Cancer Risk of Air Pollution: Epidemiological Evidence

Kari Hemminki [1] and Göran Pershagen [2]

[1] Center for Nutrition and Toxicology, Karolinska Institute, Stockholm, Sweden; [2] Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden

Epidemiological studies on the effect of urban air pollution on lung cancer were surveyed. Overall, the studies from many countries point to a smoking-adjusted risk in urban areas over countryside areas that is higher by a factor of up to 1.5. The extent to which urban air pollution contributes to this excess remains unknown. Studies on diesel-exposed occupational groups show that urban air pollution may have a causative role in lung cancer. Model calculations on unit risk factors of known human carcinogens were carried out to rank carcinogens according to their current ambient air concentrations. — Environ Health Perspect 102(Suppl 4):187–192 (1994).

Key words: air pollutions, lung cancer, urban cancer, diesel emissions, unit risk

Introduction

Of the many known causes of cancer in western industrialized countries, air pollution appears to be a minor contributor as compared to such dominant causes as tobacco smoke (*1,2*). Yet air pollution unavoidably affects the whole population and can interact with other carcinogenic factors, potentiating their effects. Thus, when considering cancer as well as other diseases, there is a reason to control air pollution and keep it at a minimum.

In this article, epidemiological evidence on air pollution-induced and engine exhaust-induced cancer is reviewed shortly. Unit risk factors for individual chemicals estimated from epidemiological studies then are used to assess the contribution of various pollutants at their present levels to the risk of cancer in the future.

Methods of Risk Estimation

Epidemiological studies provide direct evidence on presence and magnitude of cancer risk in humans. In spite of this, epidemiological approaches to assess environmental cancer risks have serious limitations. First, the effects pertain to exposures during earlier years or decades. The exposure panorama has changed extensively during the last decades, which hampers interpretation of cancer risks of current exposures. Second, as the risks are near the detection limit of present epidemiological methodology, the studies are particularly sensitive to bias resulting from uncontrolled confounding or imprecise estimation of exposures (*3*).

Epidemiological data from occupational studies may be used to estimate cancer risks related to compounds present as constituents of air pollution. In some occupational studies, the exposure levels are reasonably well assessed and the relative risks are large enough to add confidence to the risk estimates. Risks at lower levels of exposure may be estimated by extrapolation, assuming certain dose-response relationships. If a linear dose-response relationship is assumed, a unit risk factor can be calculated. This factor is usually given as the risk of cancer resulting from lifetime inhalation of 1 $\mu g/m^3$ of the substance.

A third possibility for risk estimation is the use of animal experiments. This requires many assumptions on the interspecies and high dose/low dose extrapolation, as discussed later. However, in the absence of epidemiological data, risk assessments usually are based on animal data.

Studies in Urban Areas

Cancer risks in urban areas have been studied with different epidemiological methodologies. Primarily three types of studies can be identified: ecologic studies, cohort studies, and case-control studies. In contrast to the other two, ecologic studies use groups of people rather than individuals as the unit of observation. Ecologic studies generally are not suitable for assessment of causal relationships. The epidemiologic evidence on air pollution and lung cancer has been reviewed recently by Pershagen and Simonato (*3*) and will be discussed briefly here.

The data from cohort studies on urban air pollution and lung cancer is summarized in Table 1. All but one of the investigations contain information on smoking for all study subjects. The studies come from the United States (*3*), Sweden (*2*), Finland (*1*), and Great Britain (*1*). Smoking-adjusted relative risks for lung cancer in urban areas generally were in the order of 1.5 or lower in those cohort studies reporting increased risks. The findings pertain mainly to smokers. For nonsmokers, the number of cases generally was too small for a meaningful interpretation of urban to rural differences.

