohen, A.J., Ross Alexander, H., Ostro, B., Pandey, K.D., Kryzanowski, M., Kunzail, N., et al., 2005. The global burden of disease due to outdoor air pollution. *J Toxicol Environ Health A*. 68: 1–7.]. Further research on the health effects of air pollution and air pollutant abatement methods should be very helpful to physicians, public health officials, industrialists, politicians and the general public.

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1. Introduction

Outdoor and indoor air quality are important to human health. The average 70 kg adult inhales about 20 m³ of air per day (Berne et al., 1998). Certain groups of patients such as asthmatics, atopic patients, patients with emphysema and bronchitis, heart and stroke patients, diabetes, pregnant women, the elderly and children as especially sensitive to the health effects of outdoor air toxicants (American Lung Association, 2005). It is estimated that about 20% of the US population suffers from asthma, emphysema, bronchitis, diabetes or cardiovascular disease and is thus especially susceptible to outdoor air pollution (American Lung Association, 2005). In addition, outdoor air also serves as a major source of particulate and gaseous pollutants for indoor air (Freijer and Bolemen, 2000).

In the past 30 years, outdoor levels of some pollutants such as particulates, sulfur oxides and carbon monoxide have been declining in many US and western European cities, thanks to emission controls on vehicles, heating, power generation and industry (US EPA, 2000; Godish, 2003; Defra, 2003). However, many outdoor air quality problems still exist in the developed world and may be worsened by increasing use of motor vehicles and industrial chemicals. Severe outdoor air pollution problems exist in the developing world, especially in large cities such as Beijing, Shanghai, Bombay, Karachi, Cairo, Sao Paulo and Mexico City (Mage, 1996; Akimoto, 2003).

The first main section (Section 3) of this review will begin with a brief overview of the types of air pollutants. Section 4 concentrates on the human health effects of common pollutants in outdoor air. Section 5 deals with economic effects of air pollution and Section 6 will contain some brief conclusions and suggestions for future research.

The effects of outdoor air pollution on animals, plants, manufactured materials, and visibility are considerable but will

not be discussed in this review. This review will not focus on indoor or occupational air exposures or on the increase in atmospheric carbon dioxide and global warming.

2. Materials and methods

This review was conducted by searching Pub Med and other medical databases in 2005. Approximately six hundred peer-reviewed papers were examined and those deemed to be the most important in described adverse human health effects were included. Since this review will concentrate on the recent outdoor air conditions and research, most of the papers selected for inclusion in this review were from the period 1995 to 2005. In addition, some references are included from medical conference presentations as well as websites from government and private health organizations.

3. Brief overview of air pollutant classes

The following section will briefly review the major outdoor air pollutants. Many human and natural activities produce more than one class of pollutants. The final part of this section will briefly discuss standards for common outdoor air pollutants.

3.1. Particulates

Particulates comprise a wide range of materials which are solid or liquid in the air. The sources of particulates are many and include dust from soil and roads, diesel exhaust, emissions from combustion and industrial processes, construction and demolition, powdered pesticides, bioaerosols and volcanic ash (Dickey, 2000; Brook et al., 2004). Such particulates may travel thousands of kilometers in the air across oceans and deposit themselves onto other continents (Wilkening et al., 2000; Gyan et al., 2005).

Biomass burning of wood, leaves, crops and forests is the largest source of particulates in many parts of the world. A study

of 15 US cities found that wood burning produced 36% to 95% of wintertime airborne PM_{2.5} from all sources (Rozenberg, 2003). Smoke from large forest fires in Indonesia and Quebec has been found to greatly increase airborne particulates in areas many hundreds of kilometers away (Awang et al., 2000; Sapkota et al., 2005).

Toxicity of particulates depends greatly on their size, with particulates less than 10 μm (PM₁₀) or 2.5 μm (PM_{2.5}) being considered especially dangerous since they can easily penetrate the lungs into the alveoli. Currently there is some question as to whether the PM₁₀, PM_{2.5} or PM_{2.5–10} are more important to human health (Brunekreef and Forsberg, 2005). Toxicity of particulates also varies depending upon their chemical composition. Particulates of special concern include toxic metals like lead and mercury, poly aromatic hydrocarbons (PAH's) and persistent organic toxicants such as dioxins (Dickey, 2000; Jaward et al., 2004). The main outdoor sources of PAH's are motor vehicles, coal/oil fired power plants and the biomass burning (Naumova et al., 2002).

3.2. Ozone (O₃)

The ozone molecule contains 3 oxygen atoms (O₃) instead of the usual 2 oxygen atoms (O₂). In the stratosphere ozone plays a vital role in blocking out harmful ultraviolet light from the sun, but at ground level ozone is toxic to humans. Ozone can be produced by a number of processes such as lightning (Godish, 2003), electronic devices like photocopiers (Brook et al., 2004), and by atmospheric reactions involving volatile organic chemicals, nitrogen oxides and sunlight; this indirect ozone production is most efficient during warm weather (Brook et al., 2004). Like particulates, ozone can travel for thousands of kilometers. The atmospheric half life of ozone is 1–2 weeks in summer and 1–2 months in winter (Akimoto, 2003).

3.3. Carbon monoxide (CO)

Carbon monoxide (CO) is a product of incomplete combustion. Its main sources are combustion processes from vehicles, heating, coal-fired power generation, and biomass burning (Godish, 2003). Carbon monoxide is produced in larger amounts if combustion is not efficient (i.e. a poorly tuned engine), in colder weather or at higher altitudes (Brook et al., 2004). Carbon monoxide has an atmospheric half life of 1–2 months and can also travel for thousands of kilometers away from its source (Akimoto, 2003).

3.4. Sulfur oxides (SO₂, SO₃), hydrogen sulfide (H₂S), acid gases (HF, HCl)

Sulfur dioxide is produced by burning of coal, vehicle emissions and emissions from oil/gas fields and refineries (Godish, 2003). Hydrogen sulfide is produced by many industrial processes and by decomposition of oil or dead vegetation. Sulfur containing compounds like sulfur dioxide and mercaptans are produced in papermaking, rayon manufacturing, coke ovens,

other industries and from volcanic emissions (Godish, 2003). Acid gases like hydrochloric acid (HCl) and hydrofluoric acid (HF) are produced by waste combustion and by several industries (Godish, 2003).

3.5. Nitrogen oxides (NO₂ and others)

Nitrogen oxides are produced largely by industrial/vehicle combustion and by oxidation of nitrogen fertilizers (Godish, 2003). Nitrogen oxides can also be produced in the atmosphere by reactions which combine reactive oxygen containing molecules with nitrogen from the atmosphere.

