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Associations between cigarette smoking, obesity, sociodemographic characteristics and remote-sensing-derived estimates of ambient $PM_{2.5}$: results from a Canadian population-based survey

Paul J Villeneuve,[1,2] Mark S Goldberg,[3,4] Richard T Burnett,[1] Aaron van Donkelaar,[5] Hong Chen,[6] Randall V Martin[5,7]

[1]Population Studies Division, Health Canada, Ottawa, Ontario, Canada
[2]Division of Occupational and Environmental Health, Dalla Lana School of Public Health, University of Toronto, Toronto, Ontario, Canada
[3]Department of Medicine, McGill University, Montreal, Quebec, Canada
[4]Division of Clinical Epidemiology, Research Institute, McGill University Health Center, Montreal, Quebec, Canada
[5]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada
[6]Department of Epidemiology and Biostatistics, McGill University, Montreal, Quebec, Canada
[7]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA

Correspondence to
Dr Paul J Villeneuve, Population Studies Division, Health Canada, 50 Columbine Driveway, Room 165, PL0801A, Ottawa, ON K1A 0K9, Canada;
paul_villeneuve@hc-sc.gc.ca

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ABSTRACT

Objectives Long-term exposure to ambient fine particles ($PM_{2.5}$) has been shown to increase mortality. Variables measured on the same spatial scales of air pollution may confound associations, and so the authors' objectives were to evaluate the associations between $PM_{2.5}$ and individual-level measures of smoking, obesity and sociodemographic status. The authors present an approach to evaluate the impact that uncontrolled confounding from smoking may have on associations between $PM_{2.5}$ and mortality.

Methods Individual-level behavioural and sociodemographic data were obtained from a 2003 national survey of 122 548 Canadians. Estimates of ground-level $PM_{2.5}$ at a resolution of 10×10 km between 2001 and 2006 were derived from satellite remote sensing. Exposures were assigned to the residence of the participants at the time of the survey. Differences in the prevalence of smoking across concentrations of $PM_{2.5}$ and RRs drawn from the literature were used to model the bias on rate ratios.

Results Participants in areas with higher concentrations of $PM_{2.5}$ had a higher income and educational attainment, smoked less and were more likely immigrants. Smoking had a negative confounding effect on the associations between $PM_{2.5}$ and mortality. To compensate for this bias, for a 10 $\mu g/m^3$ increase in $PM_{2.5}$, mortality from lung cancer and heart disease in the referent exposure group needed to be increased by 6.9% and 3.2%, respectively.

Conclusions Associations were found between sociodemographic and lifestyle characteristics and $PM_{2.5}$ at a resolution of 10×10 km. The authors present a model to adjust for uncontrolled confounding of smoking that can be readily adapted to exposures measured at different spatial resolutions.

What this paper adds

- Long-term exposure to higher levels of ambient air pollution is associated with increased mortality, and other variables measured on the same scale as air pollution may confound the risk estimates.
- We present an approach to evaluate the impact that uncontrolled confounding from smoking may have on associations between $PM_{2.5}$ and mortality in Canada.
- Ground-level $PM_{2.5}$ measured at a resolution of 10 km×10 km was negatively correlated with the prevalence of cigarette smoking among Canadians.
- The inability to take into account cigarette smoking results will understate the risk of mortality from $PM_{2.5}$ (measured on a 10 km×10 km area) among Canadians by up to 7%.

INTRODUCTION

It is well recognised that higher concentrations of ambient air pollution adversely affect human health. Several cohort studies, mostly in the USA and Europe, have shown that long-term exposure to fine particulate matter ($PM_{2.5}$) is associated with premature non-accidental mortality.[1–8] Increased risks of mortality have typically been observed for cardiovascular disease, non-malignant respiratory disease, lung cancer, as well as all natural causes combined.[9]

The characterisation of exposure and disease-specific risk factors over a period that spans decades is a key challenge for epidemiological studies that investigate health effects from long-term exposure to ambient air pollution. However, detailed analyses of two prominent cohort studies suggested that risk estimates derived from baseline concentrations of air-pollution exposure levels did not differ substantially from those estimated for other periods of exposure.[10 11] Most cohort studies of ambient $PM_{2.5}$ have been constrained, to varying degrees, by an inability to control for the potential confounding effects of other risk factors. For example, risk-factor data are sometimes captured at only one point in time, or individual-level data are lacking; in some studies ecological or surrogate-based measures had to be used.[8 12 13] For the mortality endpoints commonly studied, the impact of some risk factors, especially smoking, are believed by some pundits to dominate any effects that could be attributed to ambient air pollution.[14 15] This limitation has been highlighted by some to introduce an important source of bias when estimating mortality risks from exposure to ambient air pollution.[16 17] As duly noted by Pope's response[18] to these commentaries, these uncontrolled factors can produce either an upward or downward bias on the risk estimates

depending on the spatial nature of their association with ambient pollution. Just as important are the findings in some studies that levels of ambient pollution are unrelated to smoking,[6 12] and therefore, smoking behaviours may not exert any influence on the risks attributed to air pollution. Indeed, such a pattern was observed in Dockery *et al*'s Harvard Six Cities Study[6] where the rate ratio comparing the most polluted city (Steubenville, Ohio) with the least polluted one (Portage, Wisconsin) barely changed from 1.31 to 1.29 after adjusting for smoking. In contrast, Pope *et al* observed that controlling for cigarette smoking behaviours served to attenuate the risk of lung-cancer mortality in the American Cancer Society (ACS) Cancer Prevention Study-II (CPS II) study; specifically the RR associated with a 10 $\mu g/m^3$ increase in $PM_{2.5}$ decreased from 1.13 to 1.06 after adjusting for smoking.[7] These differential impacts of smoking on ambient pollution risks underscore the importance of examining correlations between ambient pollution and smoking behaviours in different target populations; indeed it seems clear that the magnitude of confounding, as in all epidemiological studies, will depend on the correlations within the study population.

