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# Disease assimilation: The mortality impacts of fine particulate matter on immigrants to Canada

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## Abstract

**Background:** Immigrants make up 20% of the Canadian population; however, little is known about the mortality impacts of fine particulate matter (PM<sub>2.5</sub>) air pollution on immigrants compared with non-immigrants, or about how impacts may change with duration in Canada.

**Methods:** This study used the 2001 Canadian Census Health and Environment Cohort, a longitudinal cohort of 3.5 million individuals, of which 764,000 were classified as immigrants (foreign-born). Postal codes from annual income tax files were used to account for mobility among respondents and to assign annual PM<sub>2.5</sub> concentrations from 1998 to 2016. Exposures were estimated as a three-year moving average prior to the follow-up year. Cox survival models were used to determine hazard ratios (HRs) for cause-specific mortality, comparing the Canadian and foreign-born populations, with further stratification by year of immigration grouped into 10-year cohorts.

**Results:** Differences in urban–rural settlement patterns resulted in greater exposure to PM<sub>2.5</sub> for immigrants compared with non-immigrants (mean = 9.3 vs. 7.5 µg/m<sup>3</sup>), with higher exposures among more recent immigrants. In fully adjusted models, immigrants had higher HRs per 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentration compared with Canadian-born individuals for cardiovascular mortality (HR [95% confidence interval] = 1.22 [1.12 to 1.34] vs. 1.12 [1.07 to 1.18]) and cerebrovascular mortality (HR = 1.25 [1.03 to 1.52] vs. 1.03 [0.93 to 1.15]), respectively. However, tests for differences between the two groups were not significant when Cochran's Q test was used. No significant associations were found for respiratory outcomes, except for lung cancer in non-immigrants (HR = 1.10 [1.02 to 1.18]). When stratified by year of immigration, differences in HRs across varied by cause of death.

**Conclusions:** In Canada, PM<sub>2.5</sub> is an equal-opportunity risk factor, with immigrants experiencing similar if not higher mortality risks compared with non-immigrants for cardiovascular-related causes of death. Some notable differences also existed with cerebrovascular and lung cancer deaths. Continued reductions in air pollution, particularly in urban areas, will improve the health of the Canadian population as a whole.

**Keywords:** immigrant, air pollution, mortality, immigrant health, demography, fine particulate matter

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Ambient fine particulate matter (PM<sub>2.5</sub>) air pollution contributes to millions of deaths around the world each year and is a major contributor to the overall global burden of disease.<sup>1</sup> Given that many immigrants to Canada arrive from countries with higher levels of ambient air pollution, they could experience an increased risk of chronic disease with exposure.<sup>1</sup> While the mortality impacts of PM<sub>2.5</sub> have been demonstrated repeatedly in large cohorts representative of the Canadian-born population, immigrants have often been excluded from these analyses to some degree.<sup>2-6</sup> The proportion of the foreign-born population living in Canada in 2011 was 21%, or 7.1 million individuals, and is projected to rise to between 25% and 30% over the next 25 years to meet demographic and labour needs.<sup>7</sup> Therefore, it is important to understand the extent to which their risks from air pollution exposure may differ from those of the general population, particularly as the population ages and a larger proportion of Canadians become seniors.<sup>8</sup>

Disentangling the role of ambient air pollution on health from other important risk factors among Canadian immigrants is not

a trivial task. The immigrant population is neither static nor homogeneous; it has seen sharp demographic shifts over time that reflect immigration policies designed to meet different strategic purposes.<sup>9-11</sup> Further, settlement patterns also differentiate immigrants from the Canadian-born population. Immigrants tend to reside primarily in the largest metropolitan areas, with very little migration over time to smaller cities or rural areas where levels of PM<sub>2.5</sub> are lower.<sup>12,13</sup> Lastly, while immigrants tend to be healthier, at least initially, their health status is highly nuanced by several intersecting factors, including duration in host country, country of origin, sex and assessed health outcome.<sup>14-17</sup>

Taken together, immigrants to Canada have a different lived experience compared with Canadian-born individuals, with unknown prior exposures and different demographic, socioeconomic and baseline health characteristics. As such, the immigrant population poses an epidemiological challenge. Crouse et al. (2015) published the most recent study that examined air pollution impacts on the whole immigrant population,

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## What is already known on this subject?

- Immigrants are often excluded from large cohort studies on air pollution because of the potential risk of confounding for the following reasons:
  - The healthy immigrant advantage is demographically heterogeneous and declines over time.
  - Immigrants tend to settle in areas with higher levels of air pollution compared with the Canadian-born population.
  - Air pollution exposure prior to immigration is not known.

## What does this study add?

- The healthy immigrant advantage does not buffer against air pollution; air pollution is an equal-opportunity risk factor for mortality.
- Recent immigrants have a pronounced risk of cardiovascular-related mortality associated with exposure to fine particulate matter (PM<sub>2.5</sub>) air pollution.
- Future studies of Canadians should stratify by immigrant status.

using the 1991 Canadian Census Health and Environment Cohort.<sup>18</sup> This study found no increased risk of non-accidental or cardiometabolic disease mortality with PM<sub>2.5</sub> or ozone among the immigrant population, but did observe an increased risk for the traffic-related pollution marker nitrogen dioxide. Urban–rural differences were suggested as a possible explanation. However, as effects on immigrants were not the main focus of the Crouse et al. (2015) study, additional immigrant-related variables such as duration, country of origin and age at immigration were not explored.

The purpose of this study was to assess the risk of non-accidental and cause-specific mortality associated with long-term exposure to PM<sub>2.5</sub> among immigrants after they arrived in Canada,

and to assess how this risk compares with that of the non-immigrant population. Further, this study sought to determine the influence of several immigrant-specific variables on the PM<sub>2.5</sub>–mortality association, including duration in Canada, country of birth, age at immigration and neighbourhood ethnic concentration.

## Materials and methods

The 2001 Canadian Census Health and Environment Cohort is a longitudinal cohort of 3.5 million non-institutional respondents to the 2001 long-form census questionnaire, linked to mortality and annual residential postal codes. All deaths registered in provincial and territorial registries between Census Day (May 15, 2001) and December 31, 2016, were eligible for linkage during the nearly 16-year follow-up period. The linkage methodology and cohort description have been provided elsewhere.<sup>4,19</sup> From the initial in-scope cohort (N = 47,953,820 person-years), the analytical cohort was restricted to people between the ages of 25 and 89 years at baseline. Once respondents turned 90, subsequent person-years were excluded (N = 449,500, or 0.9% of all in-scope person-years) because the likelihood of the addresses from tax files reflecting those older respondents' actual addresses<sup>20</sup> diminished, leading to a greater risk of exposure misclassification.