In the case-control studies, residential and smoking histories were obtained for the study subjects, and sometimes information on potential confounding factors such as occupation also would be gathered (Table 2). Increased relative risks for lung cancer were observed among men in urban areas in three British studies as well as in studies from Greece, Poland, China, and Japan. Two U.S. studies found raised lung cancer risks in urban males, while another two failed to show an effect. A recent study from the heavily polluted city of Cracow, Poland, showed an excess relative risk among men living in areas with high air pollution levels [i.e., average annual mean concentrations above 150 $\mu g/m^3$ of total suspended particulate matter and 104 $\mu g/m^3$ of sodium dioxide (*4*)]. In most studies the increased lung cancer risks were seen primarily in smokers and some findings suggested a multiplicative interaction between urban residence and smoking. The results for women were difficult to interpret because of small numbers, but at least one study indicated a raised lung cancer

This paper was presented at the Symposium on Risk Assessment of Urban Air: Emissions, Exposure, Risk Identification and Risk Quantitation held 31 May–3 June 1992 in Stockholm, Sweden.

Address correspondence to Kari Hemminki, Center for Nutrition and Toxicology, Karolinska Institute, NOVUM, 141 57 Huddinge, Stockholm, Sweden. Telephone 46 8 6089243. Fax 46 8 6091501.

Table 1. Summary of cohort studies on lung cancer in urban areas.

Study population	Area	Summary of findings on lung cancer	Standardization variables (other than age)	References
187,783 white males followed 1952 to 1955	United States (9 states)	Relative death rate = 1.33 in cities with over 50,000 population in comparison with rural areas.	Smoking	Hammond and Horn, 1958 (*25*)
69,868 men followed 1958 to 1962	California, United States	Relative death rate = 1.30 in urban counties (Los Angeles, San Francisco Bay area, and San Diego) in comparison with other California counties.	Smoking	Buell et al., 1967 (*9*)
About 500,000 men followed 1959 to 1965	United States (25 states)	Relative death rates of 1.23, 1.14, and 0.98 in metropolitan areas with more than one million inhabitants, less than 1 million, and nonmetropolitan areas, respectively, among men with occupational exposure to dust, fumes, gases, or X-rays. Corresponding rates for men without such occupational exposures were 0.98, 0.97, and 0.92.	Smoking	Hammond, 1972 (*26*)
25,444 men and 26,467 women followed 1963 to 1972	Sweden	Relative death rate about 1.6 and 1.2 in male smokers of cities and towns, respectively, in comparison with smokers in rural areas. Similar trend in women (based on small numbers). [a]	Smoking	Cederlöf et al., 1975 (*27*)
34,440 doctors followed 1951 to 1971	United Kingdom	No increase in relative death rate in "conturbations, large towns, or small towns" in comparison with rural areas.	Smoking	Doll and Peto, 1981 (*28*)
About 7.5 million men and women followed 1961 to 1973	Sweden	About 40 and 20% of male and lung cancer incidence explainable by urban factors other than smoking.	Diagnostic intensity, smoking (only available for about 1% of cohort)	Ehrenberg et al., 1985 (*12*)
4475 men followed 1964 to 1980	Finland (3 urban and 3 rural areas)	Increased incidence in urbanized (relative risk ≈ 1.2) but not in urban married smokers in relations to married smokers in rural areas.	Marital status, smoking	Tenkanen and Teppo, 1987 (*29*)

[a] An extended follow-up of the male part of the cohort through 1979 showed smoking standardized death rates of 1.4 and 1.1 in cities and towns, respectively (J Carstensen, personal communication).

risk for females and nonsmokers in urban areas (*5*). The magnitude of the excess relative risks for lung cancer in urban areas reported in the case-control studies were similar to those in the cohort studies.

A number of studies have been performed on populations living near industries, such as nonferrous smelting, with heavy emissions of air pollutants. Most of them have considered lung cancer risks. A few of the investigations focused on relationships between other diseases and sites such as mesothelioma near asbestos factories and angiosarcoma of the liver near vinyl chloride fabrication/polymerization plants. These studies are discussed in detail elsewhere (*3*).