In this study, we examined the relationships between spatially derived ambient levels of $PM_{2.5}$ and socio-demographic and lifestyle-related risk factors of physical activity, body mass index (BMI) and smoking using data from a nationally representative health survey of Canadians. We undertook this study to understand the impact that unmeasured confounders, particularly smoking, may have on the rate ratios for mortality in two retrospective Canadian cohorts. These cohorts were constructed using administrative data from the mandatory long-form 1991 Canadian Census,[19] and from income-tax filings of Ontario residents.[20] Both of these cohorts lack information on behavioural risk factors, including smoking, that are relevant to the study of mortality outcomes. A secondary objective of this study was to evaluate whether individuals of lower socioeconomic status were more likely than those of greater affluence to live in areas with higher levels of $PM_{2.5}$. Such information could prove valuable in assisting with the development of ambient air pollution regulations at an interurban scale to help mitigate health effects of exposure in vulnerable populations. To our knowledge, no population-based study has examined associations between ambient air pollution and individual-level socio-demographic characteristics using estimates of concentrations of air pollution that cover most of Canada.

METHODS

Study population

We used data obtained from participants of the 2003 Canadian Community Health Survey (CCHS) (Cycle 2.1).[21] In this cross-sectional survey, information on health status, healthcare utilisation and determinants of health for the Canadian population was collected. The survey covered the non-institutionalised Canadian population that was 12 years of age and older in all provinces and territories, and excluded individuals living on Indian Reserves, Crown Lands, institutional residents, full-time members of the Canadian Forces and residents of certain remote regions. The estimated coverage of the sampling frame was 98% of the target population. Data were collected from 127 610 individuals who completed the survey between January 2003 and December 2003. The response rate was estimated to be 80.7%.[21]

Our analyses make use of the six-character postal code for each participant's place of residence, thereby allowing ambient concentrations of $PM_{2.5}$ to be assigned to each participant's home address. While the primary focus of our analysis was to evaluate the association between socio-demographic and behavioural risk factor data for all participants, we carried out similar analyses for those who resided in the province of Ontario. This allows us to draw inferences for the ongoing Ontario tax-file cohort study that investigates associations between long-term exposure to ambient pollution and mortality.

Survey data

We used a variety of self-reported measures collected from participants of the 2003 CCHS including age, sex, household and personal income, highest level of educational attainment, marital status, immigrant status and length of time since immigration. We also evaluated the relationship between ambient $PM_{2.5}$ and several cigarette smoking measures such as: (1) smoking status at the time of interview; (2) responses to the question 'Have you ever smoked at least 100 cigarettes?' and (3) whether there were any restrictions on cigarette smoking in the home. For physical activity, participants were grouped into three categories based on their participation in leisure-time physical activities. These levels were determined according to activity-specific kilocalorie expenditure per kilogram per day (KKD). The levels were active (>3 KKD), moderate (1.5–3.0 KKD) and inactive (<1.5 KKD). Finally, individuals were classified according to their BMI using the categorisation adopted by the WHO.[22] These categories were: underweight (<18.5), normal (18.5 to <25), overweight (25 to 29) and obese (≥30). While our primary intent was to characterise differences in ambient concentrations $PM_{2.5}$ across levels of these variables, we also evaluated relationships with continuous forms of these variables where possible.

Ambient exposure to $PM_{2.5}$

While fixed site monitoring networks, such as Environment Canada's National Air Pollution Surveillance (NAPS) network,[23] are the most commonly used method to estimate exposure to ambient air pollution in epidemiological studies, they have important limitations. Specifically, they have limited geographical coverage and generally provide measures only in urban areas or around point or line sources of pollution. The use of remote sensing to model surface air quality has advanced considerably in recent years and overcomes many of these limitations.[24–27]

Estimating concentrations of fine particles from satellite observations

We made use of recently developed satellite-based long-term estimates of ground-level $PM_{2.5}$ for Canada. Details of the remote sensing methodology that was used to estimate ground-level ambient concentrations of $PM_{2.5}$ have been published.[28] Briefly, observations of total column aerosol optical depth were obtained from NASA's MODIS[29 30] and MISR[31] instruments onboard the Terra satellite. Aerosol optical depth is a measure of light extinction by aerosol in the atmospheric column above the surface of the Earth. The Terra satellite has a sun-synchronous orbit and encircles the earth approximately 15 times daily; each pass crosses the equator at approximately 10:30 local solar time. These satellite observations offer excellent horizontal coverage, but limited information about the vertical profile of fine particulate pollutants in the lower atmosphere. The estimation of ground-level $PM_{2.5}$ from total column aerosol optical depth was done using a conversion factor that accounts for their spatially and temporally varying relationship:

$$PM_{2.5} = \eta \times AOD$$

where AOD is the aerosol optical depth, and η is a function of factors that relate daily dry aerosol mass to satellite observations

of ambient AOD: aerosol size, aerosol type, diurnal variation, relative humidity and the vertical structure of aerosol extinction. The GEOS-Chem global chemical transport model (http://www.geos-chem.org) was used to calculate η for the time and location of each AOD observation. The GEOS-Chem model solves for the temporal and spatial evolution of aerosol and gaseous compounds by using meteorological data sets, emission inventories and equations that represent the physics and chemistry of atmospheric constituents. The modelled relationship between aerosol mass and relative humidity for each aerosol type was applied to estimate $PM_{2.5}$ for relative humidity values that correspond to surface measurements. Estimates of the long-term average exposure to $PM_{2.5}$ from 1 January 2001 to 31 December 2006 were made at a resolution of approximately 10 km×10 km. This was the period for which we had a consistent dataset of satellite observations of aerosol optical depth and of meteorological fields to drive the GEOS-Chem simulation. Multiple years increase the number of observations and reduce the random component of error in the $PM_{2.5}$ estimates. These estimates were validated with ground-based in situ measurements, and significant spatial agreement was achieved with North American measurements (r=0.77, slope=1.07, n=1057). The remote-sensing-derived concentrations of $PM_{2.5}$ were estimated to have an overall uncertainty of ±25%.

We linked these remote-sensing-derived estimates of ground-level $PM_{2.5}$ to place of residence among participants of the CCHS using the geographic coordinated for the centroid of the geographic coordinates for the six-character residential postal codes. The first three characters of the postal code are referred to as a forward sortation area (FSA). The first letter of an FSA code represents a particular 'postal district,' and which, apart from the provinces of Quebec and Ontario, corresponds to an entire province or territory. In urban areas, the six-character postal code typically indicates a specific block (one side of a street between two intersecting streets, a single building or sometimes a large-volume mail receiver). In contrast, in rural areas, the last characters are used to identify a specific rural community. For example, in the 2001 census year, there were approximately 1500 and 850 000 unique FSAs and postal codes in Canada, respectively.

Among the CCHS participants, we were unable to resolve the geographical coordinates for 735 individuals and therefore could not assign concentrations of $PM_{2.5}$. We were also unable to assign $PM_{2.5}$ values to 4324 postal codes using the remote-sensing algorithm. These rural areas were either in remote northern areas or in coastal regions where snow cover or cloud banks would not allow for ground-level $PM_{2.5}$ concentrations to be estimated. In total, estimates of concentrations of $PM_{2.5}$ were assigned to 122 548 individuals, or approximately 96% of the survey participants.

Statistical analyses

We first examined variations in ambient concentrations of $PM_{2.5}$ across Canadian provinces, as well as between rural and urban places of residence. For the latter, we made use of a variable derived by Statistics Canada that was designed to capture the rural–urban continuum. This variable is referred to as the Census Metropolitan area and Census Agglomeration Influenced Zones,[32] and comprises seven distinct categories. Metropolitan areas accounted for four of the categories and were defined on the basis of the following population sizes: 1.5 million and over, 500 000 to <1.5 million, 100 000 to <500 000, 10 000 to <100 000. The three remaining categories were used to classify census subdivisions that lie outside census metropolitan areas according to the degree of influence (ie, 'strong, moderate,' 'weak') that those areas have on them. The degree of influence of the census metropolitan areas was determined on the basis of distance, adjacency, accessibility, and commuter flows and place of work.[32]

We used linear regression to obtain estimates of the mean concentrations of $PM_{2.5}$ and corresponding 95% CIs. These estimates were calculated across the different categories of the socio-demographic and behavioural risk factors under study and were adjusted for the potential confounding influence of age and sex. In addition, stratified analyses were performed to characterise levels of $PM_{2.5}$ by categories of community size and metropolitan influence.

Estimating the effects of smoking on mortality for lung cancer and coronary heart disease

We then estimated the impact that differential prevalence of smoking across categories of levels of $PM_{2.5}$ would have on lung-cancer and coronary-heart-disease mortality. Estimates of smoking prevalence among CCHS participants across $PM_{2.5}$ exposure categories were obtained for current, former and never smokers. $PM_{2.5}$ exposure categories were defined by deciles of exposures based on the frequency distribution of all CCHS participants for which remote sensing estimates could be assigned. We adapted Axelson's method[33] to estimate the extent that differential smoking prevalence across exposure categories of $PM_{2.5}$ would contribute to differences in lung-cancer mortality. First, this necessitates expressing the mortality (M) in the lowest decile $PM_{2.5}$ exposure group as follows:

$$M_1 = [M_{ns} \times P_{ns}] + [M_{fs} \times P_{fs}] + [M_{cs} \times P_{cs}] \quad (1)$$

where M_1=mortality in the lowest $PM_{2.5}$ decile; P=smoking prevalence (in %); and ns, fs and cs represent never, former and current smokers, respectively. We then expressed the mortality in the lowest decile exposure group in terms of a multiple of the mortality of never smokers. Specifically:

$$\begin{aligned} M_1 &= [M_{ns} \times P_{ns}] + [M_{ns} \times P_{fs} \times RR_{fs}] + [M_{ns} \times P_{cs} \times RR_{cs}] \\ &= k_0 \times M_{ns} \end{aligned} \quad (2)$$

where RR_{fs}, and RR_{cs} are the RR of lung cancer mortality among former and current smokers, respectively, relative to never smokers. An advantage of our method is that it allows for any values of the RRs of current and former smokers to be specified.