3.6. Lead (Pb) and other metals

Lead, mercury, cadmium, arsenic and other toxic metals are released into the environment by several processes including waste and coal burning, metal mining and smelting, other industrial processes and volcanic emissions (Lee et al., 2002; Godish, 2003). Epidemiologic studies have found higher blood and body burdens of metals including lead, mercury, arsenic and cadmium in subjects living near waste incinerators (Hu and Shy, 2001).

3.7. Volatile organics (VOC's), solvents, pesticides and methane (CH₄)

This group comprises a wide range of chemicals which are easily volatilized (evaporated) into the air. Major sources include petroleum refining, petrochemicals, vehicle exhaust, natural gas fields and distribution lines, storage of fuels and wastes, household products, pesticides, combustion, many industries and volatile emissions from coniferous forests (Godish, 2003; Lerdau et al., 1997).

Methane is the most common hydrocarbon gas in outdoor ambient air, comprising about 1.8 ppm of the lower atmosphere (US EPA, 2003). About 60% of atmospheric methane is produced by anthropogenic sources including landfills and biomass burning; by the mining, distribution, and consumption of natural gas, petroleum and coal, and by methane produced by the digestive systems of cattle and other domestic animals (Breas et al., 2001). About 40% of methane is produced by such non-human sources as wetlands, decaying vegetation, termites and oceans (US EPA, 2003).

Pesticides and other VOCs can travel significant distances in the air. For example, a California study found that agricultural spraying of chlorpyrifos significantly increased airborne levels of chlorpyrifos oxon ($p < 0.0001$) at a distance of 4.8 km for a period of four days (Harnly et al., 2005).

3.8. Bioaerosols: molds, bacteria, pollen and others

Bioaerosols are airborne particles (seeds, spores, dander etc.) produced by living organisms. Such bioaerosols include pollen, seeds, bacteria, gram negative bacterial endotoxins, molds (fungi), algae, protozoans, flour, latex and animal dander/waste products. Some bioaerosols are hazardous since they are

infectious and/or produce allergens and toxins. Mold spores can travel thousands of miles across the Pacific and Atlantic Oceans and land on other continents (Shinn et al., 2003).

3.9. Radiation

Radioactive compounds can enter the atmosphere by natural decay of radioactive compounds, from nuclear power plants and nuclear weapons testing and from radioisotopes used in industrial, research and nuclear medicine facilities (Godish, 2003).

3.10. Standards for air pollutant concentrations

A number of countries and organizations have developed standards for concentrations of common pollutants in outdoor air. Table 1 lists recent outdoor air standards for the six “priority pollutants” (PM₁₀/PM_{2.5}, O₃, CO, NO₂, SO₂, Pb) for the USA EPA, Japan, Germany and the World Health Organization (WHO).

Levels of priority air pollutants often exceed these limits in many parts of the world, especially in large cities of developing countries. For example, it was estimated in 2004 that 18% of the world’s urban areas (cities with a population of over 100,000) have ambient air containing an annual mean of over 100 ug/m³ PM₁₀ or more than twice the US EPA limit (Cohen et al., 2005). It should be noted that adverse health effects have been documented at levels well below these official US EPA standards (see Section 4 for discussion of air pollutants and adverse health effects). In addition, these standards ignore the synergistic effects of combinations of toxic air pollutants. Please also note that many pollutants such as organic solvents, pesticides, mercury, dioxins and bioaerosols do not have official outdoor air standards. A total of 189 such pollutants have been defined as “air toxics” by the US Clean Air Act of 1990 (Suh et al., 2004).

Table 1 derived from USA EPA (1982, 1987, 1997, 2000), Environmental Management Centre (2006), World Bank (1995).

4. Health effects of outdoor air pollutants

Data on the human health effects of outdoor air pollutants are grouped below into eight sections based on the organ system they affect. The eight sections include respiratory effects (Section 4.1), cardiovascular effects (Section 4.2), cancer (Section 4.3), reproductive and developmental effects (Section 4.4), neurological effects (Section 4.5), mortality (Section 4.6), infection (Section 4.7) and other health effects (Section 4.8).

4.1. Respiratory effects

Most studies of the health effects of outdoor air pollution have dealt with respiratory health issues. Many of the studies have involved children and most of these studies have linked higher rates of asthma and other respiratory problems to higher outdoor air levels of priority pollutants such as particulates, ozone, sulfur and nitrogen oxides and carbon monoxide.

This respiratory health Section 4.1 is further divided into 10 subsections as follows: 1) The first three subsections deal with the respiratory health effects of the priority and other common outdoor air pollutants. 2) The next six subsections deal with respiratory health effects of specific outdoor air sources including traffic, heavy industry, bioaerosols, biomass burning, sand, volcanoes and volatile organics. 3) The last subsection will examine the interactions between air pollution, genetic and nutritional factors and respiratory health effects.

4.1.1. Common air pollutants and asthma in children

Table 2 below summarizes 10 ecologic studies in which higher levels of many common pollutants (PM₁₀ or PM_{2.5}, O₃, CO, SO₂, NO₂, benzene) are associated with higher levels of asthma symptoms, asthma consultations and/or hospital admissions.

Table 1
Recent standards for outdoor air concentrations of common “Criteria” outdoor air pollutants

Country	Particulates in ug/m ³	Ozone in ug/m ³	Carbon monoxide in mg/ m ³	Sulfur dioxide in mg/m ³	Nitrogen dioxide in mg/m ³	Lead in ug/m ³
United States EPA	PM ₁₀	1 h 240	1 h 40	Daily 0.365	Annual 0.1	3 month
	Annual 50		8 h 10	Annual 0.08		Mean 1.5
	Daily 150- PM _{2.5}					
Japan	Annual 15					
	Daily 65					
	PM ₁₀	1 h 120	8 h 22.8	Daily 0.26	Daily 0.04–0.06	*
Germany	Annual 200			Annual 0.11		
	Daily 100					
	PM ₁₀	*	1 h 30	Daily 0.40	Daily 0.3	*
WHO—World Health Org.	Annual 100			Annual 0.14	Annual 0.1	
	Daily 200					
	Total soluble particulates (TSP)	1 h 200	1 h 30	Daily 0.20	1 h 0.190 to 0.320	*
	Annual 60–90		8 h 10	Annual 0.09		
	Daily 150–230					

* Pollutant levels without an ambient standard yet.