The epidemiological studies on urban air pollution and lung cancer discussed above give somewhat inconsistent results as to the type of interaction with tobacco smoking. Some studies provided evidence of a combined effect exceeding an additive effect and often were compatible with a multiplicative interaction (*4,6–8*). Other studies were more consistent with an additive effect (*5,9,10*). In most of the studies, urban and rural differences in lung cancer rates were more pronounced or seen only among smokers. For example, a study from Utah revealed increased urban rates for non-Mormons only (*11*). A positive interaction between urban air pollution and smoking may contribute to these results.

Magnitude of Cancer Risk in Urban Areas

The strongest evidence of an effect of air pollution on cancer is seen for lung cancer. Other sites also may be affected, although supportive data are very limited. For lung cancer, smoking-standardized relative risks comparing urban and rural areas often were in the order of 1.5 or lower in the published studies and generally higher in men than in women. A relative risk of 1.5 would imply that one third of the cases among the exposed are attributable to the exposure. Corresponding attributable risks for relative risks of 1.1% and 1.3% are 9.1% and 23.1%, respectively. The attributable risk for the whole population is lower and depends on the proportion exposed in the population.

Two of the studies on urban air pollution and lung cancer provided data on attributable risks (or similar measures). In the national Swedish cohort, Ehrenberg et al. (*12*) reported that some 40 and 20% of the lung cancer incidence in men and women, respectively, was "statistically explainable" by urbanization variables other than smoking and diagnostic intensity. Smoking explained 85% and 20 to 40% of the lung cancer incidence in men and women, respectively. In the case-control study from the Cracow region, it was estimated that 4.3% of the lung cancers in men and 10.5% in women were attributable to air pollution (*4*). Corresponding estimates for smoking and occupational exposure were 74.7 and 20.6% in men, and 47.6 and 8.3 % in women.

It is of interest to examine how well the recorded excess rates of cancer in urban areas would fit with the data available from occupational studies. The World Health Organization recently evaluated cancer risks in humans exposed to various carcinogens in ambient air (*1*). Based on extrapolations from epidemiological data on occupational exposures, the lifetime lung cancer

Table 2. Summary of case-control studies on lung cancer in urban areas.