Environmental exposures were assigned to respondents using their annual residential postal code histories from tax records. Postal codes were geocoded using Statistics Canada's Postal Code Conversion File Plus (PCCF+), version 7A. The PCCF+ uses a population-weighted random allocation algorithm to assign latitude and longitude coordinates to postal codes based on the centroid of a block face, dissemination block or dissemination area.<sup>21</sup> Missing postal codes in the tax files were imputed based on those reported in adjacent years, using a method where the probability of imputation varies depending on the number of adjacent years missing.<sup>22</sup> In the analytical file, 1.4% of all per-

son-years received an imputed postal code through this process. Person-years were excluded from the final analytical cohort if a postal code of fewer than two digits was imputed, if the postal code was missing entirely, or if the postal code was not matched to a PM<sub>2.5</sub> estimate (N = 1,050,200, or 2.2%).

PM<sub>2.5</sub> estimates were derived from a North American model that combines satellite measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) and relates total column aerosol optical depth retrievals to near-surface PM<sub>2.5</sub> using the GEOS-Chem chemical transport model. Geographically weighted regression was then used to further refine the PM<sub>2.5</sub> estimates using ground-based observations from the National Air Pollution Surveillance network to produce 1 km<sup>2</sup> annual average estimates from 1989 to 2015.<sup>23-25</sup> PM<sub>2.5</sub> estimates were then assigned to all person-years based on residential postal codes, using a three-year moving average to increase the stability of near-term exposure history estimates and applying a one-year lag to ensure the exposure precedes the event (e.g., 2001 PM<sub>2.5</sub> = average PM<sub>2.5</sub> from 1998, 1999 and 2000). Further details on this methodology can be found elsewhere.<sup>4</sup> At least two out of the three previous years needed to have non-missing PM<sub>2.5</sub> concentrations, and person-years that did not meet these criteria were removed (N = 4,987,197, or 10.4%).

Person-level socioeconomic and demographic variables were collected from the 2001 long-form census questionnaire and are static with follow-up time. Described in detail elsewhere,<sup>4</sup> they include self-reported age, sex, visible minority status, Aboriginal identity, marital status, educational attainment, income adequacy quintiles, employment status and occupational classification. Immigrants were categorized based on years since becoming a permanent resident (>30 years, 21 to 30 years, 11 to 20 years, ≤10 years). There are three broad administrative immigrant categories under which people are admitted to Canada as permanent

residents: economic immigrants, immigrants who are family members (spouse, children, parents) of immigrants or permanent residents, and immigrants admitted as protected people (e.g., refugees).<sup>7</sup> All three immigrant categories were included in this analysis since there was no definitive way to distinguish them. Additional immigrant-related variables were considered, including age at immigration and geographic region of birth, both of which are crude measures of length and location of historical exposures and experiences (e.g., air pollution, sociocultural norms, diet and behaviours) before immigrating to Canada. Area-based contextual variables describing neighbourhood characteristics and geographic identifiers were used to encapsulate risk factors beyond those at the person level. These include the Canadian Marginalization Index (CAN-Marg), community size, urban form, and regional airshed (described in further detail below). Each variable was assigned to individual postal codes and PCCF+-linked census geography for the closest census year (every five years from 2001 to 2016). Person-years with missing or incomplete postal code data that resulted in missing contextual covariates were removed ( $N = 1,914,800$ , or 4.0%).

CAN-Marg consists of four dimensions that aim to capture the following different aspects of marginalization in Canada using data from the 2001 and 2006 long-form census questionnaires: material deprivation, residential (housing) instability, ethnic concentration (proportion of recent immigrants and visible minorities) and dependency (concentration of seniors or youth).<sup>26</sup> CAN-Marg was developed at two different geography levels: dissemination areas (the smallest census enumeration units, consisting of 250 to 800 people) and census tracts. Census tracts are designed to represent small, relatively stable geographic neighbourhood areas that have populations between 2,500 and 8,000 and are located in census metropolitan areas (CMAs) and census agglomerations (CAs) with core popu-

lations of 50,000 or more according to the previous census.<sup>27</sup> CAN-Marg was assigned at two different levels of geography using postal codes and the PCCF+, which were then assigned to quintiles for statistical analysis. People residing within CMAs and CAs were assigned census tract CAN-Marg estimates. Because census tracts do not exist outside these areas, the dissemination area CAN-Marg factors were aggregated up to the census subdivision, following the methodology suggested by Matheson et al. (2012), using population weighting across dissemination areas.<sup>26</sup> Census subdivision is the geographic unit for municipalities or areas that are treated as municipal equivalents for statistical purposes (e.g., First Nations reserves).<sup>27</sup>

Community (population) size was derived from the PCCF+, and each postal code was classified as belonging to a community that was either rural, small (1,000 to 29,999 residents), medium (30,000 to 99,999 residents), medium-large (100,000 to 500,000 residents), large (500,000 to 1.5 million residents) or a metropolis (>1.5 million residents). The largest community size category includes the three largest Canadian cities (Toronto, Montréal and Vancouver), where a majority of immigrants settle.<sup>12</sup> Because community size does not perfectly delineate between people living across the urban-to-rural continuum within CMAs and CAs, communities and neighbourhoods were further differentiated within the urban environment based on population density and the most frequently reported mode of transportation (active, transit or personal vehicle) in each census tract.<sup>28</sup> The final categorization of urban form was active urban core, transit-reliant suburb, car-reliant suburb, exurban and non-CMA or CA.

Airsheds have been included as a covariate to represent regional differences in mortality rates across Canada that remain uncaptured by other geographic variables. Airsheds have been defined by the Air Quality Management System and include six broad regions of Canada (Western, Prairie, West Central, Southern Atlantic, East Central and

Northern) based on large-scale differences in air masses and meteorological parameters.<sup>29</sup>

Standard Cox proportional hazards models were fitted to examine the associations between ambient  $PM_{2.5}$  exposure and non-accidental and cause-specific mortality. Respondents were followed from the census baseline year (2001) to either the year of death or the final year of follow-up (2016). The following causes of death were considered: non-accidental (International Statistical Classification of Diseases and Related Health Problems 10th Revision [ICD-10] codes A to R), cardiovascular (ICD-10 I10 to I69, with and without diabetes, E10 to E14), ischemic heart disease (ICD-10 I20 to I25), cerebrovascular disease (ICD-10 I60 to I69), non-malignant respiratory disease (ICD-10 J00-J99), chronic obstructive pulmonary disease (ICD-10 J19 to J46) and lung cancer (ICD-10 C33 to C34). All survival models were stratified by five-year age groups and sex, and adjusted for individual and contextual variables. All counts and sample sizes were rounded to base 5 for institutional confidentiality reasons. All hazard ratio (HR) estimates were provided per  $10 \mu\text{g}/\text{m}^3$  increase in  $PM_{2.5}$ , and between-group differences were tested for significance at the  $p < 0.05$  level using Cochran's Q test.