Table 2
Childhood studies linking exposure to higher air pollutant levels with significantly worsened asthma

Study	Outcome measured	Particulates PM ₁₀ or PM _{2.5}	Ozone O ₃	Carbon monoxide CO	Sulfur dioxide SO ₂	Nitrogen dioxide NO ₂	Benzene C ₆ H ₆
Barnett et al. (2005)	Respiratory hospital admissions	X				X	
Buchdahl et al. (2000)	Asthma/wheezing emergency room (ER) visits		X				X
Lee et al. (2002)	Asthma hospitalizations	X		X	X	X	X
Lin et al. (2002)	Asthma hospitalizations	X					
Linaker et al. (2000)	Worsening asthma following upper respiratory infections					X	
Thompson and Patterson (2001)	Asthma emergency room (ER) visits	X				X	
Tolbert et al. (2000)	Asthma emergency room (ER) visits	X	X				
White et al. (1994)	Asthma emergency room (ER) visits		X				
Wong et al. (2001)	Asthma hospitalizations		X	X			
Yu et al. (2000)	Worsening asthma symptoms	X		X			

X in box indicates pollutant associated with significant increase ($P < 0.05$) in asthma.

Many of these air pollutants can worsen childhood asthma at relatively modest concentrations. The limits for CO and O₃ were rarely exceeded in any of these studies listed in Table 2. The mean concentrations of PM₁₀, SO₂, and O₃ were well below US EPA standards in all but 2 of the 8 studies (Lee et al., 2002; Wong et al., 2001). This suggests that PM₁₀, CO, O₃, NO₂, SO₂ can worsen asthma in children at levels below the US EPA standards.

A Chilean study found a significant relationship between higher outdoor PM_{2.5} levels and more wheezing bronchitis in infants (Pino et al., 2004). A study conducted during the 1996 Atlanta Olympic games found that morning traffic was reduced by 29% during this period, peak O₃ levels dropped by 28% and asthma related physician visits in children dropped by about 40% (Freidman et al., 2001). A French study found that increasing levels of outdoor PM₁₀, O₃ and SO₂ were associated with significantly higher rates of childhood asthma and rhinitis (Penard-Morand et al., 2005).

4.1.2. Air pollution and respiratory health effects on the elderly

Low to moderate levels of outdoor air pollutants can greatly increase respiratory problems in the elderly. A 1980–1995 study of Tokyo residents aged over 65 years found that increasing airborne outdoor PM₁₀ concentrations were associated with significantly higher rates of asthma and bronchitis ($p < 0.001$ in both cases) (Ye et al., 2001). Higher levels of PM_{2.5} were associated with significantly higher levels of hospitalization for COPD in elderly subjects in Vancouver, Canada (Chen et al., 2004). Higher outdoor levels of O₃, PM₁₀, SO₂ and NO₂ were associated with significantly higher rates of hospital COPD admissions in Minneapolis, Minnesota, but were not related to significantly higher COPD admissions in Birmingham, Alabama (Moolgavkar et al., 1997).

4.1.3. Air pollution and other respiratory health effects

A cohort study in Los Angeles found a dose–response relationship between bronchitis and ambient PM₁₀ levels (McConnell et al., 2003). A study of 4 million hospital emergency visits in Atlanta found that higher outdoor levels of PM₁₀, NO₂ and CO were associated with significantly higher emergency room visits for upper respiratory infections and COPD (Chronic Obstructive Pulmonary Disease) (Peel et al., 2005). An Australian study

found that higher airborne levels of PM₁₀, PM_{2.5}, NO₂ and SO₂ were all associated with significantly higher rates of childhood hospital admissions for pneumonia and acute bronchitis (Barnett et al., 2005). A two winter study of adults with advanced COPD in Denver, Colorado found that higher ambient levels of CO, PM₁₀ and NO₂ were associated with poorer lung function and more rescue medication use in one of the two winters (Silkoff et al., 2005). Significantly higher levels of chronic cough and phlegm production have been found in children exposed to higher ambient O₃ levels (Romieu et al., 1997) and in adults exposed to higher ambient PM₁₀ levels (Zemp et al., 1999). Higher outdoor PM_{2.5} levels were associated with significantly higher childhood emergency room visits for pneumonia and respiratory illness in Santiago, Chile (Ilbaca et al., 1999). Large cohort studies in Austria and California found that high summer O₃ levels were associated with reduced lung function growth in children over a follow-up period of two to four years (Frischer et al., 1999; Gauderman et al., 2002).

4.1.4. Respiratory health effects of exposure to traffic and industrial pollution

Traffic pollution, coal fired power plants and industrial pollution may also be important outdoor triggers to asthma and other respiratory problems. A review of 18 papers found that higher traffic exposure (as measured by traffic density, distance from roads or vehicle produced pollutants) was related to significantly higher levels of asthma, wheezing or cough in 14 of these studies (Delfino, 2002). An Israeli study found that childhood asthma was significantly more common in children living near a coal fired power plant (Goren et al., 1991). Releases of hydrogen sulfide by a pulp mill were found to cause significant breathing problems in one-third of residents living in a nearby community (Haahtela et al., 1992). A Utah study of a community near a steel mill which closed and then reopened found that childhood hospital respiratory admissions were two to three times greater during periods in which the steel mill was open (Pope, 1989).

4.1.5. Respiratory health effects of mold, pollen and other bioaerosols

High airborne levels of mold, pollen and algae can also worsen respiratory problems. Higher outdoor mold concentrations have been linked to higher rates of asthma mortality (Targonski et al.,

1995) and higher asthma incidence (Neas et al., 1996; Delfino et al., 1997; Dales et al., 2004) in children or young adults. A study in 10 Canadian cities found that the effects of ozone and pollen had synergistic associations with increased asthma hospitalizations (Dales et al., 2004). An Ohio study reported that airborne PM₁₀ and pollen had synergistic associations with increased pediatric asthma hospital admissions (Lierl and Hornung, 2003). The increases in asthma often seen after gusty thunderstorms are mainly due to the increased levels of airborne mold and pollens blown into the air (Dales et al., 2003). A Mexico City study found that higher levels of outdoor pollen and/or fungi were associated with significantly higher rates of hospital asthma admissions (Rosas et al., 1998). Outdoor mold and pollen exposure also play a major role in the development of rhinitis (Burge and Rogers, 2000). Epidemiological evidence and environmental chamber studies suggest that exposure to low levels of ozone, diesel exhaust and other outdoor air pollutants react synergistically with pollen and mold spores and produce much greater drops in lung function than exposure to either the pollutants or molds/pollen separately (Janssen et al., 2003; Wyler et al., 2001; Molino et al., 1991). Ambient air exposure to brevetoxins from the saltwater algae *Karenia brevis* have been associated with significantly poorer lung function in asthmatics (Fleming et al., 2005).