We used the RRs to express the mortality in the lowest $PM_{2.5}$ exposure group as a function of the mortality among never smokers, through the multiplier k_0. For each of the other nine categories of $PM_{2.5}$, we similarly expressed the mortality as a function of the mortality in never smokers (k_1, k_2, … k_9). This allowed us to calculate the percentage change in mortality in a specific $PM_{2.5}$ exposure category, relative to the lowest exposure category, that was due to differential smoking behaviours. This percentage change is a function of the derived k_is, namely, the percentage change (PC) in the mortality in exposure group i, relative to the lowest exposure group that is due to smoking:

$$PC_i = \left[\frac{k_i}{k_0} - 1\right] \times 100 \quad (3)$$

We then estimated the impact that differential smoking prevalence would have on mortality when concentrations of $PM_{2.5}$ were increased by 10 $\mu g/m^3$. This was done by estimating the slope from a simple linear regression model where the mean level of $PM_{2.5}$ in each of the deciles was modelled as the

independent variable, while the percentage change (PC_i) for each group was the dependent variable.

Estimates of rate ratios associated with smoking

We used age and sex-specific RR estimates for smoking and lung cancer from the American Cancer Society's CPS II prospective study of 1.2 million individuals.[34] The ACS CPS II provides reasonable estimates of the RRs of smoking on lung-cancer mortality for the Canadian population because of the large size of the cohort, the dominant role of cigarette smoking in the aetiology of lung cancer and a greater similarity in many cultural smoking behaviours (eg, age at initiation, quantity smoked daily) between the USA and Canada than would be expected from studies conducted in other countries. As RRs between smoking and lung cancer vary considerably by age and sex, we weighted these published age- and sex-specific RRs from the ACS study[34] by the underlying age and sex distributions of participants of the CCHS. This yielded an overall RR that better represented the age–sex structure of our study population and produced RRs of 19.6 and 7.3 for lung-cancer mortality among current smokers and former smokers, respectively, relative to never smokers. Published studies of smoking and lung cancer have shown a wide range in RR values, and for that reason, sensitivity analyses were repeated for lung-cancer mortality using the summary RR estimates from a meta-analysis for lung cancer.[35] These summary risks for current and former smokers (relative to never smokers) were 9.0, and 4.0.

Similarly, we repeated the analyses for coronary-heart-disease mortality using published values for the ACS CPS II.[34]

Ethical approval

Ethics approval was provided by Statistics Canada. The population health surveys, including the CCHS, conducted by Statistics Canada consist of an advisory committee formed of provincial and federal health organisations. Any survey content or changes are reviewed and approved internally by Statistics Canada's senior management. In addition, analyses presented herein follow Statistics Canada's confidentiality rules that prevent the publication or disclosure of any information deemed confidential.

RESULTS

Figure 1 shows the variations in the concentrations of ground-level $PM_{2.5}$ throughout Canada over the period 2001–2006. Concentrations of $PM_{2.5}$ were higher in Ontario, particularly in the southern part of the province. Specifically, over the period 2001–2006, the mean ambient concentration among CCHS participants who lived in Ontario was estimated to be 12.9 $\mu g/m^3$. The average $PM_{2.5}$ concentration in the province of Quebec was 9.5 $\mu g/m^3$ while the average levels in the other provinces ranged between 5 and 7 $\mu g/m^3$. Higher concentrations of $PM_{2.5}$ were generally found in metropolitan areas with larger populations. Specifically, the mean concentrations of $PM_{2.5}$ in cities with populations of >1.5 million, >500 000 and <1.5 million, 100 000 to <500 000 and 10 000 to <100 000 were 11.8, 8.3, 9.2 and 6.5 $\mu g/m^3$, respectively.

Table 1 shows age- and sex-adjusted estimates of mean concentrations of $PM_{2.5}$ according to the selected sociodemographic variables. A separate model was fitted for each variable. Among all participants, the mean levels of $PM_{2.5}$ were highest among those with an university education above a Bachelor's degree (mean=9.00 $\mu g/m^3$, 95% CI 8.89 to 9.10) and lowest among those who had not attained at least a grade 9 level of education (mean=7.55, 95% CI 7.50 to 7.60). Similar patterns between educational attainment and levels of $PM_{2.5}$ were observed when analyses were restricted to Ontario residents. A U-shaped pattern was observed between household income and $PM_{2.5}$ levels in all three regional groupings. Specifically, concentrations of $PM_{2.5}$ were highest among those who reported no income as well as those whose household income exceeded C$80 000. Similar U-shaped patterns were observed when personal income, rather than household income, was modelled, and inverse gradients between $PM_{2.5}$ and income and educational