Study population	Area	Summary of findings on lung cancer	Standardization variables (other than age)	References
725 male lung cancer cases and about 12,000 hospital controls without cancer identified 1952 to 1954	North Wales and Liverpool, England, United Kingdom	Relative risks ranging from 1.1 to 3.4 in different groups of smokers comparing urban and rural areas. Additivity of effects from urban residence and smoking suggested.	Smoking	Stocks and Campbell, 1955 (*10*)
2381 white male lung cancer deaths and 31,516 population controls identified 1958	United States	Overall SMR [a] of 1.43 comparing urban and rural areas, with positive trend in relation to duration of residence. Joint effects of urban residence and smoking exceed additivity.	Smoking	Haenszel et al., 1962 (*6*)
749 white female lung cancer deaths and 34,339 population controls identified 1958 to 1959	United States	Overall SMR [a] of 1.27 comparing urban and rural areas with positive trend in relation to duration of residence. Additivity of effects from urban residence and smoking suggested.	Smoking	Haenszel and Taeuber, 1964 (*5*)
2873 male and 167 female lung cancer deaths; an equal number of deceased controls with nonrespiratory illness identified 1960 to 1962	Northern Ireland United Kingdom	Mortality rate ratios of about 1.5 to 5 in men and women of different groups comparing urban and rural areas. Joint effects of urban residence and smoking appear to exceed additivity.	Smoking	Dean, 1966 (*7*)
180 male and 79 female lung cancer deaths; 2241 male and 2475 female population controls identified 1960 to 1966	Two cities near Osaka, Japan	Relative risks range from 1.2 to 1.8 in men and women comparing areas having high or intermediate levels or air pollution with those having low levels. Effects primarily seen in smokers.	Smoking	Hitosugi, 1968 (*30*)
780 male and 199 female lung cancer deaths; 2563 male and 2958 female population controls identified 1969 to 1972	Northeast England, United Kingdom	Relative risks of 1.6 and 1.7 for women and men, respectively, in areas having high air pollution levels compared with areas having intermediate levels. Relative risk increases lower when compared with areas having low pollution levels.	Smoking	Dean et al., 1977 (*31*)
785 male and 138 female lung cancer cases identified 1963 to 1972; 1371 male and 1571 female population controls	Northeast England, United Kingdom	Relative risks of 1.4 and 2.3 for women and men, respectively, in areas having high air pollution levels in comparison with areas having intermediate levels.	Smoking	Dean et al., 1978 (*32*)
1425 white male and 576 female cases diagnosed 1972 to 1975; 445 male and 186 female population controls	Los Angeles County, California, United States	No association with long-term residence in high air pollution areas.	Smoking	Pike et al., 1979 (*33*)
417 white male lung cancer cases and 752 hospital controls with nonneoplastic disease identified 1957 to 1965	Erie County, New York, United States	Relative risks of about 1.1 and 1.4 for nonsmokers and smokers, respectively, associated with 50 years or more of residence in areas with high or medium levels of air pollution. Joint effects of air pollution and smoking appear to exceed additivity.	Smoking, occupation	Vena, 1982 (*8*)
283 male and 139 female lung cancer cases; 475 population controls identified 1980 to 1982	New Mexico, United States	No consistent association between residence in urban areas and cancer risk.	Smoking, occupation, ethnic group	Samet et al., 1987 (*34*)
729 male and 520 female cancer cases diagnosed 1985 to 1987; 788 male and 557 female population controls	Shenyang, China	Relative risks of 1.5 and 1.4 for males and females, respectively, residing in somewhat/slightly smoky areas compared with subjects in not smoky areas. Corresponding relative risks for subjects in smoky areas 2.3 and 2.5.	Smoking, education, indoor air pollution	Xu et al., 1989 (*35*)
901 male and 198 female lung cancer deaths; 875 male and 198 female deceased controls with nonrespiratory diseases identified 1980 to 1985	Cracow, Poland	Relative risks of 1.48 for men in areas having high air pollution levels and 1.17 in women in areas having medium or high levels compared with subjects in areas with low levels of air pollution. Multiplicative interaction suggested between smoking, occupational exposure, and air pollution.	Smoking, occupation	Jedrychowski et al., 1990 (*4*)
101 female lung cancer cases diagnosed 1987 to 1989 and 89 hospital controls with orthopedic diseases	Athens, Greece	Relative risks of 0.81, 1.35, and 2.23 comparing higest and lowest quartiles of air pollution exposure in nonsmokers and smokers of 15 and 30 years duration, respectively.	Smoking, education, interviewer	Katsouyanni et al., 1991 (*36*)

[a] SMR, standardized mortality ratio.

risk resulting from exposure to 1 $\mu g/m^3$ was estimated at 9×10^{-2} and 4×10^{-3} for benzo[*a*]pyrene and arsenic, respectively. Assuming a background lifetime risk of lung cancer of 3%, this implies that lifetime exposures of about 170 ng/m^3 of B[*a*]P or 4 $\mu g/m^3$ of arsenic are necessary to produce relative risks of the order of 1.5. Levels in this range have been recorded ear-

lier for B[*a*]P in very polluted cities and for arsenic near copper smelters (*1*).

The great uncertainty in the extrapolations should be stressed, and they should be interpreted only as providing rough estimates of risks. However, it appears that the relative risks observed in the epidemiological studies may not be unrealistic if related to earlier heavy exposure to pollutants in ambient air.