Outdoor levels of some bioaerosols like flour dust, latex and endotoxin are generally very low, but can be present in significant concentrations in outdoor areas near a source of these bioaerosols. A study in Barcelona found that unloading soybean flour was associated with significantly higher rates of asthma attacks in subjects living within several blocks of the unloading docks (Rodrigo et al., 2004). Latex PM₁₀ levels (from tire tread) were as high as 1 ng/m³ near a Los Angeles freeway (Miguel et al., 1996). Hospital studies have reported that PM₁₀ latex levels as low as 0.6 ng/m³ can induce respiratory symptoms in latex sensitive subjects (Baur et al., 1998).

4.1.6. Biomass burning and respiratory health effects

The burning of wood, leaves and agricultural residue creates large amounts of PM₁₀, CO and other pollutants that can worsen asthma and other breathing problems. Higher rates of asthma symptoms, lower lung function and/or more respiratory hospitalizations have been reported among populations exposed to outdoor smoke from rice straw burning (Torio et al., 2000; Jacobs et al., 1997), wildfire/brushfire (Viswanathan et al., 2006; Johnston et al., 2002), leaf burning (From et al., 1992) and wood burning (Koenig et al., 1993). Studies in both Seattle and San Francisco found that higher wood burning related PM₁₀ levels were associated with significantly higher rates of asthma symptoms, medication use and asthma related hospitalizations (Slaughter et al., 2003; Lipsett et al., 1997).

From July to October, 1997, large Indonesian forests were deliberately burned and created dense smoke which traveled for hundreds of kilometers into Malaysia. In September 1997, all 28 Malaysian air stations recorded concentrations of PM₁₀ above 150 ug/m³. In Hospital Kuala Lumpur, respiratory admissions were only 912 in June 1997, but were 5000 in September 1997, during the heavy Indonesian forest burning period (Awang et al., 2000).

4.1.7. Sand exposure and respiratory problems

Sand particles usually contain particulates of an aerodynamic diameter in excess of what is respirable (Korenyi-Both et al., 1997). However, many areas of the Persian Gulf contain many unusually small sand particles which can be easily inhaled into the lung alveoli during sandstorms. Inhaling such fine sand can cause a syndrome called El Eskan Disease, which involves a variety of respiratory and immunological problems (Korenyi-Both et al., 1997). El Eskan Disease may be a major factor in the development of Gulf War Syndrome (Korenyi-Both et al., 1997). Dust can also trigger respiratory problems thousands of kilometers away from the source. A Trinidad study found that dust from African dust clouds was associated with significantly higher levels of asthma related emergency room visits in children (Gyan et al., 2005).

4.1.8. Respiratory health effects of volcanic emissions

Volcanic eruptions can emit large quantities of sulfur dioxide, particulates, fluorides, hydrogen fluoride, hydrogen chloride and toxic metals like mercury, arsenic and iridium into the air. Emissions of volcanic fog (vog) can travel and produce significantly elevated levels of air pollution more than 1400 km from the volcano (Grattan et al., 1998). A New Zealand study reported personal air exposures of 75 ppm SO₂, 25 ppm HCl and 8 ppm HF in 10 human volunteers who spent 20 min near volcanic vents during a quiet period of the White Island volcano (Durand et al., 2005).

Exposure to volcanic emissions may worsen asthma. Many residents on the big island of Hawaii had reported breathing difficulties, headaches and watery eyes after being exposed to vog from the active Kilauea volcano (Durand and Grattan, 2001). A study of 10,000 government workers in Anchorage, Alaska noted that asthma medical visits increased significantly following an eruption of a nearby volcano in August 1992 (Choudhury et al., 1997).

4.1.9. Respiratory effects of outdoor volatile organic exposure

Volatile organics and other "air toxics" in outdoor air may also trigger asthma, although data from outdoor air exposures is sparse. A study of 8549 West Virginia children found that asthma rates were significantly more common in areas with higher concentrations of industry-released volatile organic chemicals (Ware et al., 1993). Decreased lung function and skin/eye/nose/throat irritation was noted in many members of a Texas community of 3000 exposed to a HF spill from a nearby oil refinery (Wing et al., 1991). Significantly higher wheezing levels have been reported in areas in which methyl tertiary butyl ether (MTBE) has been added to gasoline (Joseph and Weiner, 2002), while other studies report no relationship between asthma and MTBE in gasoline (Gordian et al., 1995).

A California report noted that about 165 residents had wheezing and eye/skin irritation from the drift of chloropicrin soil fumigant applied about a quarter mile away (O'Malley et al., 2003). On the other hand, another study reported no community adverse respiratory or other health effects following aerial spraying of *Bacillus thuringiensis* biological pesticide (Pearce et al., 2002).

4.1.10. Effects of genetics and nutrition on pollutant related adverse health effects

Genetic factors play a role in the susceptibility to respiratory effects of air pollution. A number of studies have linked alleles on chromosomes 2q, 5q, 6p, 12q and 13q as being related to differing rates of asthma (McCunney, 2005). Several studies have also found that genes on certain alleles can increase the respiratory health effects of ambient air pollutant exposure. A Taiwanese study found that in high pollution areas the risk of asthma was significantly greater in children with the Ile-105 allele of the Glutathione-S-transferase gene as compared to the Val-105 alleles (Lee et al., 2004). Risk of asthma was very similar between children with the Ile-105 allele and Val-105 alleles in areas of low air pollution (Lee et al., 2004). Glutathione-S-transferase plays a major role in reducing cell oxidative damage and the Ile-105 subjects may be less efficient in controlling cellular oxidative damage.

Adequate nutrition is also useful in reducing the respiratory effects of air pollution. A Mexico City study found that asthmatic children given antioxidant vitamin supplements were less affected by ozone than a control group which did not receive the supplements (Romieu et al., 2002). Another study found that supplemental antioxidants (400 IU vitamin E/500 mg vitamin C) significantly reduced lung function declines in adult volunteers exposed to 45 min of 0.12 ppm ozone and 10 min of 0.10 ppm SO₂ (Trenga et al., 2001). Many, but not all, studies have linked higher consumption of many nutrients to less asthma and better lung function including fruits and vegetables (at least five servings daily), phytochemicals (such as beta carotene, lutein and lycopene), magnesium, vitamins B₆, B₁₂, E and C, manganese, copper, potassium, selenium, zinc and omega 3 fatty acids (Fogarty and Britton, 2000; Smit et al., 1999; Ochs-Balcom et al., in press; Wong, 2005; Riccioni and D'Orazio, 2005).

4.2. Cardiovascular system effects

Outdoor air pollutants such as PM₁₀ or PM_{2.5}, O₃, and NO₂ have been associated with significantly higher rates of cardiac mortality and morbidity. Table 3 below reports on nine epidemiological studies which have examined the associations

between increasing levels of common outdoor pollutants with rates of heart related health conditions.

