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The influence of outdoor $PM_{2.5}$ concentration at workplace on nonaccidental mortality estimates in a Canadian census-based cohort

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Background: Associations between mortality and exposure to ambient air pollution are usually explored using concentrations of residential outdoor fine particulate matter ($PM_{2.5}$) to estimate individual exposure. Such studies all have an important limitation in that they do not capture data on individual mobility throughout the day to areas where concentrations may be substantially different, leading to possible exposure misclassification. We examine the possible role of outdoor $PM_{2.5}$ concentrations at work for a large population-based mortality cohort.

Methods: Using the 2001 Canadian Census Health and Environment Cohort (CanCHEC), we created a time-weighted average that incorporates employment hours worked in the past week and outdoor $PM_{2.5}$ concentration at work and home. We used a Cox proportional hazard model with a 15-year follow-up (2001 to 2016) to explore whether inclusion of workplace estimates had an impact on hazard ratios for mortality for this cohort.

Results: Hazard ratios relying on outdoor $PM_{2.5}$ concentration at home were not significantly different from those using a time-weighted estimate, for the full cohort, nor for those who commute to a regular workplace. When exploring cohort subgroups according to neighborhood type and commute distance, there was a notable but insignificant change in risk of nonaccidental death for those living in car-oriented neighborhoods, and with commutes greater than 10 km.

Conclusions: Risk analyses performed with large cohorts in low-pollution environments do not seem to be biased if relying solely on outdoor $PM_{2.5}$ concentrations at home to estimate exposure.

Keywords: Spatiotemporal exposure; Fine particulate matter; $PM_{2.5}$; Air pollution; Exposure misclassification; Exposure assessment; Time-activity

Introduction

Large cohort studies have established that long-term exposure to ambient air pollution (e.g., $PM_{2.5}$) can result in increased risk of nonaccidental, cardiovascular, and respiratory mortality worldwide, up to 2.9 million deaths worldwide per year.[1] Cohort-based epidemiologic research generally assigns outdoor ambient air pollution based on the approximate location of a person's residence and does not incorporate outdoor air pollutant concentrations at places of work, during a commute, during leisure activities, or during other activities of daily living[2,3]; moving away from a static understanding of exposure to a spatial or temporal model is a priority in this research field.[4,5] Canadians who participate in paid work spend approximately 40 hours per week working,[6] and outdoor ambient $PM_{2.5}$ concentration at work has been found to be the second-largest contributor to total $PM_{2.5}$ exposure.[7,8] Relying solely on outdoor ambient air pollution concentration at home has been found to underestimate exposures in observational studies of nitrogen dioxide (NO_2) in Vancouver,[9] and Montreal, Canada,[10] and Basel, Switzerland,[7] and this bias increases with commute distance and time spent away from home.

The objective of this study is to explore the extent to which inclusion of estimates of outdoor fine particulate matter ($PM_{2.5}$) at place of work, along with estimates of outdoor $PM_{2.5}$ concentration at home, affects total exposure estimates and, focusses

What this study adds

This study is the first population-based cohort study to incorporate outdoor ambient air pollution at work and home in assigning exposure estimates. We found that hazard ratios relating $PM_{2.5}$ exposure to nonaccidental mortality may not be biased if relying solely on outdoor $PM_{2.5}$ concentration at home to inform models. In Canada, it appears that there are insufficient numbers of workers who work in locations where ambient $PM_{2.5}$ concentrations at work are notably different from those at their home, to lead to meaningful differences.

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The data linkage was approved by Statistics Canada's senior management (https://www.statcan.gc.ca/eng/record/summ) and is governed by the Directive on Microdata Linkage (https://www.statcan.gc.ca/eng/record/policy4–1).

The 2001 CanCHEC dataset that supports the conclusions of this article is available to researchers through the Statistics Canada Research Data Centres. Air pollution data are available to researchers through the Canadian Urban Environmental Health Research Consortium.

SDC *Supplemental digital content is available through direct URL citations in the HTML and PDF versions of this article (www.environepidem.com).*

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specifically on whether mortality hazard ratios are sensitive to this adjustment. We did this by assigning estimates of outdoor fine particulate matter $PM_{2.5}$ concentration to the 2001 Canadian Census Health and Environment Cohort (CanCHEC). We created a time-weighted exposure estimate that integrates outdoor $PM_{2.5}$ concentration at home and at work (according to the hours the person reported working) and contrasted it with an exposure estimate based solely on outdoor $PM_{2.5}$ concentration at home. Additionally, we used Cox proportional hazard models to estimate risk of nonaccidental mortality associated with both the time-weighted and residential-only (i.e., standard) exposure estimates. This work builds on smaller studies that used dynamic exposures and person-level exposures by applying a spatiotemporal exposure estimate to a large, population-based cohort linked to mortality data.

Methods

The 2001 CanCHEC

The 2001 CanCHEC is an analytical dataset that was formed through the linkage of the mandatory 2001 Census long-form questionnaire to tax and mortality databases.[11] The long-form Census surveys approximately 20% of Canadian households and is nationally representative; the CanCHEC v3 linkage methodology and cohort have been described elsewhere.[3] Briefly, the CanCHECs are created by probabilistically linking eligible long-form Census respondents (i.e., noninstitutional residents with age 25 to 89 years) to the Canadian Mortality Database from Census day onwards and the residential postal code as indicated on tax return mailing addresses for years 1981 to 2016.[12] In urban areas, a postal code represents one to a few city blocks, and geocoding (for the purposes of attaching air pollution estimates) at this level is highly accurate with a mean positional error of 160 m.[13] In rural areas, a postal code is a larger area and geocoding is less accurate, with a mean positional error of 5.6 km.