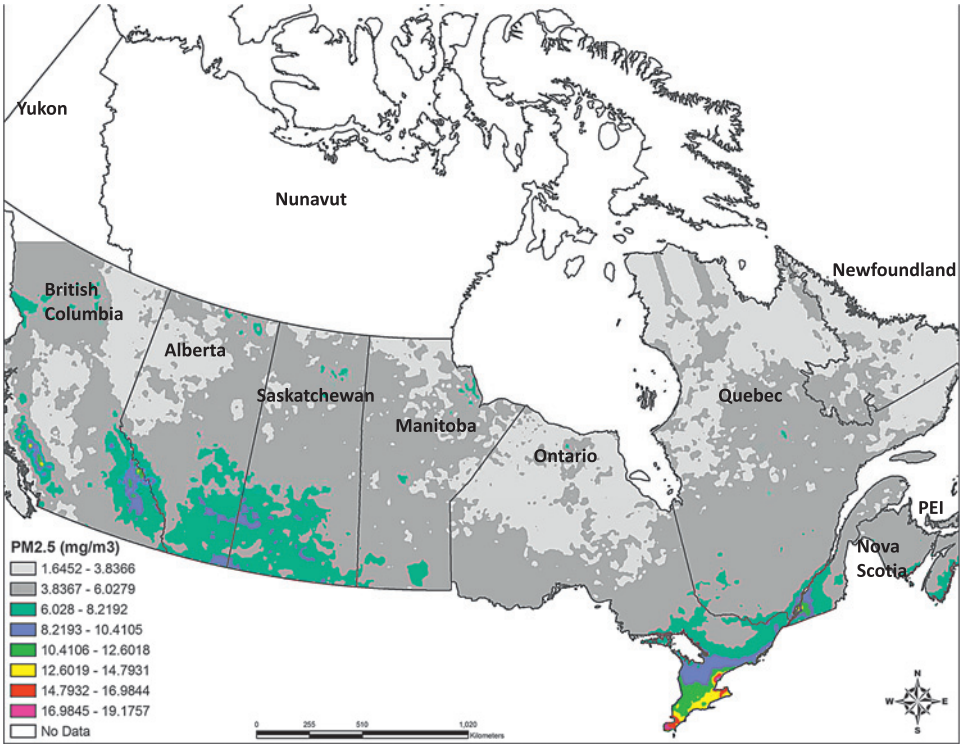

Figure 1 Mean satellite-derived estimate of ground-level ambient fine particulate matter ($PM_{2.5}$), Canadian provinces, 2001–2006. PEI, Prince Edward Island.

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Table 1 Age- and sex-adjusted mean remote-sensing-derived estimates of concentrations $PM_{2.5}$ (2001–2006) according to sociodemographic characteristics among participants of the 2003 Canadian Community Health Survey, for Canada and Ontario

	Canada (n = 122 548)			Ontario (n = 40 403)		
Characteristic	**n**	**Mean ($\mu g/m^3$)**	**95% CI**	**n**	**Mean ($\mu g/m^3$)**	**95% CI**
Highest level of education						
Grade 8 or lower	18 000	7.55	7.50 to 7.60	4945	11.11	11.01 to 11.22
Grade 9–10	13 589	7.50	7.44 to 7.56	4046	10.91	10.79 to 11.02
Grade 11–13	7237	7.83	7.74 to 7.91	2645	11.14	11.00 to 11.29
Secondary graduation	20 779	8.05	8.00 to 9.10	7549	11.36	11.27 to 11.44
Some postsecondary	8353	7.93	7.85 to 8.01	2670	11.35	11.20 to 11.49
Trade certificate/diploma	13 886	7.27	7.20 to 7.33	3358	10.82	10.69 to 10.95
College certificate/diploma	18 467	8.35	8.29 to 8.40	7400	11.25	11.16 to 11.33
University (<Bachelor's)	3261	8.25	8.12 to 8.38	1047	11.62	11.38 to 11.85
University (Bachelor)	11 987	8.60	8.53 to 8.66	4186	12.03	11.92 to 12.16
University (>Bachelor)	5011	9.00	8.89 to 9.10	2016	12.16	11.99 to 12.33
Missing	1978			541		
Marital status						
Married	53 290	7.91	7.88 to 7.94	18 997	11.25	11.20 to 11.31
Common law	9061	7.53	7.45 to 7.61	2010	10.60	10.45 to 10.79
Widowed	11 929	7.87	7.79 to 7.95	3964	11.26	11.12 to 11.40
Separated	3825	7.96	7.84 to 8.07	1334	11.12	10.91 to 11.32
Divorced	7834	8.07	7.99 to 8.15	2484	11.49	11.34 to 11.64
Single	36 410	8.07	8.03 to 8.12	11 596	11.54	11.45 to 11.63
Missing	199			35		
Household income (C$)						
None	254	8.60	8.14 to 9.05	115	11.41	10.71 to 12.11
<5000	815	7.24	6.99 to 7.50	214	11.07	10.56 to 11.59
5000 to <10 000	2688	7.44	7.30 to 7.58	621	10.95	10.65 to 11.25
10 000 to <15 000	7348	7.48	7.39 to 7.56	1981	10.95	10.78 to 11.12
15 000 to <20 000	6305	7.52	7.43 to 7.61	1734	10.94	10.76 to 11.12
20 000 to <30 000	13 001	7.68	7.61 to 7.74	3957	11.03	10.91 to 11.15
30 000 to <40 000	13 101	7.83	7.77 to 7.90	4109	11.24	11.12 to 11.35
40 000 to <50 000	10 953	7.93	7.86 to 8.00	3612	11.18	11.05 to 11.30
50 000 to <60 000	10 327	7.97	7.90 to 8.04	3515	11.20	11.08 to 11.33
60 000 to <80 000	15 886	8.09	8.03 to 8.15	5872	11.23	11.13 to 11.33
80 000+	23 428	8.60	8.55 to 8.64	9892	11.59	11.51 to 11.66
Missing	18 442			4781		
Canadian-born						
Yes	1 04 813	7.59	7.57 to 7.61	31 874	10.80	10.75 to 10.84
No	15 679	10.21	10.15 to 10.26	8033	13.36	13.28 to 13.44
<5 years in Canada	3114	10.77	10.58 to 10.95	1481	14.47	14.26 to 14.68
5 to <10 years in Canada	3639	10.68	10.53 to 10.84	1826	14.12	13.94 to 14.29
10+ years in Canada	8881	9.73	9.63 to 9.84	4703	12.55	12.44 to 12.67
Unknown	45			23		
Missing	2056			496		