## Results

In total, 3.1 million people were followed between 2001 and 2016, and 22% (684,400 people) were immigrants (Table 1). However, immigrants made up 28% of the total person-years (10,066,900 of 35,339,500 person-years). On average, immigrants had 20% higher exposure to ambient  $PM_{2.5}$  than non-immigrants ( $9.3 \mu\text{g}/\text{m}^3$  vs.  $7.5 \mu\text{g}/\text{m}^3$ ), with a trend of slightly increasing mean  $PM_{2.5}$  exposure with shorter duration in Canada. There were clear distinctions in cohort characteristics between non-immigrants, established immigrants (pre-1971) and more recent immigrants (1971 to 2000), but even further distinction among recent immi-

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**Table 1**  
**Descriptive statistics (number and percentage) of demographic and socioeconomic characteristics of the 2001 Canadian Census Health and Environment Cohort, by immigrant status and duration in Canada**

Characteristic	Full cohort	Non-immigrants	Period of immigration			
			Pre-1971	1971 to 1980	1981 to 1990	1991 to 2001
<b>Number</b>	<b>3,101,605</b>	2,417,175	255,985	138,260	125,780	164,405
	number			percentage		
<b>Mean PM<sub>2.5</sub></b>	...	7.53	9.13	9.28	9.54	9.69
<b>Standard deviation</b>	...	2.65	2.53	2.28	2.13	2.02
<b>Age (in years)</b>						
25 to 29	254,345	9.0	0.0	5.1	8.6	12.7
30 to 39	699,420	23.4	4.6	17.8	28.3	37.9
40 to 49	785,910	26.0	12.0	27.4	32.3	27.8
50 to 59	588,400	18.3	26.1	30.3	15.5	11.3
60 to 69	390,230	11.8	27.6	11.8	7.3	6.2
70 to 79	283,140	8.5	22.9	5.6	5.9	3.4
80 to 89	100,160	3.2	6.8	2.1	2.0	0.8
<b>Sex</b>						
Male	1,500,105	48.4	50.0	48.4	47.4	46.9
Female	1,601,500	51.7	50.0	51.7	52.6	53.1
<b>Visible minority status</b>						
No <sup>†</sup>	2,651,875	93.6	90.0	49.0	35.4	28.4
Yes	449,735	6.4	10.0	51.0	64.6	71.6
<b>Aboriginal identity</b>						
No <sup>†</sup>	2,974,315	94.8	99.9	99.7	99.7	99.9
Yes	127,295	5.2	0.1	0.3	0.3	0.1
<b>Marital status</b>						
Single, never married	373,240	13.0	4.9	10.0	11.2	10.8
Common-law	310,610	11.8	3.2	4.5	4.0	3.2
Married <sup>†</sup>	1,987,330	61.3	73.0	72.9	73.5	77.0
Separated	75,420	2.4	2.1	2.7	2.9	2.6
Divorced	172,030	5.8	5.6	5.4	4.4	3.1
Widowed	182,970	5.7	11.2	4.5	4.0	3.3
<b>Highest level of education</b>						
Did not complete high school	889,010	28.6	37.4	25.3	25.7	21.7
Completed high school	1,091,085	36.3	32.5	32.2	31.7	28.5
Postsecondary diploma	592,935	19.4	15.8	20.4	20.2	17.8
University degree <sup>†</sup>	528,575	15.8	14.3	22.1	22.4	32.0
<b>Income adequacy</b>						
Quintile 1 (low)	578,390	17.4	19.4	16.7	22.9	33.7
2	615,285	19.0	21.3	19.8	24.3	26.6
3	626,060	20.3	19.3	21.3	21.7	18.6
4	634,540	21.2	19.2	21.6	17.8	12.7
Quintile 5 (high) <sup>†</sup>	647,330	22.1	20.8	20.6	13.3	8.4
<b>Labour force status</b>						
Employed <sup>†</sup>	1,973,715	64.8	43.8	71.4	71.1	65.6
Unemployed	124,685	4.1	1.8	3.3	4.3	6.4
Not in labour force	1,003,205	31.1	54.5	25.3	24.6	28.1
<b>Occupational class</b>						
Management <sup>†</sup>	258,590	8.43	7.35	10.03	8.52	7.00
Professional	382,700	12.36	9.27	14.88	13.08	14.11
Skilled	699,905	23.54	16.02	23.28	22.09	18.27
Semi-skilled	654,305	21.39	12.63	22.50	25.34	25.58
Unskilled	213,175	6.76	4.24	7.33	9.24	10.44
Not in workforce	892,930	27.53	50.49	21.97	21.72	24.59
<b>Place of birth</b>						
Non-immigrant <sup>†</sup>	2,417,175	100.0	...	...	...	...
United States	31,735	...	5.0	7.1	3.9	2.6
Latin America, Caribbean	67,760	...	4.2	15.5	14.9	10.2
Europe, Oceania	333,800	...	82.1	38.3	27.4	22.1
Sub-Saharan Africa <sup>**</sup>	20,560	...	0.6	4.5	4.1	4.7
West and Central Asia, North Africa	36,245	...	2.1	4.2	7.8	9.4
East Asia	138,375	...	4.2	22.1	31.3	35.0
South Asia	55,955	...	1.9	8.3	10.5	16.1

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**Descriptive statistics (number and percentage) of demographic and socioeconomic characteristics of the 2001 Canadian Census Health and Environment Cohort, by immigrant status and duration in Canada**

Characteristic	Full cohort number	Non-immigrants	Period of immigration			
			Pre-1971	1971 to 1980	1981 to 1990	1991 to 2001
			percentage			
<b>Age at immigration</b>						
Non-immigrant <sup>†</sup>	2,417,175	100.0	...	...	...	...
Younger than 10	82,570	...	23.7	14.2	1.7	0.0
10 to 17	73,040	...	14.5	14.4	11.4	1.1
18 to 24	150,540	...	26.5	24.7	22.0	12.7
25 to 39	275,000	...	31.8	35.4	44.3	54.2
40 to 54	74,590	...	3.5	9.0	13.3	22.2
55 and older	28,690	...	0.1	2.2	7.3	9.9
<b>Neighbourhood instability</b>						
Quintile 1 (low) <sup>‡</sup>	734,265	23.9	21.4	27.0	25.1	19.7
2	802,220	26.8	24.1	23.4	22.4	20.1
3	613,760	19.5	21.6	20.0	20.5	19.9
4	553,285	17.3	20.5	17.5	18.7	21.4
Quintile 5 (high)	398,075	12.5	12.4	12.1	13.4	18.9
<b>Neighbourhood deprivation</b>						
Quintile 1 (low) <sup>‡</sup>	554,545	16.9	23.3	23.3	20.6	17.3
2	651,600	21.2	22.7	21.3	19.0	17.6
3	580,995	18.4	19.7	20.1	20.1	20.3
4	573,685	18.3	17.9	18.0	19.4	21.8
Quintile 5 (high)	740,775	25.3	16.3	17.3	21.0	23.0
<b>Neighbourhood dependency</b>						
Quintile 1 (low) <sup>‡</sup>	537,930	16.5	14.9	23.4	24.3	23.9
2	529,285	16.2	16.6	22.4	22.7	22.5
3	498,585	15.3	18.2	18.5	18.8	19.8
4	681,610	22.6	22.5	18.6	18.4	18.3
Quintile 5 (high)	854,200	29.5	27.8	17.2	15.9	15.4
<b>Neighbourhood ethnic concentration</b>						
Quintile 1 (low) <sup>‡</sup>	946,070	35.8	19.8	10.3	6.9	4.1
2	737,040	26.9	18.8	12.5	9.0	5.9
3	536,545	17.7	19.7	16.6	13.6	10.7
4	439,290	12.3	19.6	22.6	22.4	20.3
Quintile 5 (high)	442,655	7.3	22.1	38.1	48.1	59.0
<b>Urban form</b>						
Active urban core <sup>†</sup>	237,970	7.07	8.65	9.23	9.69	12.15
Transit-reliant suburb	238,645	5.60	10.90	13.57	17.27	21.18
Car-reliant suburb	1,276,230	36.41	54.19	60.96	61.37	58.41
Exurban	156,160	5.53	4.40	3.29	2.59	2.03
Non-CMA/CA	1,192,605	45.39	21.87	12.95	9.08	6.23
<b>Community size (population in 2001)</b>						
1.5 million and more <sup>†</sup>	980,060	23.7	47.7	60.1	66.0	72.5
500,000 to 1.49 million	501,910	16.3	15.6	17.0	16.6	14.2
100,000 to 499,999	518,435	17.9	17.5	11.5	9.7	8.1
30,000 to 99,000	275,900	10.2	6.7	3.9	2.7	1.9
1,000 to 29,999	111,960	4.3	2.1	1.4	0.7	0.6
Rural	713,340	27.6	10.4	6.2	4.4	2.8
<b>Airshed</b>						
Western <sup>‡</sup>	381,310	10.7	16.7	18.1	16.7	20.3
Prairie	401,165	13.9	9.0	11.0	10.1	8.3
West Central	187,180	6.8	4.1	3.5	3.1	2.0
Southern Atlantic	279,305	11.1	1.9	1.9	1.2	0.9
East Central	1,830,165	56.5	68.3	65.4	68.8	68.5
Northern	22,475	0.9	0.1	0.1	0.0	0.0