The 2001 CanCHEC includes information on commute to work and the location of a person's workplace in addition to demographic and socioeconomic variables. Workplace information was available for persons with age 15 years and over living in private households. Respondents provided place of work in the week before 2001 Census day. For those who did not work in the week before Census day but worked at some point after January 1, 2000, the location where they held a job the longest was recorded. Respondents were asked where they usually worked most of the time, and those with a fixed workplace (i.e., did not work at home, did not work outside of Canada, worked at a usual place) were asked to provide the street address of the workplace. All respondents were asked how many hours they spent working for pay or in self-employment in the week before Census enumeration, and whether in the past year (2000) when they worked, whether they worked full time (30 hours or more per week) or part time (less than 30 hours per week) for all jobs held.

The CanCHEC includes residential postal code histories from 1981 to 2016 (from tax files) that can change over time as a person moves; however, their workplace location is static, based on what was reported on the 2001 Census. For this analysis, we extrapolated workplace location to all relevant working years (described later). Further, the hours worked per week were imputed to all working years, assuming that hours worked were static over time.

We assigned contextual covariates to the CanCHEC to describe neighborhood-level characteristics for each individual. These were as follows: community size (>1,500,000, 500,000–1,499,999, 100,000–499,999, 30,000–99,999, 10,000–29,999, or non-Census Metropolitan Area [CMA] or Census Agglomeration [CA]),[3] neighborhood urban form (active urban core, transit-reliant suburb, car-reliant suburb, exurban, or non-CMA/CA), which is a classification based on population density and prevalent modes of transportation,[14] the four variables that comprise the Canadian Marginalization Index, each scored as quintiles (CAN-Marg: ethnic concentration, dependency, material deprivation, residential instability),[15] and regional airshed (East central, Northern, Prairie, Southern Atlantic, West central, or Western), which are regions of Canada that share air quality characteristics and movement patterns.[16]

Exposure estimates

We assigned residents' estimates of exposure to outdoor fine particulate matter ($PM_{2.5}$) concentration, derived from a national model (version 1, annual exposures for 1998–2012). The methodology to create this exposure dataset is described in greater detail elsewhere.[3,17] $PM_{2.5}$ concentrations were derived from aerosol optical depth retrievals related to surface $PM_{2.5}$ concentrations using simulations from the GEOS-Chem chemical transport model and calibrated to surface measurements of $PM_{2.5}$ by geographically weighted regression.[18] We estimated outdoor $PM_{2.5}$ concentration at home (hereafter referred to as "exposure at home") for all in-scope person years and outdoor $PM_{2.5}$ concentration at work (hereafter referred to as "exposure at work") and considered it only for working aged person-years; working people were those who reported commuting to regular workplace on Census day (hereafter referred to as "CRW"), and assigned workplace information from age 25 to 65 years. If a person was older than 65 on Census day and still reported commuting to a regular workplace, we assumed that this would be their final year of work. We calculated a time-weighted average exposure estimate by using the Census variable indicating hours spent working in the past week and the exposure at home and exposure at work values; reported hours worked in the past week were available for 86.9% of in-scope person-years. The equation assumed that all hours in a week (168 hours total) that were not spent at work were spent at home:

$$PM_{TW} = \frac{((h \times PM_W) + ((168 - h) \times PM_H))}{168}$$

where PMTW = time-weighted $PM_{2.5}$ concentration, PMH = home $PM_{2.5}$ concentration, PMW = work $PM_{2.5}$ concentration, and h = hours worked per week. In cases where hours spent at work were not available (i.e., they did not work in the week before Census day), but a CRW person indicated that they worked full-time or part-time (i.e., they worked at some point over the past year), we assumed a 40- or 20-hour, respectively. The CRW population accounted for 12.6% of in-scope person-years within the full cohort. For the remaining 0.5% of person-years where a person reported a workplace, reported commuting to a regular workplace, but did not indicate hours worked or full/part time status, we assumed a 40-hour work week.

We calculated, for each year of follow-up, a 10-year moving average for $PM_{2.5}$ with a 1-year lag (e.g., the average of exposures in years 1992 to 2001 is associated with the risk in the following calendar year, which is 2002) for exposures at home. For the CRW population only, we calculated a separate 10-year moving average with a 1-year lag that used the time-weighted exposure for approximate working years.

Cox proportional hazard models

We excluded person-years from analysis if the subject was not between ages 25 and 89 on Census day, if they were missing postal code or $PM_{2.5}$ values for their residence for all years of follow-up (2001–2016), missing any of the contextual covariates, or if the person had immigrated to Canada in the 10 years preceding Census day. Recent immigrants to Canada have unknown prior exposures to air pollution and therefore we are unable to calculate longer-term estimates to include in models, although we have found that this has a nondifferential effect on our hazard estimates.[19] We performed further exclusions to the file to focus on the working population, retaining only those who were CRW on Census day.