As with respiratory effects, air pollutants can increase the risk of heart problems at levels below standards set by such agencies as US EPA or WHO. For example, Peters et al. (2001a) found that higher PM₁₀ levels were associated with significantly more cardiac admissions even though median and 95% PM₁₀ levels were only 19.4 and 37.0 ug/m³ respectively.

Exposure to short term traffic pollution can also trigger heart attacks. A German study of 691 patients who experienced non-fatal heart attacks found that the risk of myocardial infarction was 2.9 times ($P < 0.0001$) within one hour after exposure to traffic as compared to periods that were more than 6 h after the last traffic exposure (Peters et al., 2004).

The effects of air pollutants on cardiovascular disease may be especially strong in certain populations like women, diabetics and the elderly. A 22 year prospective study of 3239 California adults found that higher outdoor levels of PM₁₀ or PM_{2.5} were associated with significantly higher rates of fatal coronary heart disease in postmenopausal females, but little association was found between PM₁₀ or PM_{2.5} and fatal heart disease in males (Chen et al., 2005). A study in four US cities found that increasing PM₁₀ concentrations had a significantly stronger effect in increasing hospital cardiovascular admissions in diabetic versus non-diabetic subjects under 75 years of age (Zanobetti and Schwartz, 2002). Oddly, in subjects over 75 years old, the cardiovascular effect PM₁₀ effect was less in diabetes than non-diabetics, suggesting a survivor effect. Increasing levels of PM₁₀ in eight US counties were associated with higher levels of cardiovascular hospital admissions in patients over age 65, but not in younger patients (Schwartz, 1999).

A Massachusetts study of 100 patients who underwent cardiac defibrillation found that cardiac arrhythmias were significantly associated with higher levels of airborne NO₂, CO and particulates (Peters et al., 2000). Another Massachusetts study reported that higher 3 day levels of PM_{2.5}, CO and SO₂ were associated with significantly higher rates of ventricular tachyarrhythmias in 203 heart patients with implanted cardioverter defibrillators (Dockery et al., 2005). Several studies have

Table 3
Studies linking exposure of higher levels of air pollutants with adverse heart disease events

Study	Outcome measured	Particulates PM ₁₀ or PM _{2.5}	Ozone O ₃	Carbon monoxide CO	Nitrogen dioxide NO ₂	Oxygenated volatile organic compounds
D'Ippoliti et al. (2003)	Myocardial infarction (MI)	X		X	X	
Peters et al. (2001a)	Myocardial infarction (MI)	X		X	X	
Ruidavets et al. (2005)	Acute MI-(subjects with no previous MI)		X			
Chen et al. (2005)	Fatal myocardial infarction	X (women only-little effect in men)				
Metzger et al. (2004)	MI hospital admissions	X		X	X	X
Zanobetti and Schwartz (2005)	MI hospital admissions	X				
Pantazopolou et al. (1995)	MI and respiratory hospital admissions	X		X	X	
Yang et al. (2004)	MI and respiratory hospital admissions	X		X	X	
Morris et al. (1995)	Congestive heart failure hospital admissions			X		

X in box indicates pollutant associated with significantly ($P < 0.05$) greater rates of adverse heart events.

noted significantly lower heart rate variability in humans exposed to particulate air pollution, with this effect being particularly strong in patients with diabetes, hypertension and ischemic heart disease (Pope et al., 1999; Park et al., 2005). Increases in outdoor airborne carbon monoxide concentrations were found to significantly increase systolic and diastolic blood pressure in 48 healthy traffic controllers in Sao Paulo (De Paula Santos et al., 2005). A study of 56 German males with ischemic heart disease found that exposure to PM_{2.5} was associated with significant decreases in T wave amplitude and significant increases in T wave complexity and exposure to organic carbon was associated with significant increases in QT wave duration (Henneberger et al., 2005). A Massachusetts study found that exposure to higher levels of black carbon was associated with significantly greater post exercise ST-depression in 24 elderly subjects (Gold et al., 2005). Such ST depression is often related to ischemia of myocardial tissue.

Outdoor air pollution may increase risk of strokes. A Georgia (USA) study found that admissions for strokes and peripheral vascular disease (thrombosis, claudication, aneurysm, vasculitis) were significantly associated with higher outdoor levels CO, PM_{2.5} and NO₂ (Metzger et al., 2004). A study of 19,005 stroke deaths in a seven year period in Seoul, South Korea, found that higher levels of particulates and sulfur dioxide were associated with significantly higher rates of stroke mortality (Hong et al., 2002). A study in Shanghai found that higher levels of outdoor particulates and nitrogen oxides were associated with significantly higher stroke mortality rates (Kan et al., 2003). However, a study in eight European cities found that increased levels of PM₁₀ had little effect on stroke incidence (Le Tetre et al., 2002). A 1994–8 study in Sheffield, United Kingdom found that stroke mortality was significantly higher at the highest quintile of exposure to NO₂ (37% higher mortality), PM₁₀ (33% higher) and CO (26% higher) as compared to lowest quintile of exposures to these pollutants (Maheswaran et al., 2005).

Exposure to ambient air pollutants may also have adverse effects on the blood and blood vessels. Rabbits exposed to PM₁₀ levels similar to those found in cities experienced significantly larger atherosclerotic lesions and significantly higher levels of polymorphonuclear leukocytes as compared to control rabbits (Suwa et al., 2002). A study of 798 human adults over age 40 years in Los Angeles found that exposure to higher levels of PM_{2.5} is associated with significantly greater carotid-intima media thickness (a measure of atherosclerosis) (Kunzli et al., 2005). Human exposure to air pollution has been linked to arterial vasoconstriction (Brook et al., 2002), increased plasma viscosity (Peters et al., 1997) and increased C-reactive protein (Peters et al., 2001b).

4.3. Cancer

Four out of five studies in Europe and the US have found that exposure to higher outdoor levels of PM₁₀/PM_{2.5}, vehicle traffic and NO₂ are associated with significantly higher risk of lung cancer, while the fifth study showed a non-significant increased risk of lung cancer (Vineis et al., 2004). A review of 24 published studies found that significantly higher rates of cancers

(lung, larynx, and non-Hogkins lymphoma) were reported in 16 studies of subjects living near waste incinerators (Franchini et al., 2004).