... not applicable

<sup>†</sup> Reference value in adjusted models.

<sup>‡</sup> South African immigrants were categorized based on ethnic origin (e.g., German, Chinese, Black African).

**Note:** PM: particulate matter.

**Source:** 2001 Canadian Census Health and Environment Cohort.

grants (post-1980). Recent immigrants were generally younger, and a greater proportion were women, visible minorities, married and had higher education. However, they also tended to have lower income, and a greater percentage tended to be unemployed. Geographically, all immigrant groups were much more likely to live in the Western (i.e., Vancouver) or East Central (i.e., Toronto and Montréal) airsheds. This corresponds to the large proportion of immigrants living in the largest metropolitan areas more generally. Recent immigrants were also much more likely to live in neighbourhoods with higher densities of ethnic populations and with a younger, working population demographic (i.e., low neighbourhood dependency).

Among immigrants, place of birth and age at immigration shifted considerably with the different periods of immigration. For example, before 1970, 82% of immigrants were from Europe or Oceania, but that dropped to 38% for the period of 1971 to 1980, and dropped further to 27% and 22% in subsequent immigration periods. Conversely, immigration from East Asia, South Asia, and Latin America and the Caribbean increased considerably during the latter three immigration

**Table 2**  
**Person-years, death events and cause-specific mortality hazard ratios by period of immigration**

	Non-immigrants	Period of immigration			
		Pre-1971	1971 to 1980	1981 to 1990	1991 to 2000
<b>Total person-years (number)</b>	35,339,475	3,480,635	2,055,710	1,871,820	2,658,710
<b>Non-accidental deaths (number)</b>	323,430	60,300	12,145	8,160	7,170
Hazard ratio	Ref.	0.86	0.82	0.80	0.68
(95% confidence interval)	...	(0.85 - 0.87)	(0.80 - 0.83)	(0.78 - 0.82)	(0.66 - 0.70)
<b>Cardiometabolic deaths (number)</b>	104,535	20,930	3,920	2,790	2,205
Hazard ratio	Ref.	0.90	0.84	0.84	0.66
(95% confidence interval)	...	(0.88 - 0.91)	(0.81 - 0.87)	(0.80 - 0.88)	(0.63 - 0.69)
<b>Cardiovascular deaths (number)</b>	93,535	19,040	3,430	2,465	1,985
Hazard ratio	Ref.	0.90	0.83	0.85	0.68
(95% confidence interval)	...	(0.89 - 0.92)	(0.80 - 0.86)	(0.81 - 0.89)	(0.65 - 0.72)
<b>Ischemic heart disease deaths (number)</b>	51,070	9,865	1,790	1,260	1,010
Hazard ratio	Ref.	0.87	0.80	0.81	0.65
(95% confidence interval)	...	(0.85 - 0.89)	(0.76 - 0.84)	(0.76 - 0.87)	(0.61 - 0.70)
<b>Cerebrovascular deaths (number)</b>	16,800	3,860	750	575	510
Hazard ratio	Ref.	0.97	0.95	0.97	0.87
(95% confidence interval)	...	(0.93 - 1.00)	(0.88 - 1.03)	(0.88 - 1.07)	(0.78 - 0.96)
<b>Respiratory deaths (number)</b>	29,635	4,635	855	550	520
Hazard ratio	Ref.	0.67	0.71	0.66	0.63
(95% confidence interval)	...	(0.64 - 0.69)	(0.66 - 0.76)	(0.60 - 0.73)	(0.57 - 0.70)
<b>COPD deaths (number)</b>	16,780	2,185	330	210	180
Hazard ratio	Ref.	0.57	0.57	0.58	0.51
(95% confidence interval)	...	(0.54 - 0.60)	(0.50 - 0.63)	(0.50 - 0.67)	(0.43 - 0.60)
<b>Lung cancer deaths (number)</b>	35,420	5,055	1,055	650	620
Hazard ratio	Ref.	0.72	0.66	0.67	0.62
(95% confidence interval)	...	(0.70 - 0.74)	(0.62 - 0.70)	(0.61 - 0.73)	(0.57 - 0.68)