We used demographic and socioeconomic data from the long-form Census, which are fixed at baseline, as covariates in the survival models. The covariates are described in detail elsewhere, briefly: income quintile (quintiles 1 to 5), highest level of educational attainment (less than high school, high school diploma, nonuniversity postsecondary, or university degree), occupational class (management, professional, skilled, technical, and supervisory, semiskilled, or unskilled), Indigenous identity (yes, or no), visible minority status (yes, or no; these are non-Indigenous persons who self-identify as non-White in race or non-White in color), employment status (employed, or unemployed or not in the labor force), and marital status (common-law or married, never married and not common-law, or separated, widowed, or divorced).[20]

We fit standard Cox proportional hazards models[21] to the data to explore the associations between exposures to $PM_{2.5}$ and nonaccidental mortality (International Classification of Diseases, ICD-10: A to R) in SAS 7.1 (SAS Institute, USA)[22]; resulting in a hazard ratio (HR) and 95% confidence interval (CI). We included model covariates (individual and contextual) and stratified the models by age (5-year age groups), sex (male or female), and immigrant status (immigrant or nonimmigrant). We contrasted the HRs for exposure at home with HRs that incorporated time-weighted estimates using Cochrane's Q in R software (R Foundation, Austria).[23]

Results

People commuting to a regular place of work (CRW) constituted approximately 61.4% of the in-scope person-years in the full cohort, compared with those who worked from home (6.7%) or had no fixed workplace (6.6%). Of those who work at a usual place, 6.6% work outdoors and 93.4% work indoors. Workers with a usual place of work were more likely to work full time (86.0%), working an average of 34 hours per week, and commuting 13 km to get to work. Details of the full cohort, including both CRW and those who did not work outside the home at a regular workplace, are available in the Supplemental Digital Content (http://links.lww.com/EE/A167, which provides descriptive statistics of the full cohort with hazard ratios for nonaccidental mortality, and outdoor concentrations of $PM_{2.5}$ at home and at work).

Among the CRW population (Table 1), exposure at home was highest for those living in a transit-reliant suburb (9.59 μg/m^3), or the most marginalized neighborhoods according to ethnic concentration (9.53 μg/m^3), and those who were aged 65 and older (9.72 μg/m^3). Exposure at home was lowest for those living outside of a Census Metropolitan Area (5.27 μg/m^3), or in the northern or southern Atlantic airsheds (4.93 and 4.03 μg/m^3). Exposure at work was highest for people living in communities of 1.5 million people or more (9.89 μg/m^3), the most marginalized neighborhoods according to ethnic concentration (9.94 μg/m^3), and those who were aged 65 and older (9.78 μg/m^3).

Across all person-years in the CRW population, exposure at work was higher than exposure at home, resulting in an average exposure difference (i.e., the mean of the person-level difference between outdoor $PM_{2.5}$ concentration at work and at home) of 0.92 μg/m^3 across all person-years. Exposure differences were similar for women and men, and those with age 25 to 54 years but were smaller for those with age 55 to 64 years. Exposure differences were effectively null for those above age 65, indicating that on average exposure at home was the same as at work for those in this age bracket. Immigrants had higher exposure at work and exposure at home than nonimmigrants, resulting in a smaller exposure difference. Exposure differences were highest for those living in exurban neighborhoods (i.e., low population density suburbs outside of urban centers), and least marginalized quintiles according to residential instability and material deprivation Can-MARG measures. Exposure differences were lowest (i.e., indicating higher outdoor $PM_{2.5}$ concentration at home than at work) for those with age 65 to 89 years and living in the Western or Southern Atlantic airshed.

The distribution of $PM_{2.5}$ estimates for the different exposure scenarios is shown in Table 2. For the full cohort, which includes those who are unemployed or those who do not have a regular workplace, exposure at home was not notably different from the exposure at home of those who commuted to a regular workplace (CRW). Exposure at work was higher on average than exposure at home. The time-weighted estimate that incorporated workplace concentrations in proportion to reported work hours was, as expected, higher than exposure at home but lower than exposure at work.

We present associations between nonaccidental mortality and $PM_{2.5}$ in Table 3. We first analyzed the 2001 CanCHEC using $PM_{2.5}$ estimates based on exposure at home. We started with a model stratified by 5-year age groups, sex, and immigrant status, and added individual-level covariates and contextual covariates separately before generating a fully adjusted model with all covariates (HR = 1.12; 95% CI = 1.10, 1.15). We performed the same stepwise addition of covariates with the full cohort, using the time-weighted estimate for the CRW and the exposure at home for those who were not included in the CRW group, resulting in a nearly identical hazard ratio when fully adjusted (HR = 1.11; 95% CI = 1.09, 1.13). We then limited the cohort to the CRW population and contrasted exposure at home with exposure at work, and the time-weighted estimate. The resulting effect estimates were greater than those based on the full cohort. When mortality associations were estimated using exposure at work the hazard ratio was effectively null (HR = 1.01; 95% CI = 0.93, 1.09). Further, the HR of 1.17 (95% CI = 1.07, 1.28) for exposure at home was not notably different from that estimated with the time-varying estimate (i.e., HR = 1.15; 95% CI = 1.04, 1.27) and the difference between the two was not significant (Cochrane's Q = 0.06; P = 0.80).

To explore whether associations between mortality and exposure to $PM_{2.5}$ would be affected more heavily by the inclusion of exposure at work, we examined the effect modification according to selected work-related characteristics (Table 4). When examined by residential neighborhood, using the time-weighted estimates did not result in significantly different hazard ratios than exposure at home, although for those living in cities (urban and suburban), hazard ratios decreased with the time-weighted estimate (0.68 vs. 0.63 for active urban core and transit-reliant surburbs; and 1.15 vs. 1.08 for car-reliant suburbs and exurban neighborhoods), whereas the hazard ratio increased for those working outside of census-designated cities and towns (non CMA/CA, 1.42 vs. 1.45). For those with commutes under 10 km hazard ratios did not change notably between the residential and time-weighted estimates (under 5 km, 1.32 vs. 1.32; 5 to <10 km, 1.21 vs. 1.20). For those with a commute of 10 to <15 km, the hazard ratio was highest, and there was the largest difference between the residential and time-weighted estimate, with the latter being higher (1.44 vs. 1.50). For those with commutes of 15 km or more, hazard ratios were protective, although with wide confidence intervals, and the residential estimates were higher than the time-weighted estimates (0.76 vs. 0.73 for 15 to <20 km; and 0.90 vs. 0.84 for commutes of 20 km or more). Hazard ratios were higher for outdoor workers compared with indoor workers. Outdoor workers had a small increase in risk when using the time-weighted exposure (1.22 vs. 1.25), and indoor workers small decrease in risk when using that exposure compared with residential estimates (1.16 vs. 1.13). Skilled workers had lower hazard ratios compared with semiskilled and skilled workers. Skilled workers had hazard ratios around 1 with wide confidence intervals with both exposure estimates. Unskilled workers had similar hazard ratios for both exposure estimates (1.37 vs. 1.38) and wide confidence intervals.