Studies in asphalt workers and coke oven workers have found a significant link between airborne exposures to polycyclic aromatic hydrocarbons (PAH's) such as benzo(a)pyrene and lung cancer (Armstrong et al., 2004). No data currently exists which links outdoor PAH exposure and cancer, although outdoor PAH levels can be considerable. Annual mean air benzo(a) pyrene concentrations have been reported as 0.4 ng/m³ in San Francisco (Flessel et al., 1991), and 2.0 ng/m³ in Stockholm (Bostrom et al., 2002). Mean outdoor air levels of benzo(a) pyrene from October to April were 106 ng/m³ in Redwood City, California, a town with many wintertime wood burners (Ott and Kleipas, 1998). Calculation from occupational exposure research estimates that annual outdoor air benzo(a) pyrene concentrations of only 1 ng/m³ is associated with 150 more lifetime lung cancer cases per one million population (Moolgavkar et al., 1998). Some studies have linked traffic exposure to increased childhood leukemia (Savitz and Feingold, 1989), while other studies have not found any relationship (Reynolds et al., 2001).

Several recent studies have found that exposure to high residential indoor radon levels can cause a modest but significant increase in lung cancer rates (Bayyson et al., 2004). Studies in Iowa and Minnesota have noted that outdoor radon levels are variable and can be comparable to moderately high indoor radon levels (Steck et al., 1999). However, no good studies exist which examine a possible link between outdoor radon levels and lung cancer.

Radioactive fallout from nuclear bombs and nuclear power has been associated with significantly higher rates of thyroid cancer and other malignancies. Studies of the survivors of the 1945 Hiroshima and Nagasaki atomic bombs have found significantly increased rates of many forms of cancer including breast, colon, esophagus, lungs, stomach, thyroid, urinary tract as well as increases in leukemia and multiple myeloma (Schull, 1983). Studies of populations near the Hanford, Washington plutonium production site, from atomic tests in Nevada and the Marshall Islands, and from the 1986 Chernobyl nuclear accident have firmly established a relationship with exposure to radioactive ¹³¹I and increased rates of thyroid cancer (Grossman et al., 2003; Gilbert et al., 2002). Significantly greater rates of breast cancer, female reproductive organs and the central nervous system have also been observed among residents downwind from the Hanford plutonium production site (Grossman et al., 2003). A study in Ukraine, Belarus and Russia found that areas exposed to more than 5 mGy radiation from Chernobyl had a much greater risk of childhood leukemia (OR 2.60, 95% CI of 1.70–3.96, *P*=0.003) than areas with less radiation (Davis et al., in press). Other European studies suggest that the fallout from the Chernobyl accident produced a small but significant increase in childhood leukemia in Greece and Germany and no apparent change of childhood leukemia rates in Hungary (Hoffmann, 2002; Torok et al., 2005). The leukemia risks are especially high for those exposed in utero (Hoffmann, 2002; Davis et al., in press).

While the carcinogenic effects of many organic chemicals are well known from human occupational and animal studies, relatively little epidemiological information exists which links exposure to organic chemicals in outdoor air to cancer (Suh et al., 2004). A British nationwide study from 1966 to 1980 found significantly higher cancer death rates for children living within one kilometer of areas of high industrial emissions of PM₁₀, NO₂, total volatile organic compounds, benzene, dioxins, 1,3-butadiene, and benzo(a) pyrene (Knox, 2005). Estimates of cancer risk due to exposure to outdoor airborne chemicals can be made based on occupational and animal studies. Estimated air concentrations of 148 air toxics needed to cause a one in a million lifetime cancer risk were calculated as a benchmark (Woodruff et al., 1998). A 1990 study found that the levels of benzene, formaldehyde and 1,3-butadiene were each higher than their cancer benchmark level in over 90% of all USA census tracts. The average census tract had 14 chemicals whose individual concentrations exceeded this one in a million cancer benchmark (Woodruff et al., 1998).

4.4. Reproductive and developmental effects

Some outdoor air pollutants have been linked to reproductive and developmental problems. A study of births in Vancouver from 1985 to 1998 found that increasing levels of outdoor carbon monoxide and sulfur oxides significantly increased risk of pre-term births (Liu et al., 2003). Air pollution levels are fairly low in Vancouver, with values well below the US EPA limits (Liu et al., 2003). Other studies have linked increased rates of pre-term births to exposure to ambient formaldehyde levels (Maroziene and Grazuleviciene, 2002) and living near an oil refinery (Lin et al., 2001), while another study found no relationship between pre-term birth and maternal residence near an oil refinery (Yang et al., 2002).

Studies in Mexico and the Czech Republic have reported a relationship between ambient particulate levels and excess infant deaths (Loomis et al., 1999; Bobak and Leon, 1999). A study of four million US infants born from 1989 to 1991 has found that higher PM₁₀ levels were associated with significantly higher death rates from sudden infant death syndrome (SIDS) (Woodruff et al., 1997). A California case-control study found that higher levels of outdoor NO₂ were associated with significantly higher SIDS deaths, while higher CO levels were not associated with higher SIDS deaths (Klonoff-Cohen et al., 2005). A study of 221,406 live births in New Jersey in 1990–1 found that low birth weight, premature birth and fetal death were significantly more common in mothers living in areas with high levels of airborne PAH's (Vassilev et al., 2001). A Pennsylvania study found that higher outdoor air levels of PM₁₀ and SO₂ were associated with significantly higher rates of preterm birth (Sagiv et al., 2005). A Texas study found that higher levels of CO were associated with significantly higher levels of Teratology of Fallot, higher PM₁₀ levels were associated with significantly higher levels of atrial septal defects and higher SO₂ levels were associated with significantly higher rates of ventral septal defects (Gilboa et al., 2005).

A Belarus study noted significantly increased rates of several congenital abnormalities following the 1986 Chernobyl accident

(Feschenko et al., 2002). Higher outdoor levels of CO in Los Angeles (Ritz et al., 2002) and industrial pollution in Moravia (Smrcka and Leznarova, 1998) have been associated with significantly higher rates of congenital cardiac defects such as ventricle septal defects. A French retrospective cohort study found a significant relationship between traffic exposure and cardiac birth defects, a borderline relationship to urinary tract defects and no relationship to oral cleft defects (Cordier et al., 2004).

4.5. Neurological and neuropsychiatric effects

Several studies have found that higher levels of outdoor air pollution can increase risk of neurological and psychiatric problems. An Italian study found that headaches were significantly more common among 32 headache-prone adults when outdoor levels of carbon monoxide and nitrogen oxides were high ($P=0.0008$) (Nattero and Enrico, 1996). Higher outdoor levels of CO and NO₂ were associated with significantly higher admission rates to a St. Louis, Missouri psychiatric hospital (Strahilevitz et al., 1979). A prospective study of 7455 Danish children noted that proximity to traffic and exposure to higher levels of benzene and carbon monoxide were associated with significantly higher rates of schizophrenia (Pedersen et al., 2004). A Ukrainian study found significantly higher incidence of schizophrenia spectrum disorders in workers who spent more than five years exposed to moderately high radiation levels in the Chernobyl exclusion zone from 1986 to 1997 (Loganovsky and Loganovskaja, 2000). A Belarus study of children aged 6–11 years found that those exposed to Chernobyl radiation in utero had significantly lower IQ and significantly more emotional and development disorders as compared to unexposed children (Kolominsky et al., 1999).

