ABSTRACT

Objective: Determine the risk of premature mortality due to the urban ambient air pollution mix in Canada.

Methods: The number of daily deaths for non-accidental causes were obtained in 11 cities from 1980 to 1991 and linked to concentrations of ambient gaseous air pollutants using relative risk regression models for longitudinal count data.

Results: Nitrogen dioxide had the largest effect on mortality with a 4.1% increased risk (p<0.01), followed by ozone at 1.8% (p<0.01), sulphur dioxide at 1.4% (p<0.01), and carbon monoxide at 0.9% (p=0.04) in multiple pollutant regression models. A 0.4% reduction in premature mortality was attributed to achieving a sulphur content of gasoline of 30 ppm in five Canadian cities, a risk reduction 12 times greater than previously reported.

Conclusions: Ambient air pollution generated from the burning of fossil fuels is a risk factor for premature mortality in 11 Canadian cities.

ABRÉGÉ

Objectif : Évaluer le risque de décès prématuré dû aux divers polluants atmosphériques dans les villes au Canada.

Méthodes : On a déterminé le nombre quotidien de décès non accidentels dans 11 villes entre 1980 et 1991 et établi un lien entre les concentrations de polluants gazeux dans l'atmosphère au moyen de modèles de régression du risque relatif pour des données longitudinales.

Résultats : Le dioxyde d'azote avait l'influence la plus marquée sur la mortalité, se traduisant par une majoration du risque de l'ordre de 4,1 % (p<0,01); venaient ensuite l'ozone, 1,8% (p<0,01), l'anhydride sulfureux, 1,4% (p<0,01) et le monoxyde de carbone, 0,9% (p=0,04), dans des modèles de régression portant sur plusieurs polluants. Dans cinq villes canadiennes, une réduction des décès prématurés de l'ordre de 0,4% a été attribuée par obtenu une teneur en soufre d'essence de 30 mg/L, l'importance du risque étant 12 fois plus élevée que ce qu'on avait signalé auparavant.

Conclusions : La pollution atmosphérique engendrée par la combustion des carburants fossiles est un facteur de risque de décès prématuré dans les villes canadiennes.

The Effect of the Urban Ambient Air Pollution Mix on Daily Mortality Rates in 11 Canadian Cities

Richard T. Burnett, PhD,[1] *Sabit Cakmak*, PhD,[1] *Jeffrey R. Brook*, PhD[2]

It has long been recognized that exposure to ambient air pollutants generated from the combustion of fossil fuels can have adverse health effects.[1] Western countries, including Canada, set stringent ambient air quality objectives, guidelines, and regulations in order to protect both the general population and those thought to be most at risk (children, the elderly, and those with pre-existing cardio-respiratory disease).[2] Ambient air pollution levels have declined in Canada due, in part, to these regulatory efforts.[3]

A series of new studies over the past decade have demonstrated a link between ambient air pollution and several adverse human health effects even at the lower concentrations typically observed in North America and Europe today,[4] suggesting that air pollution may still pose a risk to public health.

Several efforts have been made to assess the public health effects of selected programs to reduce air pollution in Canada[5,6] and the United States.[7,8] Much of the evidence, however, is based on the effects of PM_{10} (particulate mass less than 10 µm in average diameter) or $PM_{2.5}$ (particulate mass less than 2.5 µm in average diameter) on U.S. and European populations. The effects on human health of gaseous air pollutants, such as ozone, nitrogen dioxide, sulphur dioxide, and carbon monoxide, are not as well established.

Estimates of the reduction in risk of adverse health outcomes, such as premature mortality and hospitalization, have been almost entirely attributed to reductions in PM_{10} or $PM_{2.5}$,[5-8] although reductions in gaseous pollutants have been predicted to be greater than in particulate matter alone.[6] The purpose of the present investigation was to determine the risk of premature mortality due to exposure to mixtures of gaseous ambient air pollutants in 11 Canadian cities. Our methods are illustrated using the example of estimating the reduction in mortality risk attributable to reductions in several ambient air pollutants due to achieving a 30 ppm concentration of sulphur in gasoline by 2020.