... not applicable

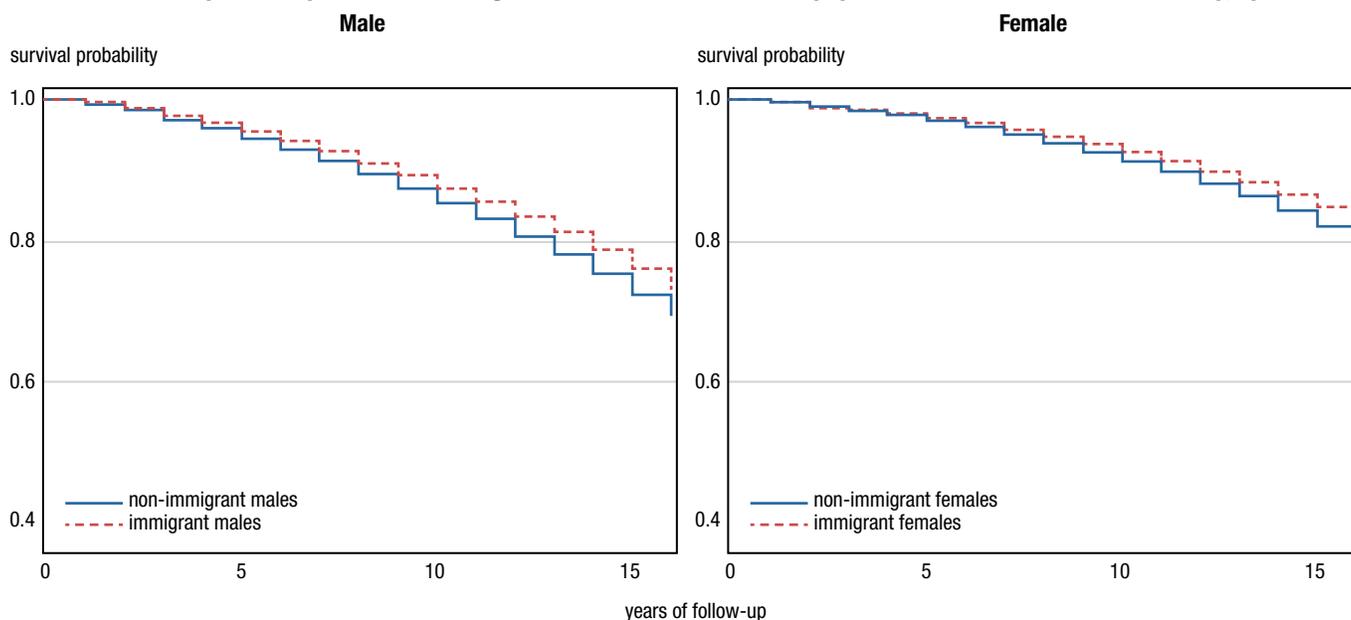
Ref. = Reference category is non-immigrants.

Notes: COPD: chronic obstructive pulmonary disease.

Hazard ratios are stratified by sex and by five-year age groups, and adjusted for visible minority; Aboriginal identity; marital status; education; income quintile; employment status; occupational class; community size; urban form; airshed; and neighbourhood instability, deprivation, dependency and ethnic concentration.

Source: 2001 Canadian Census Health and Environment Cohort.

**Figure 1**  
**Predicted survival probability curves for immigrants and the Canadian-born population for non-accidental mortality, by sex**



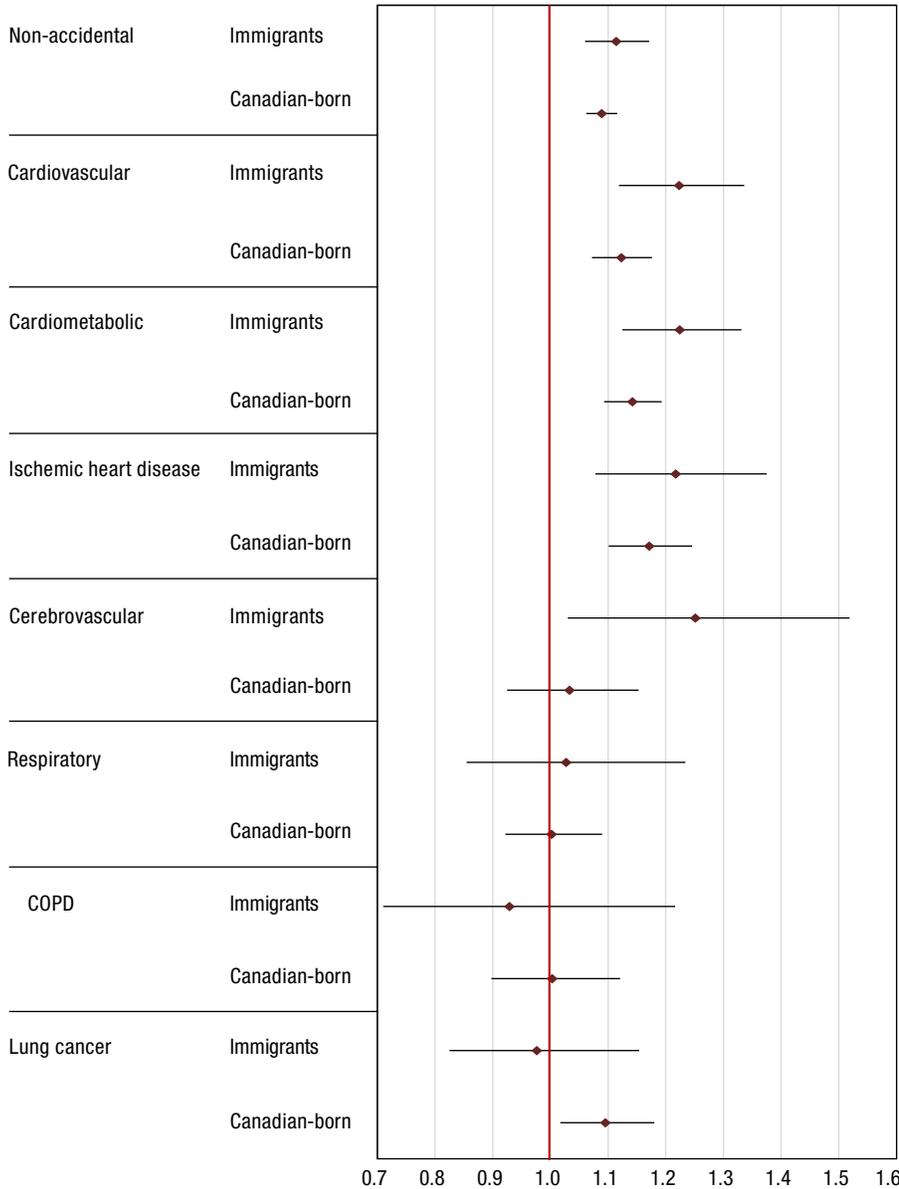
Source: 2001 Canadian Census Health and Environment Cohort.

periods. Age at immigration exhibited similar shifts over time. Established immigrants arrived much earlier in their lives, whereas recent immigrants arrived mostly as young or middle-aged adults (aged 25 to 54).

Immigrants exhibited lower non-accidental and cause-specific mortality HRs than non-immigrants, with a downward trend among more recent immigrants (Table 2). There were also sex differences between immigrants and non-immigrants

in survival probability (Figure 1). The relationships between  $PM_{2.5}$  and non-accidental and cause-specific mortality among the immigrant and non-immigrant populations are presented in Figure 2, displaying their HRs and 95% confidence intervals (CIs). These results show an increased risk of non-accidental, cardiovascular, cardiometabolic and ischemic heart disease mortality with increased  $PM_{2.5}$  exposure for both immigrants and non-immigrants, and an increased risk of cerebrovascular mortality with increased  $PM_{2.5}$  exposure among immigrants only. While the HRs were higher for immigrants than for non-immigrants, tests for differences between the two groups were not significant when Cochran's Q test was used. Among the three respiratory causes of death, only lung cancer had a positive association with  $PM_{2.5}$  exposure, and only among the non-immigrant population. Figure 3 shows the stratified models by year of immigration. In fully adjusted models, recent immigrants tended to exhibit similar or greater sensitivity to  $PM_{2.5}$  exposure compared with established immigrants and non-immigrants, although wide CIs challenge the ability to interpret observed trends. For example, exposure to  $PM_{2.5}$  increased the risk of mortality for non-immigrants and established immigrants (>30 years) for non-accidental mortality by 9% and 11%, respectively (HR [95% CI] = 1.09 [1.06 to 1.12] and 1.11 [1.05 to 1.18]). However, recent (11 to 20 years) and very recent ( $\leq 10$  years) immigrants exhibited a 24% and 19% increase in risk per  $10 \mu g/m^3$  (HR [95% CI] = 1.24 [1.03 to 1.49] and 1.19 [0.97 to 1.45]). Similar patterns were observed with cardiovascular, cardiometabolic and ischemic heart disease mortality, but not with cerebrovascular mortality or mortality for any of the pulmonary conditions. Recent immigrants (11 to 20 years) were the only subpopulation group to show an increased risk of lung cancer mortality with increased  $PM_{2.5}$  exposure (HR [95% CI] = 1.81 [0.96 to 3.44]). Semi-established immigrants (21 to 30 years) consistently exhibited no association with  $PM_{2.5}$  exposure for all