Table 1.

Descriptive statistics of CRW population with hazard ratios for nonaccidental mortality, and outdoor concentrations of $PM_{2.5}$ at home and at work

Characteristic	CRW person-years (n)[a]	Deaths (n)[a]	HR[b]	95% CI Lower	Upper	$PM_{2.5}$ at home (μg/m^3) Mean ± SD	$PM_{2.5}$ at work (μg/m^3) Mean ± SD	Exposure difference (μg/m^3)[c] Mean ± SD
Total	10,872,400	24,100	–	–	–	7.30 ± 2.40	8.22 ± 2.57	0.92 ± 1.86
Sex								
Female	5,487,200	9,800	–	–	–	7.32 ± 2.41	8.05 ± 2.58	0.94 ± 1.82
Male	5,385,200	14,400	–	–	–	7.29 ± 2.40	9.70 ± 1.93	0.89 ± 1.89
Age (years)								
25–34	2,883,000	1,400	–	–	–	7.23 ± 2.33	8.18 ± 2.56	0.96 ± 1.83
35–44	3,961,600	5,900	–	–	–	7.19 ± 2.36	8.17 ± 2.56	0.97 ± 1.85
45–54	3,280,500	12,500	–	–	–	7.32 ± 2.41	8.23 ± 2.57	0.90 ± 1.85
55–64	731,200	4,200	–	–	–	8.05 ± 2.68	8.61 ± 2.61	0.55 ± 1.92
65–89	16,100	100	–	–	–	9.72 ± 3.04	9.78 ± 2.83	0.06 ± 2.08
Immigrant status								
No	9,739,800	21,700	–	–	–	7.11 ± 2.34	8.05 ± 2.58	0.94 ± 1.88
Yes	1,132,700	2,500	–	–	–	9.01 ± 2.25	9.70 ± 1.93	0.69 ± 1.66
Marital status								
Never married/not common-law[d]	2,351,900	4,900	1.00	–	–	7.81 ± 2.43	8.43 ± 2.47	0.62 ± 1.77
Common-law or married	7,186,300	14,100	0.57	0.55	0.59	7.06 ± 2.34	8.11 ± 2.60	1.06 ± 1.88
Separated, widowed, divorced	1,334,300	5,100	0.91	0.87	0.95	7.74 ± 2.47	8.43 ± 2.53	0.69 ± 1.79
Income quintile								
Q1 (lowest income)[d]	1,212,000	3,800	1.00	–	–	7.33 ± 2.46	7.96 ± 2.64	0.63 ± 1.76
Q2	1,820,500	4,200	0.75	0.72	0.79	7.34 ± 2.43	8.13 ± 2.59	0.79 ± 1.78
Q3	2,454,300	5,300	0.65	0.62	0.68	7.29 ± 2.40	8.17 ± 2.58	0.88 ± 1.81
Q4	2,712,300	5,600	0.56	0.54	0.59	7.25 ± 2.38	8.24 ± 2.56	0.99 ± 1.87
Q5 (highest income)	2,673,400	5,300	0.46	0.44	0.48	7.33 ± 2.38	8.42 ± 2.51	1.09 ± 1.95
Visible minority status								
No[d]	10,050,400	22,400				7.24 ± 2.36	8.19 ± 2.55	0.95 ± 1.87
Yes	822,100	1,700	1.24	1.18	1.31	8.06 ± 2.72	8.55 ± 2.83	0.49 ± 1.55
Indigenous identity								
No[d]	10,639,200	23,400	1.00	–	–	7.35 ± 2.39	8.28 ± 2.54	0.93 ± 1.86
Yes	233,200	800	1.92	1.79	2.05	5.29 ± 2.05	5.43 ± 2.54	0.14 ± 1.44
Employment status								
Employed[d]	9,922,100	21,000	1.00	–	–	7.35 ± 2.39	8.30 ± 2.53	0.95 ± 1.85
Unemployed or Not in labor force[e]	950,300	3,200	1.53	1.47	1.59	6.81 ± 2.53	7.44 ± 2.88	0.63 ± 1.85
Educational attainment								
<High school graduation[d]	1,847,900	6,700	1.00	–	–	6.95 ± 2.50	7.71 ± 2.75	0.77 ± 1.80
High school—with or without trades certificate	4,128,900	9,900	0.77	0.75	0.80	7.13 ± 2.36	8.09 ± 2.59	0.96 ± 1.86
Postsecondary nonuniversity	2,566,200	4,400	0.65	0.62	0.67	7.35 ± 2.35	8.39 ± 2.50	1.03 ± 1.88
University degree	2,329,400	3,200	0.49	0.47	0.51	7.84 ± 2.36	8.67 ± 2.37	0.84 ± 1.86
Occupational class								
Management	1,233,100	2,400	1.00	–	–	7.56 ± 2.40	8.53 ± 2.47	0.97 ± 1.86
Professional[d]	2,003,200	3,100	0.93	0.88	0.98	7.61 ± 2.38	8.53 ± 2.45	0.92 ± 1.88
Skilled, technical, and supervisory	3,243,000	7,100	1.44	1.38	1.51	7.17 ± 2.37	8.17 ± 2.57	0.99 ± 1.88
Semiskilled	3,329,400	8,200	1.25	1.19	1.31	7.27 ± 2.41	8.18 ± 2.57	0.90 ± 1.83
Unskilled	1,063,700	3,400	1.75	1.66	1.84	6.92 ± 2.46	7.59 ± 2.74	0.67 ± 1.77
Community Size								
>1,500,000	3,876,000	8,000	0.96	0.92	0.99	8.92 ± 1.90	9.89 ± 1.38	0.97 ± 1.82
500,000–1,499,999	1,319,200	2,800	0.95	0.91	1.00	7.66 ± 1.98	8.59 ± 1.86	0.93 ± 1.90
100,000–499,999	1,905,500	4,400	1.03	0.99	1.07	7.11 ± 2.37	8.02 ± 2.59	0.90 ± 1.80
30,000–99,999	997,800	2,400	0.98	0.93	1.03	6.45 ± 2.09	7.56 ± 2.54	1.11 ± 1.94
10,000–29,999	389,500	900	1.01	0.94	1.08	5.52 ± 1.56	5.71 ± 2.05	0.19 ± 1.67
Non-CMA/CA[d]	2,384,600	5,700	1.00	–	–	5.27 ± 1.50	6.16 ± 2.50	0.88 ± 1.89
Airshed								
East Central[d]	7,877,500	16,800	1.00	–	–	8.03 ± 2.25	9.23 ± 2.01	1.20 ± 1.90
Northern	135,000	300	1.12	1.00	1.26	4.03 ± 1.06	4.19 ± 1.70	0.17 ± 1.54
Prairie	368,200	1,000	1.49	1.40	1.59	6.57 ± 1.57	6.91 ± 1.86	0.34 ± 1.79
Southern Atlantic	2,006,700	4,500	1.02	0.99	1.06	4.93 ± 1.26	5.06 ± 1.62	0.13 ± 1.38
West Central	144,400	500	1.76	1.62	1.92	6.00 ± 1.33	6.55 ± 1.74	0.55 ± 1.32
Western	340,500	1,000	1.42	1.33	1.51	7.13 ± 1.78	7.15 ± 1.76	0.02 ± 1.70
Urban form								
Active urban core[d]	900,100	2,400	1.00	–	–	9.07 ± 2.00	9.22 ± 1.96	0.14 ± 1.59
Transit-reliant suburb	733,600	1,700	0.94	0.89	1.00	9.46 ± 1.94	9.66 ± 1.79	0.19 ± 1.50
Car-reliant suburb	4,635,300	9,400	0.79	0.76	0.83	8.18 ± 2.08	9.25 ± 1.94	1.07 ± 1.81
Exurban	685,100	1,400	0.78	0.73	0.84	6.24 ± 1.87	8.15 ± 2.35	1.91 ± 1.91
Non-CMA/CA	3,918,300	9,300	0.85	0.81	0.89	5.64 ± 1.79	6.52 ± 2.57	0.88 ± 1.90