METHOD

The number of deaths for non-accidental causes (ICD9 codes 1-799) were obtained for the 4,383 days from January 1, 1980 to December 31, 1991 in 11 Canadian cities (Table I). The 24-hour average concentrations of ozone, nitrogen dioxide, carbon monoxide, and sulphur dioxide were also obtained for the same period. Data were averaged over all monitoring stations in each city. Missing values were imputed using regression models containing month of study and day of week.

Since we are interested in the acute effects of air pollution on mortality, time series of daily counts of deaths were pre-filtered to remove city-specific long-term trends (mortality increases with increasing population), seasonal (mortality rates are higher in the winter than summer) and sub-seasonal (short-term epidemics) cycles using non-parametric smoothed functions of day of study,[9] and day of the week effects (mortality rates tend to be slightly

1. Environmental Health Directorate, Health Canada
2. Atmospheric Environment Service, Environment Canada

Correspondence and reprint requests: Richard T. Burnett, PhD, Environmental Health Directorate, Health Canada, 203 Environmental Health Centre, Tunney's Pasture, Ottawa, ON, K1A 0L2 Tel: 613-952-1364, Fax: 613-941-4546, E-mail: rick_burnett@hc-sc.gc.ca

lower on Sundays). City-specific weather effects recorded on the day of death and one and two days prior to death (daily one-hour maximum and minimum temperature, daily average dew point and relative humidity) were also removed from the time series using non-parametric smoothed functions. A minimal set of the 12 weather predictors (4 variables and 3 time lags) were selected using forward inclusion stepwise regression methods with Akaike's Information Criteria[10] as the selection method for each city separately.

The relative risk of death attributable to each pollutant and city separately were determined using generalized additive models for longitudinal count data[10] for single, two-day and three-day averages of the pollutant concentrations lagged zero, one, and two days. A single averaging time and days lagged was selected for each pollutant and city based on the largest relative risk (Table II). City-specific regression models containing all four pollutants were examined. Summary risks were obtained by averaging risks among cities.

RESULTS

There were 816,991 deaths for non-accidental causes between 1980 and 1991 in the 11 Canadian cities comprising a population of 10.8 million people based on the 1986 census. Air pollution concentrations varied among the locations with no region having uniformly higher or lower levels of all pollutants (Table I). Day-to-day variations in ozone were negatively correlated with nitrogen dioxide (average correlation of -0.1 and range of -0.5 in Calgary to 0.2 in Hamilton), sulphur dioxide (average correlation of -0.2 and range of -0.3 in Montreal to 0.0 in Quebec), and carbon monoxide (average correlation of -0.3 and range of -0.6 in Edmonton and Calgary to 0.0 in Windsor). Carbon monoxide and nitrogen dioxide were highly correlated (average correlation of 0.5 and range of 0.4 in Windsor to 0.7 in Edmonton). Nitrogen dioxide and sulphur dioxide were also positively correlated (average correlation of 0.3 and range of 0.1 in Edmonton to 0.5 in Toronto), as were carbon monoxide and sulphur dioxide (average correlation of 0.3 and range of 0.1 in Edmonton to 0.7 in Montreal).

TABLE I
City-specific Summary Statistics for Population, Daily Mortality Rates and Daily Average Air Pollution Concentrations, 1980-1991

City	Census Division Code	Population* ($x 10^5$)	Mortality Rate/Day	CO† (ppm)‡	NO_2† (ppb)¶	SO_2† (ppb)	O_3† (ppb)
Quebec	24-20,21	5.7	9.4	0.9	24.1	10.1	14.1
Montreal	24-56,64,65, 66,78,79	24.6	46.1	1.0	24.3	7.2	14.1
Ottawa	35-06	8.0	11.6	1.2	22.3	4.4	14.0
Toronto	35-19,20	31.4	50.6	1.5	26.4	4.8	14.8
Hamilton	35-25	4.2	8.5	0.9	23.1	10.5	17.8
London	35-39	3.3	6.6	0.4	20.8	4.0	20.5
Windsor	35-37	3.2	6.7	0.9	27.0	7.9	18.5
Winnipeg	46-11	5.9	12.0	0.6	14.1	0.7	17.9
Edmonton	48-11	7.2	9.8	1.2	26.7	1.6	16.1
Calgary	48-06	8.1	8.6	1.3	27.5	2.6	17.6
Vancouver	59-11,15	14.0	26.6	1.3	22.5	5.2	12.3
Average		9.9	17.9	1.0	23.5	5.4	16.2

* Based on 1986 census.
† CO - carbon monoxide, NO_2 - nitrogen dioxide, SO_2 - sulphur dioxide, O_3 - ozone.
‡ ppm - parts per million.
¶ ppb - parts per billion.