N, number of participants.

attainment were found among participants who lived in both metropolitan and non-metropolitan areas (data not shown). There was no association between marital status and levels of $PM_{2.5}$, but higher concentrations of $PM_{2.5}$ were found among those who had immimigrated to Canada (mean=10.21 $\mu g/m^3$, 95% CI 10.15 to 10.26) compared with those who were born there (mean=7.59 $\mu g/m^3$, 95% CI 7.57 to 7.61). Further, the data indicated that the mean levels of $PM_{2.5}$ among immigrants decreased with increasing time spent in Canada, and a linear test for trend of this association was statistically significant ($p<0.05$).

The relationships between behavioural risk factors and $PM_{2.5}$ are described in table 2. The mean levels of $PM_{2.5}$ were related to participants' smoking status at the time of interview. We observed that among all participants as well as those who resided in Ontario, the concentrations of $PM_{2.5}$ were highest among those who had never smoked. Specifically, the mean concentrations of $PM_{2.5}$ among daily smokers were 7.79 and 11.02, in Canada and Ontario, respectively, while the corresponding concentrations for never smokers were 8.21 and 11.69. Similarly, we found that those who placed restrictions on smoking within the home lived in areas that had higher ambient levels of $PM_{2.5}$ (mean=8.03 $\mu g/m^3$, 95% CI 8.00 to 8.05) when compared with those with no restrictions (mean=7.80 $\mu g/m^3$, 95% CI 7.76 to 7.83). In all regions, BMI and activity levels were inversely related to $PM_{2.5}$ levels.

Table 3 shows the estimated impact on lung-cancer and coronary-heart-disease mortality from differential prevalences of smoking across categories of $PM_{2.5}$. In the highest category of $PM_{2.5}$, where the prevalence of never smoking is the highest relative to other exposure categories, there is an estimated 10.5% difference in lung cancer mortality that is due to smoking. In other words, one would have to decrease the number of lung-cancer deaths in the lowest-exposure group by 10.5% to take

Table 2 Age- and sex-adjusted mean remote-sensing-derived estimates of concentrations $PM_{2.5}$ (2001–2006) for selected behavioural chronic disease risk factors, participants of the 2003 Canadian Community Health Survey, for Canada and Ontario

	Canada (n = 122 548)			Ontario (n = 40 403)		
Characteristic	**N**	**Mean $\mu g/m^3$**	**95% CI**	**N**	**Mean $\mu g/m^3$**	**95% CI**
Smoking status at interview						
Daily	23 032	7.79	7.74 to 7.83	7228	11.02	10.93 to 11.11
Occasional	3560	8.01	7.89 to 8.13	1187	11.32	11.11 to 11.54
Always occasional	2143	8.16	8.01 to 8.32	706	11.53	11.25 to 11.82
Former daily	31 794	7.66	7.61 to 7.70	9913	10.90	10.83 to 10.98
Former occasional	18 484	7.95	7.90 to 8.01	6051	11.39	11.29 to 11.48
Never	43 180	8.21	8.18 to 8.25	15 242	11.69	11.63 to 11.76
Missing	355			76		
Ever smoke 100 cigarettes						
Yes	62 623	7.75	7.72 to 7.78	19 731	11.00	10.95 to 11.06
No	59 767	8.14	8.11 to 8.17	20 637	11.62	11.56 to 11.67
Missing	158			35		
Restrict smoking in home						
Yes	73 312	8.03	8.00 to 8.05	26 559	11.44	11.39 to 11.48
No	48 546	7.80	7.76 to 7.83	13 533	11.07	11.01 to 11.13
Missing	690			311		
Physical-activity level						
Active	32 295	7.81	7.76 to 7.85	10 814	11.06	10.99 to 11.13
Moderate	29 585	7.95	7.90 to 7.99	9892	11.22	11.14 to 11.29
Inactive	57 984	8.02	7.99 to 8.05	18 787	11.53	11.47 to 11.58
Missing	2684			910		
Body mass index*						
Underweight	2469	8.59	8.45 to 8.74	820	11.99	11.72 to 12.25
Normal	47 655	8.14	8.11 to 8.18	15 799	11.53	11.47 to 11.59
Overweight	37 243	7.84	7.80 to 7.88	12 330	11.18	11.11 to 11.24
Obese	18 565	7.65	7.60 to 7.71	6031	10.99	10.90 to 11.09
Missing	16 616			5423		

*Body mass index (BMI) categories were defined as follows: underweight (BMI<18.5), normal (18.5≤BMI<25), overweight (25≤BMI<30) and obese (BMI≥30).
N, number of participants.

into account the estimated effect from smoking. The corresponding percentage decrease in coronary-heart-disease mortality was estimated to be 4.9%.