Studies in Populations Exposed to Engine Exhausts

In 1988 the International Agency for Research on Cancer (IARC) evaluated the carcinogenicity of diesel and gasoline engine exhausts (*13*). IARC concluded, based on the epidemiological data available, that there was limited human evidence for the carcinogenicity of diesel engine exhaust, inadequate evidence of gasoline engine exhaust carcinogenicity, and limited evidence of unspecified engine exhaust carcinogenicity (*13*). The risk ratios (SMRs) were between 1.2 and 1.5 in a Canadian and U.S. cohort study on diesel-exposed railroad workers and in two case-control studies. The inability to exclude exposure to diesel exhausts was the main reason the gasoline engine exhaust evidence was inadequate. Three out of four case-control studies showed an excess of bladder cancer, in addition to lung cancer, in diesel-exposed workers (*13*).

Since the IARC evaluation, several relevant epidemiological studies have been published. In a large U.S. cohort study of 460,000 men at ages 40 to 79 years, the crude relative risk of lung cancer among those exposed to diesel exhaust was 1.4. After adjustment for a number of factors, including smoking, the relative risk fell to 1.18 (95% confidence interval [CI] 0.97–1.44). There was a moderate ($p<0.1$) trend with duration of exposure; among the occupational categories a significant additional lung cancer risk was observed for miners and users of heavy engines (*14*).

In a large U.S. case-control study (2584 cases and 5099 controls), diesel exposure was one of the exposes considered (*15*). Again, the crude risk of lung cancer for diesel exposure fell from 1.31 to 1.02 after adjustment for confounding factors. The duration of exposure showed a nonsignificant correlation with risk.

A Swedish cohort study of 695 bus garage workers indicated a slight, statistically nonsignificant elevation of lung cancer risk as compared to Stockholm workers in general. However, a nested case-control study within the cohort showed a significant trend in lung cancer risk with estimated exposure to diesel exhaust (*16*).

A U.S. case-control study analyzed the exposures of 996 union members who died of lung cancer and 1085 control individuals who died of other causes. Occupational histories were reconstructed from the union files, and additional information was obtained by interviewing relatives. Truck and trailer drivers were at an increased risk, which significantly correlated with duration of exposure (*17*). Mortality of Icelandic professional truck (n = 868) and taxi (n = 26) drivers from lung cancer was significantly elevated for the former group only, with SMR = 2.14 (95% CI 1.37–3.18) as compared to the national rate. There was no systematic dependence on the length of follow-up or latency. Smoking habits of a subpopulation of truck drivers did not differ from those of taxi drivers or other men (*18*).

The studies that have been published since IARC's evaluation of diesel exhaust lend further support to the association between occupational exposure to diesel exhausts and lung cancer. There is no further evidence on the possible association between gasoline engine exhaust and lung cancer.

Table 3. Unit risk factors obtained from epidemiological studies and the calculated numbers of cancer cases at given ambient air concentrations of pollutants.

Pollutant	A Unit risk factor (site), $\mu g/m^3$ [a]	B Ambient air level, $\mu g/m^3$	C Lifetime cancer risk	D Cancer, year/10^6
Arsenic	4×10^{-3} (lung)	0.007	2.8×10^{-5}	0.4
Cadmium	2×10^{-3} (lung)	0.0002	4.0×10^{-7}	0.006
Chromium (6+,1%)	1×10^{-2} (lung)	0.00003	3.0×10^{-7}	0.004
Nickel	1×10^{-4} (lung)	0.002	2.0×10^{-7}	0.003
Asbestos	2×10^{-5} (100 F/m^3) (lung and pleura)	200(F/m^3)	4.0×10^{-5}	0.6
Benzene	8×10^{-6} (leukemia)	3.7	3.0×10^{-5}	0.5
PAH (as B[*a*]P)	1×10^{-1} (lung)	0.0007	7.0×10^{-5}	1.0

[a] Lifetime cancer risk at an ambient air level of 1 $\mu g/m^3$, main reference EPA (*19*). [b] Mean exposure from ambient air in Sweden (*20*).

Extrapolation of Cancer Risk at Currently Known Pollution Levels

In the above sections, evidence for the association of past environmental and occupational exposures and risk of cancer was surveyed. In the present section, current ambient air levels are used in an extrapolation of cancer risk.