TABLE II
Percentage Increased Risk of Death Attributable to Change in Study Mean Air Pollution Concentrations Examined Separately by City, 1980-1991

City	Ambient Air Pollutants			
	CO	NO_2	SO_2	O_3
Quebec	2.1 $^{(2,0)}$*	5.4 $^{(2,0)}$	0.4 $^{(2,1)}$	3.1 $^{(1,0)}$
	(2.3)†	(5.2)	(2.1)	(3.3)
Montreal	5.0 $^{(3,0)}$	6.3 $^{(3,0)}$	2.4 $^{(3,0)}$	3.3 $^{(2,0)}$
	(7.8)	(7.9)	(11.7)	(7.4)
Ottawa	1.8 $^{(2,0)}$	3.1 $^{(1,1)}$	1.3 $^{(3,0)}$	1.1 $^{(1,0)}$
	(2.0)	(2.5)	(2.4)	(1.2)
Toronto	2.2 $^{(1,1)}$	3.8 $^{(2,0)}$	1.2 $^{(2,1)}$	1.1 $^{(2,0)}$
	(4.9)	(5.3)	(4.5)	(2.3)
Hamilton	2.6 $^{(2,0)}$	4.7 $^{(1,0)}$	1.3 $^{(2,0)}$	2.6 $^{(1,0)}$
	(2.2)	(4.0)	(3.1)	(3.2)
London	1.9 $^{(2,1)}$	9.9 $^{(3,0)}$	1.6 $^{(1,1)}$	1.3 $^{(1,1)}$
	(1.3)	(5.1)	(2.6)	(1.3)
Windsor	1.8 $^{(3,2)}$	1.2 $^{(3,2)}$	0.1 $^{(2,0)}$	1.6 $^{(1,2)}$
	(1.5)	(0.6)	(0.2)	(1.6)
Winnipeg	4.4 $^{(2,0)}$	7.3 $^{(2,1)}$	2.6 $^{(3,2)}$	0.2 $^{(1,0)}$
	(2.6)	(4.6)	(1.2)	(0.1)
Edmonton	0.4 $^{(3,2)}$	0.6 $^{(1,2)}$	2.7 $^{(2,0)}$	0.7 $^{(1,1)}$
	(0.5)	(0.5)	(1.6)	(0.6)
Calgary	3.0 $^{(2,0)}$	8.2 $^{(2,0)}$	4.2 $^{(2,0)}$	-1.6 $^{(1,0)}$
	(3.7)	(5.2)	(4.3)	(-1.5)
Vancouver	2.0 $^{(3,0)}$	7.7 $^{(2,1)}$	1.5 $^{(3,0)}$	1.8 $^{(1,0)}$
	(4.3)	(7.0)	(3.2)	(2.2)
Average	2.5	5.3	1.8	1.4
	(6.4)	(6.0)	(5.0)	(3.3)

* (number of days air pollution levels averaged, number of days levels recorded prior to death).
† t-ratio - ratio of risk to standard error, value for Average obtained from variation among cities.

City-specific relative risks of mortality evaluated at the study averages (in order to compare risks among cities) are given in Table II based on single pollutant models. Relative risks vary among cities with little consistency within regions of Canada, except for low ozone risks in Winnipeg, Edmonton, and Calgary. Carbon monoxide risks were most consistent between cities, based on the t-ratio (T) of the mean risk which is 6.4 (ratio of average risk to standard error among cities). The risks varied most for ozone (T=3.3).