**Figure 2**  
Adjusted hazard ratios (95% CI) of  $PM_{2.5}$  for cause-specific mortality per  $10 \mu g/m^3$  among all immigrants† and the Canadian-born population



† Immigrant models did not adjust for Aboriginal identity and were additionally adjusted for place of birth, age at immigration and year of immigration.

CI: confidence interval

$PM_{2.5}$ : fine particulate matter

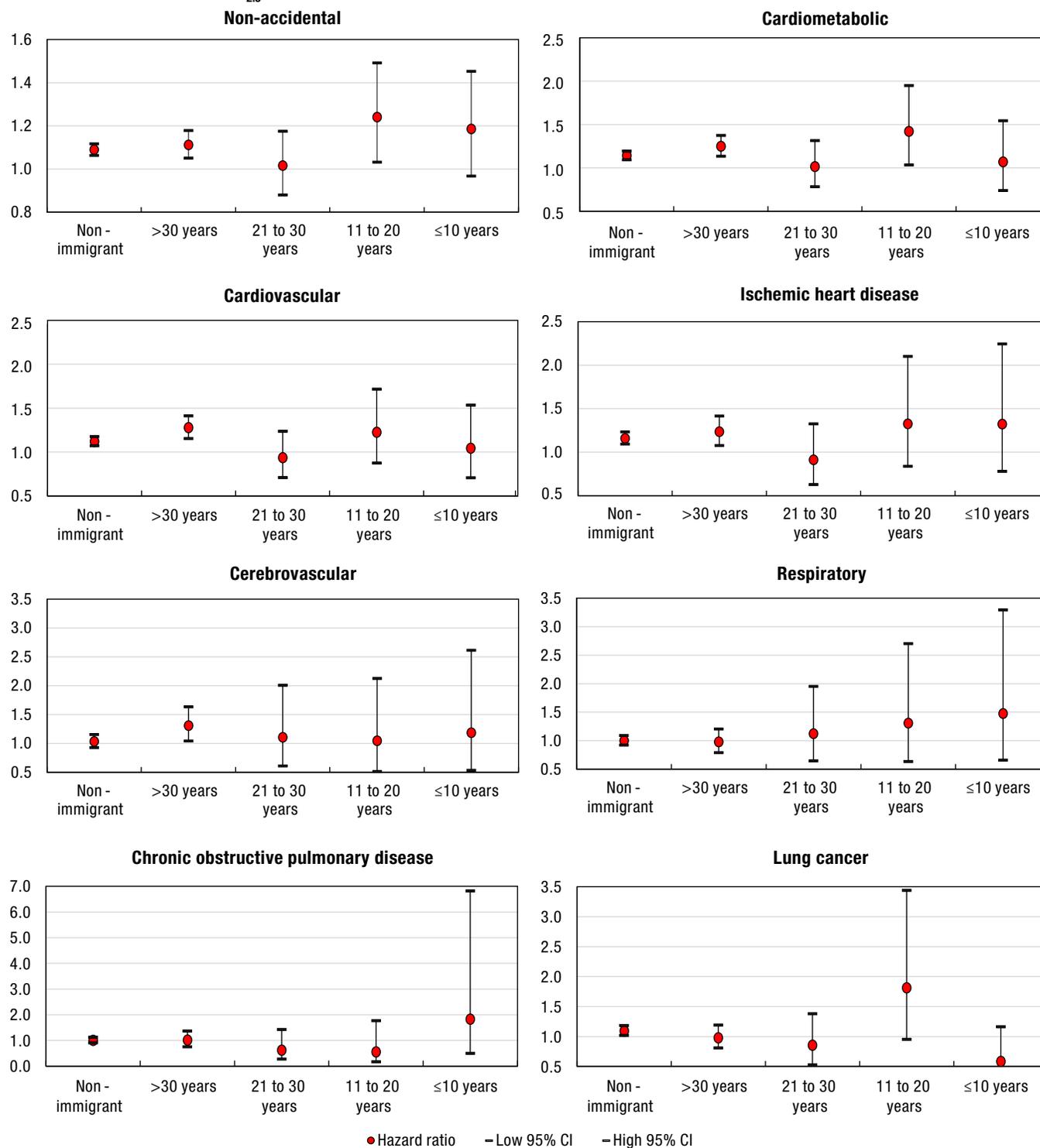
COPD: chronic obstructive pulmonary disease

**Notes:** Hazard ratios are stratified by sex and by five-year age groups, and adjusted for visible minority; Aboriginal identity; marital status; education; income quintile; employment status; occupational class; community size; urban form; airshed; and neighbourhood instability, deprivation, dependency and ethnic concentration.

**Source:** 2001 Canadian Census Health and Environment Cohort.

*Disease assimilation: The mortality impacts of fine particulate matter on immigrants to Canada • Research Article*

**Figure 3**  
**Hazard ratios (95% CI) for PM<sub>2.5</sub> and cause-specific mortality by immigrant status† per 10µg/m<sup>3</sup>**



† Immigrant models did not adjust for Aboriginal identity, and were additionally adjusted for place of birth, age at immigration and year of immigration.

**Notes:** Hazard ratios are stratified by sex and by five-year age groups, and adjusted for visible minority; Aboriginal identity; marital status; education; income quintile; employment status; occupational class; community size; urban form; airshed; and neighbourhood instability, deprivation, dependency and ethnic concentration. CI: confidence interval. PM<sub>2.5</sub>: fine particulate matter.  
**Source:** 2001 Canadian Census Health and Environment Cohort.

causes of mortality. Tests for significant differences between subgroups using Cochran's Q test were not significant.

When the influence of waves of immigration was assessed against increasing levels of  $PM_{2.5}$  exposure (Figure 4), semi-established immigrants (21 to 30 years) had a slightly decreased HR with increasing  $PM_{2.5}$ , compared with established immigrants (>30 years). Very recent immigrants ( $\leq 10$  years) showed an increased HR with increasing  $PM_{2.5}$  exposure, compared with established immigrants. Conversely, recent immigrants (11 to 20 years) showed a large increase in HR with increasing  $PM_{2.5}$ . While place of birth, age at immigration and neighbourhood ethnic concentration were important mortality risk factors, their impact on  $PM_{2.5}$ -related mortality was negligible (results not shown). In this study's analysis of different adjustment strategies, there was little difference between stratification by immigrant status and adjustment by year of immigration. Both variables exhibited larger HRs compared with models that included all immigrants but did not adjust for them (Figure 5).