A 1990 study in all 3111 US counties found significantly higher murder rates in counties with high levels of airborne lead (Stretesky and Lynch, 2001) (results adjusted for socioeconomic factors). A Taiwan study reported air lead levels of 10 $\mu\text{g}/\text{m}^3$ in a kindergarten near a battery recycling plant (Wang et al., 1998). Lead levels in these children reached 15 to 25 μg per deciliter of blood and these lead exposed children had a significantly lower IQ than children living in unexposed areas (Wang et al., 1998). A study in a Mexican manganese mining area found that airborne manganese levels were about three times that of urban areas (Santos-Burgoa et al., 2001). Subjects who lived in these manganese mining areas had significantly lower cognitive function and significantly more hand numbness than controls (Santos-Burgoa et al., 2001). Residents living near oil reprocessing and Superfund toxic sites reported significantly more depression, confusion, and chronic fatigue as well as poorer scores on neuropsychological tests for memory, concentration, balance, reaction time and cognitive function as compared to unexposed controls (Kilburn and Warshaw, 1995; Kilburn, 1999). Two Minnesota studies found that ragweed allergic patients had significantly poorer memory, slower cognitive processing and more depression during periods of high outdoor ragweed pollen levels (Marshall et al., 2000, 2002).

4.6. Mortality

Numerous studies have linked exposures to higher levels of outdoor pollutants to significantly higher rates of mortality (Brunekreef and Holgate, 2002). Two large studies of the effects of outdoor PM₁₀ and mortality/morbidity were conducted among 43 million European city dwellers and 50 million US city dwellers (Katsouyanni et al., 2001; Atkinson et al., 2001; Samet et al., 2000; Zanobetti et al., 2000). For each 10 µg/m³ increase in PM₁₀, daily mortality increased by about 0.6% in the European study and 0.5% in the US study. In addition, each 10 µg/m³ increase in PM₁₀ resulted in the statistically significant increases in hospital admissions for chronic obstructive pulmonary disease (COPD) of 1.0% (Europe) and 1.5% (US) and statistically significant increases in heart disease admissions of 0.5% (Europe) and 1.1% (US) (Katsouyanni et al., 2001; Atkinson et al., 2001; Samet et al., 2000; Zanobetti et al., 2000). A study of 14 large US cities from 1986 to 1993 reported a 0.36% mortality increase per 10 µg/m³ increase in PM₁₀ (Schwartz, 2004). A Chinese study of 61,000 deaths found that higher air levels of PM₁₀, SO₂ and NO₂ all corresponded to significantly higher death rates (Kan and Chen, 2003). A 14 year study of 95 large US communities found that an increase of 24 h O₃ concentrations of 10 parts per billion was associated with a 0.52% increase in daily mortality (95% confidence interval of 0.27% to 0.77%) (Bell et al., 2004). A meta-analysis found that for each PM₁₀ increase of 10 µg/m³, there is a 5% increase in neonatal deaths of all causes and a 22% increase in neonatal respiratory deaths (Lacasana et al., 2005). A Los Angeles study found that each 10 µg/m³ increase in PM_{2.5} was associated with a 1.17 greater relative risk of mortality (95% CI of 1.05–1.30, data adjusted for 44 covariates) (Jerrett et al., 2005). On the other hand, another study found very little relationship between PM_{2.5} levels and mortality in elderly Californians (Enstrom, 2005). A Shanghai study reported that exposures to 10 µg/m³ higher levels of PM₁₀ or NO₂ were associated with significantly higher rates of diabetes related mortality (Kan et al., 2004).

Some recent studies have suggested that exposure to higher levels of PM₁₀ or PM_{2.5} are associated with shorter lifespan (Dockery et al., 1993; Pope et al., 1995). One study estimated that exposure to fine particulate matter in the USA was associated with an average one to two year loss of lifespan (Brunekreef, 1997). It has been estimated that outdoor air pollution is responsible for 0.8 million annual worldwide premature deaths (1.2% of total deaths), including 5% of deaths from respiratory cancer, 3% of cardiovascular diseases and 1% of acute respiratory infections (Cohen et al., 2005).

A study in Dublin, Ireland found that reducing airborne particulates can significantly reduce cardiovascular and respiratory deaths (Clancy et al., 2002). Following a 1990 coal burning ban, average annual levels of black smoke (particulates) were reduced by 35.6 µg/m³ (Clancy et al., 2002). Death rates for all non-traumatic causes, respiratory diseases and cardiovascular problems fell by 5.7%, 15.5% and 10.3% respectively in the six years following the 1990 ban as compared to the six year period before 1990 ($P < 0.0001$ for all 3 cases) (Clancy et al., 2002). This mortality drop amounted to an estimated 116

fewer respiratory and 243 fewer cardiovascular deaths annually in Dublin (Clancy et al., 2002).

4.7. Infection

It has been well established that significantly higher rates of respiratory infection have been linked to indoor exposure to wood, coal or dung burning or living in poorly ventilated buildings (Brundage et al., 1988; Chauhan and Johnston, 2003). Recent research also suggests that high levels of outdoor air pollution may also increase risk of respiratory infections. A German study of 6000 croup cases found that increases in outdoor levels of total particulates and nitrogen dioxide levels of 10 and 70 µg/m³ were associated with statistically significant 27% and 28% increases in croup respectively (Schwartz et al., 1991). Ecuadorian children exposed to higher levels of CO were found to have significantly more upper respiratory infections (Estrella et al., 2005). Studies in Finland and Turkey have found that childhood respiratory infections are about twice as common in cities with high air pollution levels as compared to less polluted areas (Jaakkola et al., 1991; Keles and Ilicali, 1998). Higher outdoor levels of PM₁₀ and O₃ have been linked to significantly higher rates of hospital pneumonia admissions (Schwartz, 1994; Ye et al., 2001). Higher daily levels of O₃ and SO₂ have been linked to significantly increased influenza admissions (Martins et al., 2002). Higher outdoor dust exposure can increase risk of *Coccidioidomyces* infection in endemic areas (Durry et al., 1997). A Nicaraguan study found that childhood diarrhea illness increased 6 fold in a community exposed to large quantities of volcanic ash containing large amounts of fluorides and toxic metals (Malilay et al., 1996).