When the four pollutants were examined simultaneously (Table III), a different pattern emerged. The average risk for carbon monoxide was 0.9% (T=1.9; p=0.04, one-sided test), for sulphur dioxide 1.4% (T=3.9; p<0.01), and for nitrogen dioxide 4.1% (T=3.9; p<0.01). These risks decreased compared to estimates based on single pollutant models, while the ozone

TABLE III
Percentage Increased Risk of Death Attributable to Change in Study Mean Air Pollution Concentrations Examined Simultaneously by City, 1980-1991

City	Ambient Air Pollutants				
	CO	NO_2	SO_2	O_3	All Pollutants
Quebec	1.4	5.2	0.4	4.2	11.2
Montreal	2.2	0.0	2.1	3.9	8.2
Ottawa	0.2	3.3	1.0	0.8	5.3
Toronto	1.3	2.1	0.7	1.6	5.7
Hamilton	2.0	3.5	1.2	2.4	9.1
London	-2.9	10.6	1.1	1.3	10.1
Windsor	1.8	0.0	0.2	1.6	3.6
Winnipeg	3.2	5.6	2.6	0.6	12.0
Edmonton	1.1	0.2	3.3	1.0	5.6
Calgary	-0.1	6.6	2.9	0.6	10.0
Vancouver	0.0	7.5	-0.3	1.8	9.0
Average	0.9	4.1	1.4	1.8	8.2
	(1.9; 0.04)*	(3.9; <0.01)	(3.9; <0.01)	(4.8; <0.01)	(9.9; <0.01)

* t-ratio - ratio of average risk to standard error obtained from variation in risks among cities; one-sided p-value

TABLE IV
Percentage Increased Risk of Death Attributable to City-specific Change in Air Pollution Concentrations Examined Simultaneously by City, 1980-1991

City	Ambient Air Pollutants				
	CO	NO_2	SO_2	O_3	All Pollutants
Quebec	1.2	5.4	0.8	3.6	11.0
Montreal	2.1	0.0	2.9	3.4	8.4
Ottawa	0.2	3.1	0.8	0.7	4.8
Toronto	2.0	2.4	0.6	1.5	6.5
Hamilton	1.8	3.5	2.3	2.7	10.3
London	-1.2	9.4	0.8	1.6	10.6
Windsor	1.5	0.0	0.2	1.9	3.6
Winnipeg	2.0	3.4	0.3	0.7	6.4
Edmonton	1.3	0.3	1.0	1.0	3.6
Calgary	-0.1	7.7	1.4	0.7	9.7
Vancouver	0.0	7.2	-0.3	1.4	8.3

TABLE V
Predicted Reductions in Ambient Concentrations of Air Pollutants for 30 ppm Sulphur Concentration in Gasoline in 2020

City	Ambient Air Pollutants				
	Sulphates (μg/m³)	$PM_{2.5}$ (μg/m³)	CO (ppm)	NO_2* (ppb)	SO_2 (ppb)
Montreal	0.11	0.09	0.03	0.86	0.67
Toronto	0.38	0.32	0.07	1.71	1.55
Winnipeg	0.02	0.02	0.01	0.48	0.35
Edmonton	0.05	0.04	0.02	0.79	0.54
Vancouver	0.11	0.10	0.03	1.30	1.01

* Predicted reductions given for NO_x , converted to NO_2 by dividing NO_x by 2.

risk increased due to the correlation structure among the pollutants. It appears that sulphur dioxide and nitrogen dioxide are explaining much of the carbon monoxide effect on mortality. When the data were reanalyzed with carbon monoxide removed from the multiple pollutant model, the average risk for nitrogen dioxide was 4.6% (T=5.0; p<0.01), for sulphur dioxide 1.5% (T=4.0; p<0.01), and for ozone 1.7% (T=4.6; p<0.01), with the average risk for all three pollutants combined of 7.7% (T=8.0; p<0.01).

In order to examine the impact of air pollution on mortality in each location, city-specific relative risks evaluated at the city-specific mean air pollutant concentrations are given in Table IV. Edmonton and Windsor were the least impacted by air pollution with a relative risk for all four pollutants combined of 3.6% while Quebec was the most impacted city (11.0%). Note that different pollutants contribute to the overall risk differently in each city with no consistent pattern within regions.