(*Continued*)

Table 1.

(*Continued*)

Characteristic	CRW person-years (n)[a]	Deaths (n)[a]	HR[b]	95% CI Lower	Upper	$PM_{2.5}$ at home (μg/m³) Mean ± SD	$PM_{2.5}$ at work (μg/m³) Mean ± SD	Exposure difference (μg/m³)[c] Mean ± SD
Residential instability (CAN-Marg)								
Q1 (low marginalization)[d]	2,450,400	4,600	1.00	–	–	6.69 ± 2.32	8.09 ± 2.77	1.40 ± 1.89
Q2	2,774,600	5,900	1.03	0.99	1.07	6.65 ± 2.24	7.81 ± 2.66	1.16 ± 1.85
Q3	1,988,400	4,500	1.07	1.03	1.12	7.20 ± 2.39	8.00 ± 2.56	0.80 ± 1.83
Q4	1,997,700	4,900	1.13	1.09	1.18	8.00 ± 2.35	8.58 ± 2.38	0.59 ± 1.74
Q5 (high marginalization)	1,661,300	4,300	1.22	1.17	1.27	8.60 ± 2.12	8.93 ± 2.08	0.34 ± 1.73
Dependence (CAN-Marg)								
Q1 (low marginalization)[d]	1,911,700	3,500	1.00	–	–	7.60 ± 2.28	8.74 ± 2.31	1.14 ± 1.93
Q2	1,821,900	3,700	1.01	0.96	1.06	7.58 ± 2.25	8.83 ± 2.24	1.25 ± 1.92
Q3	1,723,400	3,800	1.04	1.00	1.09	7.75 ± 2.40	8.75 ± 2.36	1.00 ± 1.89
Q4	2,187,600	5,000	1.04	0.99	1.08	7.34 ± 2.47	8.14 ± 2.58	0.80 ± 1.78
Q5 (high marginalization)	3,227,900	8,200	1.07	1.03	1.11	6.70 ± 2.39	7.34 ± 2.73	0.64 ± 1.75
Material deprivation (CAN-Marg)								
Q1 (low marginalization)[d]	1,820,400	3,100	1.00	–	–	7.66 ± 2.27	9.01 ± 2.15	1.35 ± 1.92
Q2	1,894,600	3,700	1.08	1.03	1.14	7.65 ± 2.18	8.94 ± 2.18	1.29 ± 1.90
Q3	2,005,800	4,400	1.17	1.12	1.23	7.50 ± 2.26	8.54 ± 2.33	1.04 ± 1.89
Q4	1,938,300	4,600	1.26	1.20	1.31	7.64 ± 2.36	8.38 ± 2.40	0.75 ± 1.80
Q5 (high marginalization)	3,213,400	8,300	1.33	1.27	1.38	6.57 ± 2.55	7.06 ± 2.82	0.48 ± 1.69
Ethnic concentration (CAN-Marg)								
Q1 (low marginalization)[d]	4,084,300	8,900	1.00	–	–	6.18 ± 2.01	7.33 ± 2.60	1.14 ± 1.92
Q2	3,058,400	6,800	1.08	1.04	1.11	7.06 ± 2.21	8.11 ± 2.52	1.05 ± 1.91
Q3	1,591,400	3,600	1.14	1.09	1.18	8.11 ± 2.26	8.84 ± 2.36	0.73 ± 1.77
Q4	1,224,500	2,700	1.18	1.13	1.23	8.95 ± 2.10	9.40 ± 1.96	0.45 ± 1.64
Q5 (high marginalization)	913,800	2,100	1.29	1.23	1.36	9.53 ± 2.00	9.94 ± 1.74	0.41 ± 1.50