Extrapolation from Human Data

Unit risk factors calculated by the U.S. Environmental Protection Agency (*19*) from epidemiological studies on occupationally exposed populations were used to estimate the annual number of cancers caused by air pollution. Unfortunately, unit risk factors are available for a limited number of exposures only. Table 3, column A gives the unit risk factor as a number of cancer cases following a lifetime exposure to a pollutant at 1 $\mu g/m^3$.

Column B is the estimated mean exposure from ambient air in Sweden (*20*). Column C is the product of figures in columns A and B and gives the lifetime cancer risk; column D is the annual number of cancers caused by the inhaled pollutant/1 million population (i.e., D = A × $B/10^6/70$, where 70 is used as the mean age and is applied to convert a lifetime risk to an annual risk).

The largest contribution to cancer burden is estimated for polycyclic aromatic hydrocarbons (PAH) (lung cancer), asbestos (lung cancer and mesothelioma), benzene (leukemia), and arsenic (lung cancer), each causing 0.5 to 1.0 annual cases/10^6 inhabitants. The contribution of cadmium, chromium (6-valent), and nickel is about 100 times less.

There are three important qualifiers to the figures given in Table 3. *a*) While indoor air concentrations are likely to be higher for exposures such as asbestos, benzene, and PAH, only outdoor ambient air concentrations are used (*21,22*). *b*) The levels cited are low in comparison to measurements carried out in other countries (*1*). There are a number of reasons for this: true decline in ambient air concentrations of pollutants, as in the case of PAH in many countries; particularly low concentrations in Sweden; and paucity of measurements available in Sweden. *c*) All of the metals and PAH are derived primarily from food through soil or deposition of airborne particulate material (*1,23*). At the levels cited in Table 3, 99% or more of the metal and PAH exposure may be from food, making inhalation exposure toxicologically less relevant. To illustrate this point, Table 4 lists the estimated routes of exposure to B[*a*]P in the United States around 1980 (*24*). Intake through air accounts for 0.1 to

Table 4. Exposure to polycyclic aromatic hydrocarbons (*36*).

Source	B[*a*]P, ng/day
Air	1 to 40
Water	1
Food	160 to 1600
Tobacco smoke [a]	400

[a] Active smokers.

Table 5. Cases of lung cancer if air pollution caused the risk indicated.

Risk ratio	Lung cancers/year/10^6	Excess cases
1.0	300	0
1.1	330	30
1.2	360	60
1.3	390	90
1.4	420	120
1.5	450	150

20% of the total for a nonsmoker and even less for a smoker. There is no *a priori* reason to assume that the oral intake would be less harmful. PAHs represent a large group of compounds that are persistent and mainly ingested rather than inhaled. The cancer studies from which the unit risk factors are derived are based on occupational exposures, inhalation being the main route of intake. Thus, the present approach is not applicable to oral exposure. The unit risks do not necessarily take account of interactions, which may differ in type and magnitude between the general and occupational environments.

Another way to approach risk estimation from epidemiological data is to base the calculations on observed risk ratios. In Table 5 it is assumed that air pollution increases the risk of lung cancer in the total, leading to relative risks between 1.1 and 1.5. In a western population of 1 million, about 300 male and female lung cancers are diagnosed annually. In case air pollution caused a relative risk of 1.1, 30 excess cases of lung cancer would appear annually per population of 1 million. If the relative risk were 1.5, 150 air pollution-related cases would be caused. Because the relative risks of lung cancer associated with air pollution range between 1.0 and 1.5 in the epidemiological studies, it may be an important factor in the causation of cancer if sites other than the lung also are considered.