To illustrate the use of multiple pollutant relative risk models for mortality, consider the scenario of reducing the sulphur content in gasoline. A multi-stakeholder committee was established to assess the public health benefits and industry-related costs of reducing sulphur in gasoline[6] in several Canadian cities. Five of the cities examined were included in our study (Montreal, Toronto, Winnipeg, Edmonton, and Vancouver). We considered the most stringent scenario of reducing the sulphur content in gasoline from present levels down to 30 ppm. Two time frames were also examined, 2001 and 2020 with greater reductions in concentrations predicted for 2020. We selected the 2020 period for our illustrative analysis. Predicted reductions in particulate sulphates, $PM_{2.5}$, carbon monoxide, sulphur dioxide and nitrogen dioxide for the five cities are given in Table V (ozone reductions were negligible and not considered although risk models did include ozone).[11]

The Health and Economics Assessment Panel[12] used sulphate as a marker for the pollution mix due to the number of studies which have related particulate sulphate to a variety of health outcomes. The Panel noted, however, that the use of any single pollutant to represent the total risk of the mix may result in underestimates of the health benefits due to air pollution reductions. An increase in particulate sulphate of 10 μg/m³ was associated with a 2.2% increase in non-accidental mortality based on a study of mortality rates in 6 U.S. cities.[13] We note that the risk of a change in $PM_{2.5}$ of 10 μg/m³ was 1.5% from the same study.

The percentage reduction in daily mortality rates due to reductions in air pollution concentrations given in Table V are displayed in Table VI for five cities. Reductions in risk due to reductions in concentration of the mix of carbon monoxide, sulphur dioxide, and nitrogen dioxide averaged among the five cities were 12 times greater than that for particulate sulphate and 19 times greater than for $PM_{2.5}$. In fact, each one of the pollutants in the multiple pollutant model had an average risk greater than that attributable to sulphate or $PM_{2.5}$.

DISCUSSION

Exposure to ambient air pollutants generated from the combustion of fossil fuels poses a public health risk to Canadians. Risk of premature mortality was shown to be attributable to a mixture of gaseous air pollutants with positive risks detected in all 11 Canadian cities examined.

Exposure to both $PM_{2.5}$ and PM_{10} have been related to daily variations in mortality rates in a number of studies worldwide.[4] Daily measures of these pollutants were not available for analysis, however, and thus could not be included in the multiple pollutant models. Exposure to $PM_{2.5}$ or PM_{10} has been shown not to improve the predictive power of the air pollution mix on cardiorespiratory hospitalizations[14] or nonaccidental mortality[15] in Toronto. Mortality risks, based on single pollutant models, are plotted against mean concentrations of $PM_{2.5}$ in 8 of the 11 cities examined (not including Quebec, Hamilton and London) in Figure 1. [Every sixth day, $PM_{2.5}$ measurements were collected using a dichotomous sampler by Environment Canada[16]]. City-specific mortality risks due to either carbon monoxide or nitrogen dioxide exposure do not appear to be dependent on the city-specific average concentrations of $PM_{2.5}$ (Figure 1). However, the risks associated with sulphur dioxide exposure are greater in those cities with lower $PM_{2.5}$ levels, while ozone risks increase with increasing concentrations of $PM_{2.5}$. Thus $PM_{2.5}$ may act as a potential confounder for these latter two pollutants. There is no apparent association, however, between the total risk of the air pollution mix, based on multiple pollutant models and $PM_{2.5}$ concentrations (plot not shown), suggesting that the four gaseous pollutants can adequately explain daily variations in mortality rates and that the addition of $PM_{2.5}$ is unlikely to add any additional predictive power.

There is a large body of epidemiological evidence that has related selected measures of particulate matter, such as $PM_{2.5}$, PM_{10} and particulate sulphates, to a number of health outcomes, including increased respiratory symptoms, lost school and work time, restricted activity, asthma attacks, emergency room visits, hospital admissions, and death.[4] The Health and Economics Assessment Panel[12] used particulate sulphate as a marker for the air pollution mix. Sulphates were selected since they have been related to a number of health outcomes and predicted reductions in sulphates were greater than for $PM_{2.5}$ due to reductions in the sulphur content of gasoline. We relied on estimates of the sulphate risk on mortality obtained from time series studies that were used by the Panel since daily concentrations of particulate sulphate were not available in the present study. The effect of using estimates of risk based on a mixture of atmospheric pollutants (i.e., sulphur dioxide, nitrogen dioxide, and carbon monoxide) was compared to that obtained from a single marker of the mix (sulphates).