[a]Rounded to nearest hundred.
[b]Hazard ratio for nonaccidental mortality relative to reference category (d), stratified by age (5-year categories), sex, and immigrant status.
[c]Exposure at work (outdoor $PM_{2.5}$ concentration at workplace) minus exposure at home (outdoor $PM_{2.5}$ concentration at home) calculated at an individual level.
[d]Reference category.
[e]There is place of work information for those who are unemployed and not in the labor force on account of how the Census questions are asked: those who are unemployed or not in the labor force are defined as such if they were not active in the labor force in the week before Census day, yet work location was collected if they had worked that year.

Table 2.

Distribution of outdoor $PM_{2.5}$ concentration at work, home, and for the time-weighted exposure, for all person-years and the CRW population, μg/m³

Cohort	Exposure	Person-years[a] (n)	Deaths[a] (n)	$PM_{2.5}$ (μg/m³) percentiles Mean	Minimum	5th	25th	50th	75th	95th	Maximum
Full cohort	Exposure at home	42,653,300	401,900	7.29	0.60	3.82	5.24	6.94	8.97	12.04	18.50
Full cohort[b]	Time-weighted between work and home	42,653,300	401,900	7.35	0.60	3.83	5.31	7.04	9.04	12.02	18.50
CRW only	Exposure at home	10,872,400	24,100	7.30	0.77	3.89	5.38	7.07	8.97	11.45	18.29
CRW only	Exposure at work	10,872,400	24,100	8.22	0.00	3.66	6.25	8.75	10.17	11.76	18.70
CRW only	Time-weighted between work and home	10,872,400	24,100	7.51	0.79	3.95	5.72	7.45	9.16	11.33	17.78

[a]Rounded to nearest hundred.
[b]Time-weighted between work and home for those who are CRW, and exposure at home for everyone else.

Discussion

We examined a common limitation of studies examining associations between health outcomes and environmental exposures. In a large cohort, instead of relying solely on location of residence to estimate exposure to ambient $PM_{2.5}$, we considered workplace ambient $PM_{2.5}$ (when applicable), and a time-weighted average exposure estimate. The result is a first step toward exposure estimates based on daily behaviors at a population level. Importantly, we found that there was no significant difference in this cohort between a hazard ratio for nonaccidental mortality relying on outdoor $PM_{2.5}$ concentrations at home and a time-weighted exposure incorporating outdoor $PM_{2.5}$ concentrations at work and home. This result was true particularly if we examined the full cohort, although marginally tighter CIs were observed after including workplace exposures among the population that commuted to a regular workplace (CRW).

When examining exposure estimates within the CRW, exposure at work and exposure at home were overall higher for people living in marginalized neighborhoods, transit-reliant suburbs, large cities, and among those aged 65 or older (and still in the workforce). These results were as expected for a Canadian cohort[24] and broader environmental exposure work, which finds sociodemographic patterns of exposure,[25,26] with some materially and socially deprived people also being exposed to higher levels of ambient air pollution.

Exposure differences, that is, the difference between exposures at work and home, were highest for those who were living in exurban neighborhoods, and living in neighborhoods that were not considered marginalized. These results are consistent with a study of exposure misclassification in the United States, which found that exposure differences were largest for suburban and rural residents.[27] Among the CRW population in Canada, the

Table 3.