Conclusions

Epidemiological studies performed during the last few decades seem to indicate that urban residents have a smoking-adjusted increase in lung cancer up to 1.5 times that of the countryside residents. While more studies were carried out on men, the studies including women were consistent with such a risk. In some studies effects were seen only among smokers, and some studies suggested that smoking had a multiplicative interaction with air pollution. Whether the excess risk of lung cancer can be attributed to urban air pollution cannot be determined conclusively, but it is suggested that it at least contributes to the risk. There may be positive confounding in the urban environment by lifestyle factors other than smoking in the urban environment. However, it should be pointed out that negative confounding also is likely in cases such as higher residential radon concentrations in rural homes and more frequent domestic wood and coal burning in the countryside. Additionally, studies on occupations involving exposure to diesel exhaust add further support to a causative role of urban air pollution in lung cancer. It is by no means excluded that urban air can contribute to risks of cancers at sites other than lung.

The spectrum of carcinogens in urban air has changed extensively and continues to change. It is difficult to predict how much the current urban air pollution can contribute to the future risk of cancer. Extrapolations based on the present-day concentrations of pollutants and the unit cancer risks obtained from occupational epidemiological studies are applicable only for a few carcinogens because of the sparcity of epidemiological data. Such calculations have drawbacks because they do not usually consider interactions. They also are not wholly justified as the pollutants. Although chemically similar, they may not be present in the same physical form in the urban air than they were in the occupational environments. Such calculations were done for seven compounds, and they resulted in 2.5 urban air-related cancer cases/year/10^6 inhibatants.

This figure is an underestimate of the total cancer risk, but it may give a relative order of importance for lung cancer risk of these seven agents. Further epidemiological data that use more detailed exposure information are necessary to reduce the uncertainties in the risk estimations.

REFERENCES

1. WHO Office for Europe. Air Quality Guidelines for Europe. European Series Vol 23. Copenhagen:World Health Organization Regional Publications.
2. Tomatis L. Air Pollution and Human Cancer. Berlin:Springer, 1990.
3. Pershagen G, Simonato L. Epidemiological evidence on air pollution and cancer. In: Air Pollution and Human Cancer (Tomatis L, ed). Heidelberg:Springer-Verlag, 1990;63–74.
4. Jedrychowski W, Becher H, Wahrendorf J, Basa-Cierpialek Z. A case-control study of lung cancer with special reference to the effect of air pollution in Poland. J Epidemiol Commun Health 44:114–120 (1990).
5. Haenszel W, Taeuber KE. Lung cancer mortality as related to residence and smoking histories: white females. J Natl Cancer Inst 32:803–838 (1964).
6. Haenszel W, Loveland DB, Sirken MG. Lung cancer mortality as related to residence and smoking histories: white males. J Natl Cancer Inst 28:947–1001 (1962).
7. Dean G. Lung cancer and bronchitis in Northern Ireland. Br Med J 1:1506–1514 (1966).
8. Vena JE. Air pollution as a risk factor in lung cancer. Am J Epidemiol 116:42–56 (1982).
9. Buell P, Dunn JE, Breslow L. Cancer of the lung and Los Angeles type air pollution. Cancer 20:2139–2147 (1967).
10. Stocks P, Campbell J. Lung cancer death rates among non-smokers and pipe and cigarette smokers. Br Med J 2:923–929 (1955).
11. Lyon JL, Gardner JW, West DW. Cancer risk and life style; cancer among Mormons from 1967–1975. In: Cancer Incidence in Defined Populations (Cairns J, Lyon JL, Skonick M, eds). New York:Cold Spring Harbor Laboratory, 1980;3–30.
12. Ehrenberg L, von Bahr B, Ekman G. Register analysis of measures of urbanization and cancer incidence in Sweden. Environ Int 11:393–399 (1985).
13. IARC. Monographs on the Evaluation of Carinogenic Risks to Humans: Diesel and Gasoline Engine Exhausts and Some Nitroarenes, Vol 46. Lyon:International Agency for Research on Cancer, 1989.
14. Bofetta P, Stellman SD, Garfinkel L. Diesel exhaust exposure and mortality among males in the American Cancer Society prospective study. Am J Ind Med 14:403–415 (1988).
15. Bofetta P, Harris RE, Wynder EL. Case-control study on occupational exposure to diesel exhaust and lung cancer risk. Am J Ind Med 17:577–591 (1990).
16. Gustavsson P, Plato N, Lidström E-B, Hogstedt C. Lung cancer and exposure to diesel exhaust among bus garage workers. Scand J Work Environ Health 16:348–354 (1990).
17. Steenland NK, Silverman DT, Hornung RW. Case-control study