TABLE VI
Percentage Reductions in Risk of Death Attributable to Predicted Reductions in Ambient Air Pollution for a 30 ppm Sulphur Concentration in Gasoline in 2020 by City

City	Model Specification					
	Single Pollutant		Multiple Pollutants			
	Sulphate	$PM_{2.5}$	CO	NO_2	SO_2	Total*
Montreal	0.02	0.01	0.07	0.00	0.27	0.34
Toronto	0.08	0.05	0.09	0.15	0.20	0.44
Winnipeg	0.00	0.00	0.05	0.12	0.17	0.33
Edmonton	0.01	0.01	0.02	0.01	0.33	0.36
Vancouver	0.02	0.02	0.0	0.42	-0.06	0.35
Average	0.03	0.02	0.05	0.14	0.18	0.37

* Sum of risks for carbon monoxide, nitrogen dioxide, and sulphur dioxide.

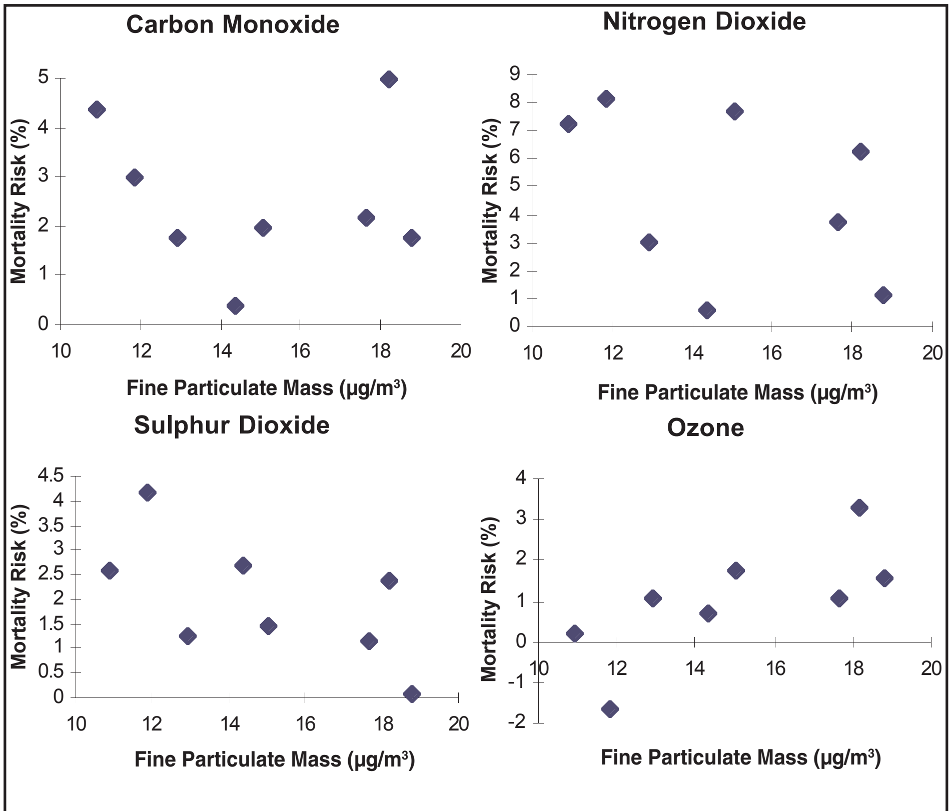

Figure 1. Percent change in mortality rates for gaseous pollutants plotted against city average fine particulate mass ($PM_{2.5}$) concentrations for eight Canadian cities.

Although air pollution mitigation strategies have been designed, in part, to reduce ambient levels of $PM_{2.5}$ or PM_{10},[5,6] levels of several gaseous pollutants were also predicted to be reduced.[6] The improvement in public health associated with these gaseous pollutant reductions may be much larger than that predicted by either $PM_{2.5}$ or PM_{10}, as in the example of sulphur reductions in gasoline.

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