Cox proportional hazard ratios of nonaccidental mortality for exposure to $PM_{2.5}$, per increase of 10 μg/m³, for all person-years and the CRW population

Cohort	Exposure at home HR[a]	95% CI Lower	Upper	Exposure at work HR[a]	95% CI Lower	Upper	Time-weighted between work and home HR[a,b]	95% CI Lower	Upper
Full cohort									
Stratified by sex + age + immigrant[c]	0.99	0.97	1.00	–	–	–	0.98	0.96	0.99
+ individual-level covariates[d]	1.05	1.03	1.06	–	–	–	1.04	1.03	1.06
+ contextual covariates[e]	1.15	1.13	1.17	–	–	–	1.13	1.11	1.15
Fully adjusted model[c,d,e]	1.12	1.10	1.15	–	–	–	1.11	1.09	1.13
CRW only									
Stratified by sex + age + immigrant[c]	1.11	1.05	1.18	0.88	0.83	0.92	1.03	0.97	1.10
+ individual-level covariates[d]	1.17	1.10	1.24	1.03	0.98	1.09	1.14	1.07	1.21
–+ contextual covariates[e]	1.32	1.21	1.44	0.97	0.90	1.05	1.26	1.14	1.38
Fully adjusted model[c,d,e]	1.17	1.07	1.28	1.01	0.93	1.09	1.15	1.04	1.27

[a]Hazard ratios were compared (exposure at home vs. time-weighted) with Cochrane's Q and none were significantly different at $P < 0.05$.
[b]The time-weighted estimate was only available for the for CRW subpopulation within the full cohort and exposure at home was used for everyone else.
[c]Models were stratified by sex, age (5-year categories), immigrant status.
[d]Adjusted for income quintile, visible minority status, indigenous identity, educational attainment, labor force status, occupational group, marital status.
[e]Adjusted for community size, airshed, urban form, and four dimensions of CAN-Marg (instability, deprivation, dependency, and ethnic concentration).

Table 4.

Cox proportional hazard ratios of nonaccidental mortality for exposure to $PM_{2.5}$, per increase of 10μg/m³, for the CRW population, by subgroups

Characteristic	Person-years (n)[a]	Deaths (n)[a]	Exposure at home HR[c,d]	95% CI Lower	Upper	Time-weighted between work and home HR[c,d]	95% CI Lower	Upper	Exposure difference (μg/m³)[b] Mean	SD
Residential neighborhood										
Active urban core/transit-reliant suburb	1,633,700	4,100	0.68	0.53	0.88	0.63	0.48	0.82	0.17	1.55
Car-reliant suburb/exurban	5,320,400	10,700	1.15	1.00	1.31	1.08	0.93	1.25	1.18	1.85
Non-CMA/CA	3,918,300	9,300	1.42	1.22	1.65	1.45	1.24	1.69	0.88	1.90
Commute distance										
Less than 5 km	4,085,400	9,800	1.32	1.15	1.52	1.32	1.14	1.54	0.62	1.64
5 to <10 km	2,454,600	5,400	1.21	0.99	1.48	1.20	0.97	1.49	0.82	1.76
10 to <15 km	1,480,000	3,000	1.44	1.11	1.87	1.50	1.12	1.99	1.05	1.83
15 to <20 km	916,700	1,900	0.76	0.54	1.06	0.73	0.50	1.06	1.14	1.94
Greater than 20 km	1,935,700	4,100	0.90	0.73	1.11	0.84	0.67	1.06	1.47	2.20
Workplace										
Indoor workers	10,157,200	21,800	1.16	1.05	1.27	1.13	1.02	1.26	0.94	1.86
Outdoor workers	715,200	2,400	1.22	0.91	1.63	1.25	0.91	1.70	0.67	1.84
Occupational Class										
Skilled	6,479,300	12,600	1.01	0.89	1.15	0.97	0.84	1.11	0.97	1.88
Semiskilled or unskilled	4,393,200	11,600	1.37	1.20	1.56	1.38	1.20	1.59	0.85	1.82

[a]Rounded to nearest hundred.
[b]Exposure at work (outdoor $PM_{2.5}$ concentration at workplace) minus exposure at home (outdoor $PM_{2.5}$ concentration at home).
[c]Models were stratified by sex, age (5-year categories), immigrant status, and adjusted for income quintile, visible minority status, Indigenous identity, educational attainment, labor force status, occupational group, marital status, community size, airshed, urban form, and four dimensions of CAN-Marg (instability, deprivation, dependency, and ethnic concentration).
[d]Hazard ratios were compared (exposure at home vs. time-weighted) with Cochrane's Q and none were significantly different at $P < 0.05$.

average exposure difference was 0.92 μg/m³, which was larger than expected given the narrow range of possible exposures in Canada (0.0–18.70 μg/m³). A census-based study in the United Kingdom found a lower difference between residential and a time-weighed work-home estimate (0.1 μg/m³) despite having a similar range of exposures at the national level (2.3–21.8 μg/m³),[28] as did a smaller regional study from the United States (0.03 μg/m³; range = 1.25–16.58).[29] A study in Israel found that there was no difference in NO_2 exposures at work and home for a majority of the study sample[30] and a study by Yu et al.[31] found that home-based exposure estimates in China were not substantially different from cell-phone tracked exposures at the population level.

As stated by Dhondt, "detailed exposure models are of little use in public health if they cannot be used for assessing health impacts."[32] To quantify whether these exposure differences have a tangible impact on mortality estimates, we assessed them using the 2001 CanCHEC, a population-based cohort linked to mortality, which we have used to model mortality and $PM_{2.5}$ exposure at residence.[3] When we limited our cohort to the CRW population, the risk of death decreased by 2%, from 1.17 (95% CI = 1.07, 1.28) to 1.15 (95% CI = 1.04, 1.27). These results were not significantly different (i.e., Cochrane's Q results) but illustrate the magnitude of a possible difference if exposure at work was incorporated into a large, population-based mortality cohort, particularly if examining outcomes that are more prevalent among younger populations.