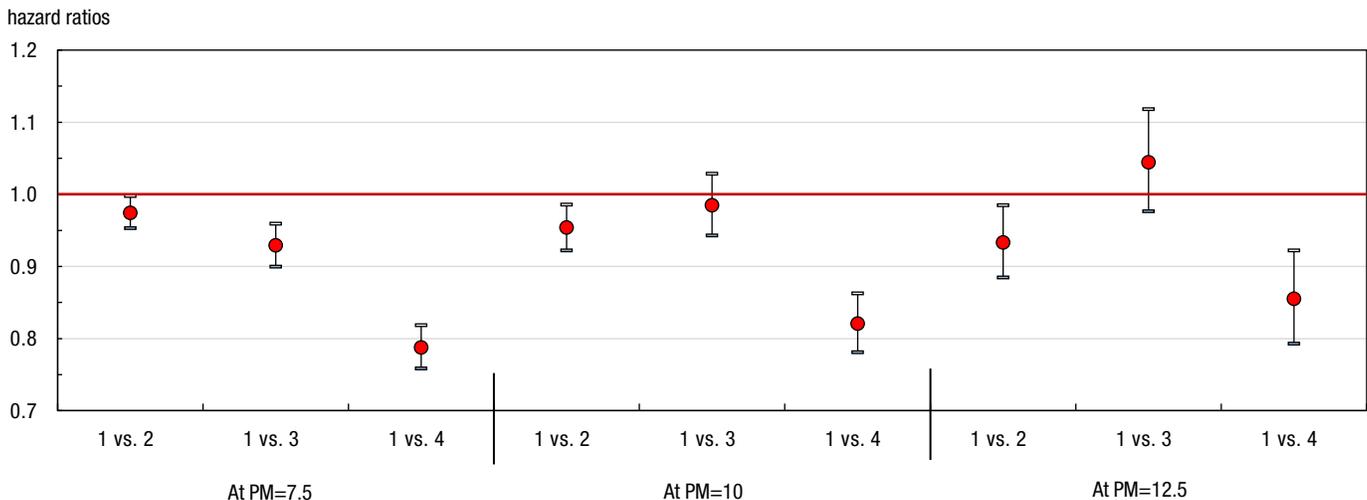
## Discussion

Air pollution is a leading risk factor for mortality among the Canadian population, with an estimated 14,400 attributable annual deaths.<sup>30</sup> The overarching purpose of this study was to establish, using a large Canadian longitudinal census cohort, whether immigrants are similar to non-immigrants in their sensitivity to  $PM_{2.5}$  exposure in terms of mortality, and whether that sensitivity changes with duration of residence in Canada and for different causes of death. The analysis included other immigrant-related factors—such as place of birth, age at immigration and neighbourhood ethnic concentration—as covariates in the  $PM_{2.5}$ -mortality risk models.

Overall, immigrants had higher exposure levels to  $PM_{2.5}$  than non-immigrants, a difference that is most pronounced in the first few years since immigration.<sup>13</sup> This is because of settlement patterns where recent immigrants initially move into the urban core of the largest metropolitan centres in Canada, where there are higher levels of  $PM_{2.5}$ . However, even after adjusting for these variables, immigrants were more sensitive to  $PM_{2.5}$  exposure than

non-immigrants, with larger HRs for cardiovascular, ischemic heart disease, cardiometabolic and cerebrovascular mortality outcomes. When stratified by wave of immigration, the results varied slightly according to cause of death, but generally showed higher HRs for established immigrants (>30 years) and recent immigrants (11 to 20 years) than for the Canadian-born population and the other immigrant cohort groups. Despite the overall higher levels of  $PM_{2.5}$  exposure among immigrants, these results were somewhat surprising given the well-documented healthy immigrant advantage with mortality, particularly among more recent immigrants, found in previous research.<sup>14,15</sup> The consistently elevated HRs among recent immigrants (11 to 20 years) are of particular interest, especially considering that this was the only group in which elevated HRs for lung cancer mortality were observed. This could be explained by certain characteristics of this group, such as place of birth in regions with typically higher levels of ambient and indoor air pollution,<sup>1</sup> and with higher smoking prevalence (e.g., Asia, North Africa, Middle East, Latin America), despite immigrants overall having lower

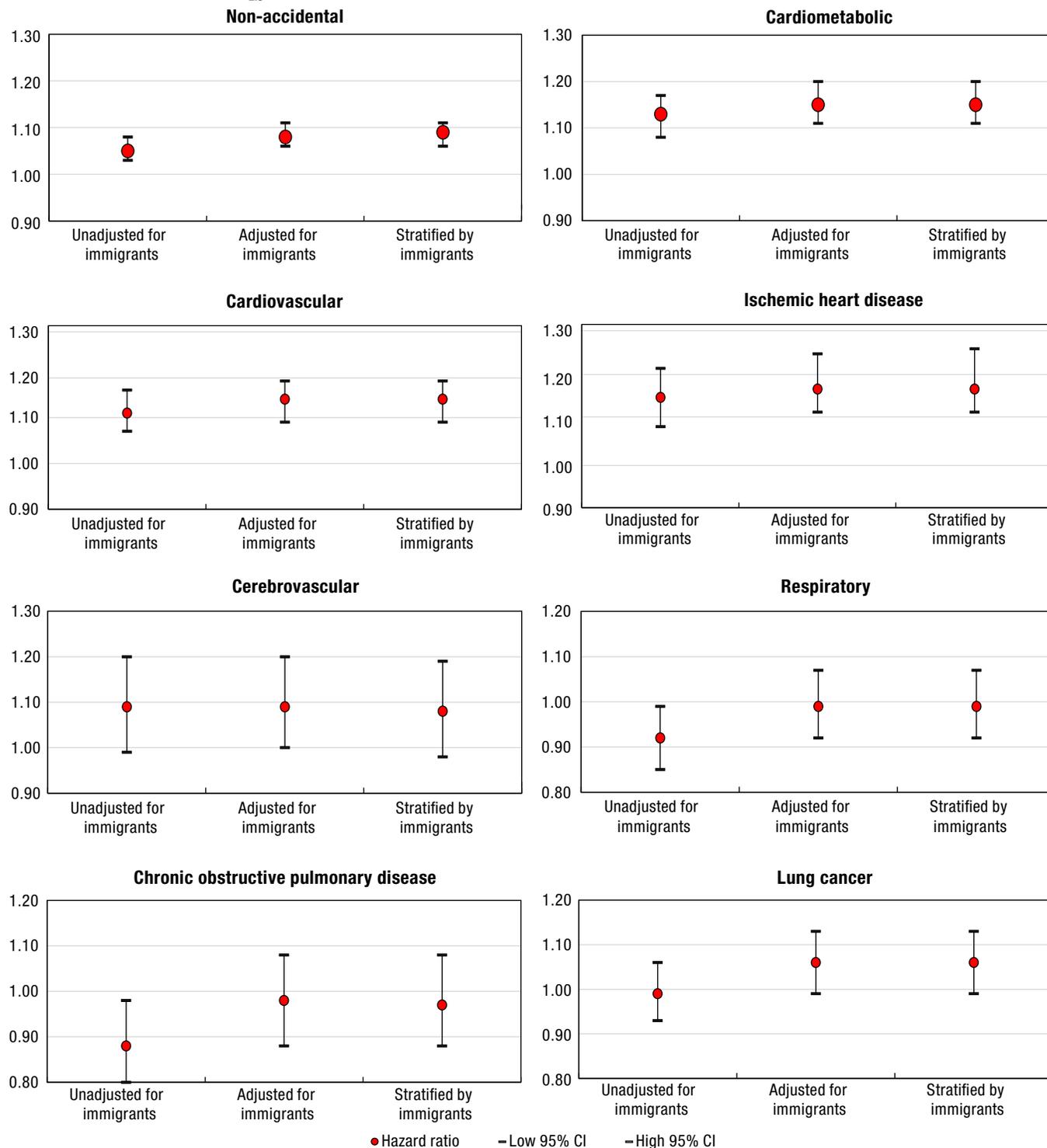
**Figure 4**  
**Wave of immigration by  $PM_{2.5}$  exposure among all immigrants, hazard ratios (95% CI) for non-accidental mortality**