4.8. Other health effects

Exposure to air pollution may alter hematological and immunological parameters. A Singapore study reported significant increases in band neutrophils in 30 healthy young men during the heavy 1997 Indonesia forest fires (Tan et al., 2000). Other studies have noted that levels of IgE and other immunological modulators are increased among those with higher levels of airborne particulate exposure (Boezen et al., 1999), while other studies do not show such an association (Hirsch et al., 1999). Exposure to airborne ozone and particulates has been linked to higher type 1 diabetes incidence (Hathout et al., 2002). Burning high arsenic containing coal can contaminate air and foodstuffs and produce skin cancer, neuropathy and damage to the lungs and kidneys (Liu et al., 2002; Pesch et al., 2002). An Indonesian study found significantly higher levels of tooth and skeletal fluorosis in children and adults living near a volcano which emits large amount of fluorides in the air and water (Heikens et al., 2005).

5. Economic effects of air pollution

The economic costs of air pollution are difficult to estimate accurately (Levy, 2003). Exposure to various air pollutants

and combinations of air pollutants create major economic costs by increasing mortality, morbidity, and increased absenteeism and lost productivity. Air pollution related adverse health effects also cause a lot of human suffering which is hard to measure in terms of money. In addition, air pollution also creates a large amount of non-human health related economic costs including reduced visibility, global warming, building and vehicle damage, and harm to many types of plants and animals.

Kunzli et al. (2000) estimated that in France, Switzerland and Austria, air pollution annually causes more than 40,000 early deaths, more than 25,000 new cases of adult bronchitis, more than 290,000 episodes of childhood bronchitis, more than 500,000 asthma attacks and over 16 million person-days of restricted activity. Wong et al. (2004) estimated that the US Clean Air Act Amendments of 1990 would by the year 2010 reduce annual US health costs by about \$10 billion and reduce mortality costs by about \$100 billion (in 1990 US\$). In addition, the 1990 Clean Air Amendments are estimated to reduce annually 40,000 childhood asthma emergency room visits, produce 10,000 fewer infants with low birth weight and avoid 20,000 school absences in children aged 6 to 11 years (Wong et al., 2004). Another US study estimated that nationwide attainment of the US EPA ozone standard would reduce annual childhood school absences by 890,000 and would reduce annual adult restricted activity days by 1,200,000 (Hubbell et al., 2005).

Outdoor air pollutants may play a major role in increasing elementary school absenteeism. A California study found that for every 0.02 ppm increase in daily maximum hourly O₃ levels there was a 63% increase in elementary school absenteeism (Gilliland et al., 2001). A South Korean study reported that higher outdoor levels of PM₁₀, O₃ and SO₂ were associated with significantly higher levels of elementary school absenteeism (Park et al., 2002). A Nevada (USA) study reported that high ambient levels of CO and O₃ were associated with significantly higher levels of elementary school absenteeism, while, oddly enough, higher levels of PM₁₀ were associated with significantly lower rates of absenteeism (Chen et al., 2000).

6. Conclusions and suggestions for further research

Outdoor air quality plays an important role in human health. Air pollution causes large increases in medical expenses, morbidity and is estimated to cause about 800,000 annual premature deaths worldwide (Cohen et al., 2005). The outdoor air often contains biologically significant levels of many pollutants including particulates (PM₁₀ or PM_{2.5}), ozone, carbon monoxide, oxides of nitrogen and sulfur, bioaerosols, metals, volatile organics and pesticides. A large percentage of these pollutants are produced by anthropogenic activities. While most people spend the majority of their time indoors, outdoor air quality can affect indoor air quality to a large degree. In addition many patients such as asthmatics, patients with allergies and chemical sensitivities, COPD patients, heart and stroke patients, diabetics, pregnant women, the elderly and children are especially susceptible to poor outdoor and indoor air quality.

It is now well documented that higher levels of many airborne pollutants can affect many of the body's systems adversely, including the respiratory, cardiovascular (including heart and brain), reproductive/developmental, and neurological/neuropsychiatric systems. Air pollution has also been associated in some studies to increase rates of infection, cancer and mortality. Especially well documented are the respiratory and cardiovascular effects of common air pollutants such as PM₁₀ or PM_{2.5}, ozone, carbon monoxide and oxides of nitrogen and sulfur. Many studies have reported a strong association between adverse health effects and levels of priority air pollutants (PM₁₀/PM_{2.5}, O₃, NO₂, SO₂ and CO) which are well below standards set by US EPA, WHO and other agencies. In addition, the outdoor air often contains significant levels of many other pollutants such as metals (lead, mercury, cadmium, manganese and nickel), isocyanates, ethylene oxide, aldehydes (acrolein, formaldehyde) and other volatile organic chemicals. The health effects (such as cancer or asthma) of occupational exposure to these chemicals are well known, however few studies have looked at the health effects of ambient air exposures to metals or volatile organics (Leikauf, 2002). Combinations of many of these air pollutants can have additive or synergistic adverse health effects.

Most studies dealing with health effects of air pollutants have involved either experimental animals or human epidemiological or occupational studies. A few studies have employed environmental chambers to measure the respiratory effects of typical ambient levels of outdoor air pollutants on humans (Molfinio et al., 1991; Sandstrom, 1995). The use of environmental chambers should be a promising way to measure many types of ill health effects after exposure to low levels of single or multiple airborne toxics. Environmental chamber testing has already proven to be an effective way to measure immediate health effects of exposure to low level exposures to common indoor and industrial airborne chemicals (Rea, 1996). Environmental chamber testing has special promise for measuring the neurological effects of exposure to typical outdoor levels of air pollutants. Environmental chamber subjects can be tested before and after low level air toxic exposure and the neurological effects can be measured by such instruments as brain EEG, brain SPECT/PET, nerve conduction studies, autonomic nerve function studies and neuropsychiatric tests for concentration, memory, balance and mood. Of course, there are always ethical concerns with human testing and researchers must be careful to keep toxic exposures at a low enough level so as to avoid permanent harm in the test subjects.

Further research on the health effects of outdoor air pollutants is needed. Some important areas for future research include: 1) Additional study of non-respiratory and non-cardiovascular health effects of air pollution, 2) Additional study of the health effects of metals and volatile organic chemicals in outdoor air, 3) Synergistic effects of air pollutants and 4) The effects of air pollution on especially susceptible populations. Additional studies are also needed to estimate the public health and economic benefits/costs to reductions in outdoor air pollutants. The study of genetic and nutritional factors which influence the health effects of outdoor air quality should also be a fruitful area for further research. Further research on the health effects of air pollution, medication and nutritional treatments to reduce the adverse effects

of air pollution and air pollutant abatement methods should be very helpful to physicians, public health officials, industrialists, politicians and the general public.

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