The slopes obtained from fitting a linear regression model of the mean concentration of $PM_{2.5}$ against the percentage change in mortality are presented for several scenarios (table 4). Using RR estimates for the ACS CPS II study,[34] for a 10 $\mu g/m^3$ increase in $PM_{2.5}$, the lung-cancer mortality needs to be increased within the referent exposure group by 6.9% (95% CI 2.8% to 11.0%) to compensate for differences in smoking. This indicates that rate ratios of mortality for $PM_{2.5}$ will be underestimated by approximately 7% if cigarette smoking is not taken into account. For other causes of death, the impact is not nearly as large. We estimated the negative bias on the RR for a 10 $\mu g/m^3$ increase in $PM_{2.5}$ to be 3.2% for coronary heart disease and 2.8% for cerebrovascular-disease mortality.

DISCUSSION

We have shown that certain socio-demographic and behavioural characteristics in Canadians, which are recognised determinants

Table 3 Impact of differential smoking prevalence on lung cancer and coronary-heart-disease mortality across deciles of fine particulate matter ($PM_{2.5}$) exposure, Canadian Community Health Survey (CCHS) participants aged 35 years and older

Cigarette smoking prevalence (%)						Lung cancer		Coronary heart disease	
Exposure category	**Range of $PM_{2.5}$ values**	**Mean $PM_{2.5}$ ($\mu g/m^3$)**	**Never smokers**	**Former smokers**	**Current smokers**	**Estimated mortality***	**Percentage change due to smoking†**	**Estimated mortality***	**Percentage change due to smoking†**
1	<4.44	3.75	25.3	50.6	24.1	124.5	0	282.9	0
2	4.44 to <4.96	4.72	25.5	50.4	24.1	124.3	−0.1	282.8	−0.1
3	4.96 to <5.38	5.17	26.6	50.1	23.3	121.9	−2.1	280.1	−1.0
4	5.38 to <5.99	5.67	27.6	49.3	23.1	120.7	−3.1	278.8	−1.5
5	5.99 to <6.81	6.39	28.0	51.1	21.0	116.7	−6.3	274.4	−3.0
6	6.81 to <7.48	7.11	30.5	48.6	20.9	114.2	−8.3	271.6	−4.0
7	7.48 to <8.69	8.01	27.9	48.9	23.2	120.6	−3.2	278.7	−1.5
8	8.69 to <11.42	9.96	27.7	49.1	23.2	120.8	−3.0	278.9	−1.4
9	11.42 to <13.80	12.61	31.6	46.0	22.5	116.1	−6.8	274.2	−3.1
10	13.80+	15.84	35.1	43.2	21.7	111.4	−10.5	269.1	−4.9

*Per 100 000; based on Canadian age–sex-specific lung-cancer mortality[36] weighted to the age–sex distribution of CCHS participants, the prevalence of never, former and current smokers, as well as the RR of lung cancer (based on American Cancer Society Cancer Prevention Study-II data); assumes exposure to ambient $PM_{2.5}$ is unrelated to lung cancer mortality (see equations (1)–(3)).
†Relative to mortality rates in the lowest $PM_{2.5}$ exposure category.

Table 4 Estimated bias in the RR of mortality for a 10 μg/m^3 increase in fine particulate matter ($PM_{2.5}$) in Canada due to differences in smoking prevalence

Outcome	Reference	RR of mortality by smoking status†		Estimated bias (%)* and CI	
		Current relative to never	Former relative to never	Bias	95% CI
Lung cancer	Malarcher *et al*[34]	19.60	7.26	−6.93	(−2.84 to −11.03)
Coronary heart disease	Malarcher *et al*[34]	2.80	1.55	−3.18	(−1.21 to −5.15)
Cerebrovascular disease	Malarcher *et al*[34]	3.82	1.19	−2.60	(0.40 to −5.61)
Lung cancer	Gandini *et al*[35]	8.96	3.95	−6.18	(−3.45 to −9.63)

*Based on a linear regression of percentage change in mortality (dependent variable) against mean $PM_{2.5}$ (independent variable) observed across the decile exposure categories (see table 3).
†RRs were weight by the age-sex structure of the CCHS participants.

of health, are also associated with ground-level estimates of ambient concentrations of fine particulate matter measured from remote sensing at a resolution of 10×10 km. Specifically, individuals with a higher educational attainment and income were more likely to live in areas characterised by higher levels of ambient $PM_{2.5}$. We also found that immigrants were more likely to live in areas with higher ground-level concentrations of $PM_{2.5}$ than those born in Canada. These concentrations decreased with increasing length of time of residency. This may be due in part to the tendency of individuals who immigrate to Canada to first take up residency in larger metropolitan areas where pollution levels are higher. For example, data from the 2001 Canadian census revealed that approximately 75% of recent immigrants took up residence in Toronto, Montreal or Vancouver.[37] Immigrants to Canada are generally highly educated, as more than half (54%) have a university education,[37] and in general, they have a lower cancer incidence and mortality relative to native-born Canadians.[38 39] However, longitudinal analyses of the health status and healthcare utilisation practices suggest that this healthy immigrant effect is short-lived.[40 41] Disentangling the role of ambient pollution from other important factors among immigrants is by no means a trivial task, and we suggest that longitudinal studies, in Canada at least, should endeavour to characterise $PM_{2.5}$ health effects separately for both immigrant and non-immigrant populations.