**Notes:** CI: confidence interval. PM: particulate matter. Group 1 (reference group; >30 years): established immigrants (pre-1970); Group 2 (21 to 30 years): semi-established immigrants (1971 to 1980); Group 3 (11 to 20 years): recent immigrants (1981 to 1990); Group 4 ( $\leq 10$  years): very recent immigrants (1991 to 2000). Hazard ratios are stratified by sex and by five-year age groups, and adjusted for place of birth; age at immigration; visible minority; marital status; education; income quintile; employment status; occupational class; community size; urban form; airshed; and neighbourhood instability, deprivation, dependency and ethnic concentration.

**Source:** 2001 Canadian Census Health and Environment Cohort.

**Figure 5**  
**Hazard ratios (95% CI) for PM<sub>2.5</sub> and cause-specific mortality by adjustment method for immigrant status per 10µg/m<sup>3</sup>**



**Notes:** Hazard ratios are stratified by sex and by five-year age groups, and adjusted for visible minority; Aboriginal identity; marital status; education; income quintile; employment status; occupational class; community size; urban form; airshed; and neighbourhood instability, deprivation, dependency and ethnic concentration. CI: confidence interval. PM<sub>2.5</sub>: fine particulate matter.  
**Source:** 2001 Canadian Census Health and Environment Cohort.

smoking rates than non-immigrants.<sup>31</sup> These previous exposures and behaviours could have predisposed this group to higher PM<sub>2.5</sub>-related mortality risk, with sufficient follow-up time compared with the subsequent immigrant cohort with similar characteristics.

This study's results corroborate that the healthy immigrant advantage dissipates with duration in Canada (Table 2),<sup>15</sup> and also show how this relationship changes with increasing levels of PM<sub>2.5</sub> exposure (Figure 4). Again, recent immigrants (11 to 20 years) presented the most dramatic changes, in stark contrast with semi-established immigrants (20 to 30 years). Possible explanations for the loss of the healthy immigrant advantage observed among this group could be related to changes in immigration policy, coupled with macroeconomic factors. The semi-established (20 to 30 years) immigrants who arrived in Canada during the 1970s enjoyed a time of good job prosperity and subsequent upward socioeconomic mobility and stability. However, the following decade introduced policies to double annual immigration targets—from 100,000 to over 200,000—resulting in greater employment competition exasperated by a recession and higher unemployment rates during the 1980s and early 1990s.<sup>9,32</sup> Therefore, a larger percentage of immigrants who arrived during the 1980s may never have gained an economic foothold in their new country, which could have led to poorer health outcomes. Table 1 shows a slight increase in the proportion of unemployment and unskilled labour for the two most recent immigrant groups, along with higher neighbourhood instability and deprivation. This socioeconomic instability is further compounded by wide earnings differences between 1980s immigrants and Canadian-born workers, with only marginal convergence over 20 years and only for more educated workers.<sup>33</sup>

While this study had a number of advantages, including a large population-based cohort with detailed exposure measurements, there are some notable limitations.

First, it is unknown whether immigrants were refugees, family-sponsored immigrants or economic immigrants. National immigration policies have changed over time, and this has resulted in a shift in the ratio between these three main immigrant groups. Previous work has shown that, while refugee immigrants do not have the same health advantage as non-refugee immigrants, they still have a lower mortality rate for all-cause and chronic disease outcomes, compared with the Canadian-born population.<sup>34</sup>

Second, year of immigration is based on when permanent residency was established. Therefore, the exact time spent in Canada is unknown, although it is likely to be less than five years. Additionally, grouping immigrants based on 10-year increments from permanent residency is arbitrary and only follows the convention used in previous literature. It may mask patterns that could be seen if another time-based categorization was used, such as immigration policy changes.

Third, country of birth was grouped into seven geographic regions to approximate cultural, ethnic and racial similarities to use as a proxy for previous exposure history and experiences. However, this is likely not true for all immigrants, who may live in several countries prior to arriving in Canada. For example, a large proportion of immigrants from South Africa self-identify as German, Chinese or Jewish. Despite these limitations, the cohort size was large enough to negate these approximations. Sensitivity tests with additional regional place of birth groupings did not alter the observed PM<sub>2.5</sub> mortality relationships.

Finally, language proficiency in either English or French was not assessed. Despite language proficiency being a known barrier to accessing health care, particularly among older immigrants, and being associated with a transition over time to self-reported poor health,<sup>35,36</sup> its omission is unlikely to bias this study's overall findings given the use of other correlated covariates such as education, birth country, occupation and neighbourhood ethnic concentration.

## Conclusion

Immigrants to Canada have a different lived experience compared with Canadian-born individuals, with different previous and current exposures, and different socioeconomic, demographic and baseline health characteristics. Immigration policy has resulted in profound impacts on the societal constitution of Canada, particularly in large urban centres, since the ethnic diversity of incoming immigrants shifted drastically in the 1970s and reshaped neighbourhoods, local economies, language, food and demographics. Although immigrants have a lower mortality hazard ratio in general, they show an increased risk of non-accidental and cardiovascular disease mortality with exposure to PM<sub>2.5</sub> compared with non-immigrants. Continued reductions in air pollution, particularly in urban areas, will improve the health of the Canadian population as a whole.

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Data access: Researchers can access the analytical cohort used (2001 Canadian Census Health and Environment Cohort) through Statistics Canada’s Research Data Centres Program. The programs used to assign environmental exposures

(PCCF+ and postal code imputation) are also available to researchers through subscription or request. Environmental exposures are available upon request to the original authors of the data. The

analytical codes used were all standard SAS code (e.g., data steps, proc phreg).

The authors have no competing interests to declare. ■

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