of lung cancer and truck driving in the teamsters union. Am J Publ Health 80:670–674 (1990).
18. Rafnsson V, Gunnarsdottir H. Mortality among professional drivers. Scand J Work Environ Health 17:312–317 (1991).
19. U.S. EPA. Cancer Risk from Outdoor Exposure to Air Toxics, Vol 1. Research Triangle Park, NC:United States Environmental Protection Agency, 1989;450–451.
20. Boström C-E, Almén J, Steen B, Westerholm R. Human exposure to urban air pollution. Environ Health Perspect 102(Suppl 4):39–47 (1994).
21. U.S. EPA. The Total Exposure Assessment Methodology (TEAM) Study: Summary and Analysis. Washington:United States Environmental Protection Agency, 1987.
22. Hemminki K. Measurement and monitoring of individual exposures. In: Air Pollution and Human Cancer (Tomatis L, ed). Berlin:Springer, 1990;33–47.
23. Hemminki K. Environmental carcinogens. In: Handbook of Experimental Pharmacology (Cooper CS, Grover PL, eds). Heidelberg:Springer-Verlag, 1990;31–61.
24. United States Department of Health and Human Services. Toxicological profile for polycyclic aromatic hydrocarbons TP-90-20. Washington, 1990.
25. Hammond EC, Horn D. Smoking and death rates: report on forty-four months of follow-up of 187,783 men. J Am Med Assoc 166:1294–1308 (1958).
26. Hammond EC. Smoking habits and air pollution in relation to lung cancer. In: Environment Factors in Respiratory Disease (Lee D, ed). New York:Academic Press, 1972;177–198.
27. Cederlöf R, Friberg L, Hrubec Z, Lorich U. The relationship of smoking and some social covariables to mortality and cancer morbidity. Stockholm:Department of Environmental Hygiene, The Karolinska Institute, 1975.
28. Doll R, Peto R. The causes of cancer: quantitative estimates of avoidable risks of cancer in the United States today. J Natl Cancer Inst 66:1191–1308 (1981).
29. Tenkanen L, Teppo L. Migration, marital status and smoking as risk determinants of cancer. Scand J Soc Med 15:67–72 (1987).
30. Hitosugi M. Epidemiological study of lung cancer with special reference to the effect of air pollution an smoking habit. Bull Inst Publ Health 17:236–255 (1968).
31. Dean G, Lee PN, Todd GF, Wicken AJ. NLM report on a second retrospective mortality study in north-east England. Part 1. London:Tobacco Research Council, 1977.
32. Dean G, Lee PN, Todd GF, Wicken AJ. NLM report on the second retrospective mortality study in north-east England. Part 2. London:Tobacco Research Council, 1978.
33. Pike MC, Jing JS, Rosario IP, Hendersson BE, Mench HR. Occupation: explanation of an apparent air pollution related localized excess of lung cancer in Los Angeles County. In: Energy and Health (Breslow L, Shittermore A, eds). Philadelphia, PA: SIAM–SIMS Conference Series, 1979; 3–16s.
34. Samet JM, Humble CG, Skipper BE, Pathak DR. History of residence and lung cancer risk in New Mexico. Am J Epidemiol 125:800–811 (1987).
35. Xu ZY, Blot WJ, Ziao HP, Wu A, Feng YP, Stone BJ, Jie S, Ershow AG, Henderson BE, Fraumeni JF. Smoking, air pollution and the high rates of lung cancer in Shenyang, China. J Natl Cancer Inst 8:1800–1806 (1989).
36. Katsoyanni K, Trichopoulos D, Kalandidi A, Tomos P, Riboli E. A case-control study of air pollution and tobacco smoking in lung cancer among women in Athens. Prev Med (in press).