Those who were classified as obese (based on BMI) and were smokers lived in areas that had lower remote-sensing-derived concentrations of $PM_{2.5}$. The nature of these associations indicates that these risk factors may negatively confound associations between ambient pollution and mortality. This implies that associations with $PM_{2.5}$ in nationwide or provincewide cohort studies will be understated if adjustments are not made for cigarette smoking. Other studies have found that adjustment for cigarette smoking can increase,[42 43] decrease[7] or not materially affect[1 6] the RRs of adverse health outcomes from long-term exposure to $PM_{2.5}$. Indeed, we estimate that the RR for lung cancer in relation to a 10 μg/m^3 increase in $PM_{2.5}$ would be understated by about 6.9%. For example, if the unadjusted RR for a 10 μg/m^3 increase in ambient $PM_{2.5}$ for lung cancer mortality was found to be 1.10, then our estimate of the RR that takes into account smoking status would be 1.18 (=1.10×1.069). If we were to apply more conservative estimates of smoking RRs from smoking, the impact of the negative bias for lung-cancer mortality changes only modestly from 6.9% to 6.2%. These effects are of similar magnitude but in the opposite direction found by Pope in his analysis of data from the ACS CPS II Study. There, adjustment for smoking status reduced the RR of lung cancer mortality associated with a 10 μg/m^3 increase in ambient $PM_{2.5}$ from 1.13 to 1.06.[7] The impacts on RRs for $PM_{2.5}$ on other causes of deaths would not be affected to the same degree given that the RRs of smoking are much smaller for these conditions than for lung cancer. Our analyses for cardiovascular and all-cause mortality suggest that the magnitude of the bias would be in the range of 2–3%.

An important limitation of this study is that these associations apply only to estimates of ground-level $PM_{2.5}$ that are modelled at a resolution of 10×10 km. We recognise that ambient pollution, including fine particulate matter, varies at a much smaller scale within cities, often by following the social inverse gradients found around roadways. Beckerman *et al*, for example, found that ambient $PM_{2.5}$ concentrations were strongly related to distance to expressway in Toronto, Canada.[44] Elsewhere, Jerrett *et al* observed that chronic health effects associated with within-city gradients in $PM_{2.5}$ exposure are greater that those reported across metropolitan areas.[4] At this time, national ambient air pollution monitoring programmes, including Canada's, typically consist of a sparse network of fixed site monitoring stations designed primarily to ensure that pollution levels are compliant to national air quality standards. Therefore, population-based evaluations of the associations between long-term exposure to ambient air pollution and chronic disease continue to be carried out at a regional or interurban level. In our view, the remote-sensing-derived estimates of $PM_{2.5}$ provide important advantages over the fixed site monitors in terms of increased resolution, and coverage of areas outside Canada's fixed site monitoring network. Further improvements that increase the resolution of the remote-sensing estimates of ground-level $PM_{2.5}$ will allow for an improved understanding of the health impact from long-term exposure.

This study has several important strengths. First, ambient $PM_{2.5}$ could be assigned to virtually all participants of this population-based survey. The participation rates were fairly high, as more than 80% responded to their invitation to participate, and the number of participants was large (122 548). Thus, there was excellent coverage of the target population, and it is likely that the data fairly represent the Canadian population. The survey collected data for an extensive list of socio-demographic and behavioural risk factors. A limitation of the investigation was that the observed associations with $PM_{2.5}$ may differ substantially from that of other ambient pollutants. For example, nitrogen dioxide, a marker of traffic-related pollution, has been shown to exhibit far more heterogeneity on an intraurban scale than $PM_{2.5}$.[45] Recent studies have demonstrated that within-city variations in ambient pollution are related to the risk of mortality.[1 4] Unfortunately, we do not have detailed high-resolution maps at the national level of this pollutant or of the other criteria pollutants such as ozone and sulfur dioxide.

The methodology we have presented to indirectly adjust the $PM_{2.5}$ risk estimates for effects of smoking takes into account the effects of age and sex. For a disease such as lung cancer, where smoking is responsible for approximately 90% of all deaths,[46] the influence of any other risk factors, in our view, would not change our estimate of the bias in an important way. However, for other health conditions where risk factors such as

BMI, physical activity and alcohol are correlated with both smoking and the health outcome under study, our estimated bias should be carefully interpreted when applied to multivariable models. Some of the smoking effect may be captured by other risk factors that are already included in the model, and therefore, in these cases, our estimate of bias may be overstated. Efforts to extend our approach to take into account the confounding role of other salient risk factors are recommended.

In summary, our findings suggest that observed associations between long-term exposure to increased levels of $PM_{2.5}$ among Canadians cannot be dismissed owing to an inability to control for several determinants of health, including cigarette smoking. The results should be interpreted cautiously, as the impact of these variables on $PM_{2.5}$ risk estimates may well differ when ambient pollution is described on a finer (or larger) geographical scale. Regardless, the method that we developed to characterise the bias from uncontrolled confounding due to smoking can be easily applied to other ambient pollutants, or those measured at different spatial resolutions.

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