Including exposure at work into time-weighted estimates did not result in a difference for the full cohort, producing nearly identical hazard ratios and confidence intervals (i.e., HR = 1.12; 95% CI = 1.10, 1.15 for the exposure at home, and HR = 1.11; 95% CI = 1.09, 1.13 for the time-weighted estimate). These hazard ratios are higher than previously published results from the 2001 CanCHEC (HR = 1.08; 95% CI = 1.06, 1.11) which used a 3-year moving average,[3] whereas we used a 10-year moving average to align with analysis by Crouse et al.,[33] who indicated that a longer moving-average/spatial scale produced stronger associations between $PM_{2.5}$ and nonaccidental mortality. Our results suggest that incorporating outdoor $PM_{2.5}$ concentrations into a full cohort results in virtually no difference in the risk estimates for nonaccidental mortality. This may be due to workers being only a small subset of the population, working for a fraction of their adult life, working hours being a fraction of total hours each week, and most workers not living far enough away from home for air pollution levels to be drastically different. Importantly, nonaccidental deaths were more common among older adults who were no longer part of the working population.

We then examined cohort subgroups to identify which populations may be affected most by a time-weighted estimate. Although none of the time-weighted estimates were significantly different from the residence-only estimates, some differences are worthy of consideration in future work. When workplace exposures were included, those who lived outside of census-designated cities and towns (CMAs and CAs) and those with commutes of 10 to <15 km had higher HRs than other subgroups (when considered by commute-distance and neighborhood). The largest differences between the hazard ratios calculated with residential and time-weighted estimates were found in the group living in car-reliant suburbs and exurban neighborhoods, and those with commutes of 10 km or more, indicating that these two groups may be subject to greater exposure misclassification. Rural and suburban areas have been identified in the literature as an area of particular concern for exposure misclassification,[27,34] although we found that misclassification may be more likely for those living in the suburbs. We did find that misclassification may be higher for those with longer commutes, which is supported elsewhere in the literature.[9] Similar studies have found that exposure from workplace ambient $PM_{2.5}$ is not disproportionately higher than residential exposure.[8,27] Our findings indicate, however, that this is not the case for those with longer commutes where the residence-only and work-only exposure estimates differ, although the hazard ratios between these groups were not significantly different.

For those with lengthy commutes (time or distance), exposure during a commute may provide another possible route of substantial personal exposure to air pollution.[7,35] It may be valuable for cohorts of working age persons to consider workplace outdoor $PM_{2.5}$,[36,37] in places where long commutes and car-reliance are common. It may be that for these group, exposure during commute is a significant source compared with others, implying that our estimates (at home or time-weighted) are still an underestimation of exposure. It is worth noting that researchers in this field will need to reassess assumptions about commute and time-activity as working from home becomes routine for certain workers. Similarly, if proximity to an office is no longer a consideration, there may be significant shifts in where certain classes of workers choose to live and the nature of commutes will change. Our results indicate that there are already differences in exposure at work and home based on occupational class and whether a person works indoor or outdoors. New expectations about working from home may change or exacerbate these differences.

Strengths and limitations

A strength of the CanCHEC cohorts is the relatively accurate postal code histories that we rely on from 1981 to 2016.[13] In this study, we only had workplace location reported during the Census year, and we assumed that it did not change during subsequent years. Although this analysis did not account for leaving the workforce before age 65, entering the workforce after Census day, or change of work location, these limitations are comparable to those in other cohort studies that infer lifelong residential location from baseline.[38,39] Other research from Statistics Canada has also found that labor mobility (i.e., changing jobs) declines with age and more than two-thirds of Canadians held the same job for more than 10 years; these findings support our decision to assume a static workplace over the 15 years of follow-up.[40,41] To the best of our knowledge, Census workplace location provides the best available data in a large cohort to explore the impact of workplace outdoor $PM_{2.5}$ on nonaccidental mortality.

This work is limited in that we do not account for indoor or workplace concentrations of air pollutants for indoor or outdoor workers. This is an inherent limitation of large population-based cohorts for this type of research; rich data on time-activity patterns and concentrations encountered throughout the day would be best examined through a smaller point-of-contact study that includes personal monitoring with a time-activity survey,[4,42] which can be complemented by cell phone data.[31,43,44] These studies, in addition to ours, are limited in that they do not account for personal exposure and the variability in how air pollution dose interacts with the body.[4,42] Studies with time-activity surveys can inform models or datasets of varying complexity for predicting outcomes.[8,9,27,29,32,35,45,46] Review papers by Dias and Tchepel[4] and Steinle et al.[34] summarize the different methods available and the data gaps in the field. Large, population-based cohorts like ours could be enhanced through modeling of ambient air pollution encountered throughout the day as increased complexity has been shown to reduce exposure misclassification.[10,43,46,47] With the location of work and home, one could use traffic and travel models to predict commute path and outdoor concentrations of air pollutants during the commute.[7,45] This approach would be best if time of commute were available and if hourly air pollutant levels could be used. In this work, we used annual ambient $PM_{2.5}$ exposures at work and home in our model, which did not account for variation in exposure over the course of the day or year.

The results of this work indicate that hazard ratios relating $PM_{2.5}$ exposure to nonaccidental mortality may not be biased if relying solely on outdoor $PM_{2.5}$ concentration at home to inform models, at least in the Canadian context. Overall, in our Canadian cohort (i.e., low levels of exposure to $PM_{2.5}$), it appears that there are insufficient numbers of people within the population who work, and moreover who work in locations where ambient $PM_{2.5}$ concentrations at work are notably different from those at their home, to lead to meaningful differences between residential-only and exposures weighted to residence and place of work. It was unclear whether differences were meaningfully different from standard models; cohorts of workers or working age people may want to consider the potential for bias, especially if cohort members live in suburban or rural communities. Cohorts of different populations with more detailed spatiotemporal data, examining different exposures, expecting higher or lower exposures at work and at home, and following cohorts for a longer period may be better suited to examine this question.

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