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CAREX Canada: an enhanced model for assessing occupational carcinogen exposure

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ABSTRACT

Objectives To estimate the numbers of workers exposed to known and suspected occupational carcinogens in Canada, building on the methods of CARcinogen EXposure (CAREX) projects in the European Union (EU).

Methods CAREX Canada consists of estimates of the prevalence and level of exposure to occupational carcinogens. CAREX Canada includes occupational agents evaluated by the International Agency for Research on Cancer as known, probable or possible human carcinogens that were present and feasible to assess in Canadian workplaces. A Canadian Workplace Exposure Database was established to identify the potential for exposure in particular industries and occupations, and to create exposure level estimates among priority agents, where possible. CAREX EU data were reviewed for relevance to the Canadian context and the proportion of workers likely to be exposed by industry and occupation in Canada was assigned using expert assessment and agreement by a minimum of two occupational hygienists. These proportions were used to generate prevalence estimates by linkage with the Census of Population for 2006, and these estimates are available by industry, occupation, sex and province.

Results CAREX Canada estimated the number of workers exposed to 44 known, probable and suspected carcinogens. Estimates of levels of exposure were further developed for 18 priority agents. Common exposures included night shift work (1.9 million exposed), solar ultraviolet radiation exposure (1.5 million exposed) and diesel engine exhaust (781 000 exposed).

Conclusions A substantial proportion of Canadian workers are exposed to known and suspected carcinogens at work.

INTRODUCTION

The International Agency for Research on Cancer (IARC) has evaluated more than 900 agents and classified more than 400 as known or suspected carcinogens.¹ Of these, 168 individual agents and 18 exposure situations (particular jobs or industries) are found in occupational environments.² Accordingly, much epidemiological study of the carcinogenic properties of various agents occurs in occupational settings where exposures are often higher than in the general environment. In both occupational and environmental settings, exposure to known and suspected carcinogens is modifiable, and measures aimed at reducing or eliminating exposures will contribute to a lower risk of developing cancer in the future.^{3,4} A major challenge in occupational cancer prevention, however, is a lack

What this paper adds

- A major challenge in occupational cancer prevention is a lack of knowledge of where carcinogenic exposures are occurring and how many workers are affected.
- The CARcinogen EXposure (CAREX) system was developed in the European Union and subsequently adapted for use elsewhere, but no estimates had been produced for Canada.
- CAREX Canada produced estimates of the prevalence of occupational exposure for 44 carcinogens and did so at a finer level of detail than previously attempted (by categories of industry, occupation, region and sex).
- This type of carcinogen exposure surveillance data can be used for the identification of high-risk groups, setting priorities for prevention-related activities, monitoring trends in exposure over time and assessing the impact of changing regulations.

of knowledge of where carcinogenic exposures are occurring and how many workers are affected.⁵

Previous projects have attempted to address this knowledge gap. The CARcinogen EXposure (CAREX) surveillance system was developed by the Finnish Institute of Occupational Health, in collaboration with IARC and leading exposure assessment experts, as part of a larger project to estimate the burden of occupational cancer in Europe.⁶ The inputs to the CAREX system were developed by a team of international experts from across the European Union (EU). The EU CAREX included estimates of carcinogen exposure for 15 countries by 55 broad industry categories. The CAREX approach was also subsequently established in Estonia, Latvia, Czech Republic and Lithuania.⁷ Variations of this approach, such as Finnish job exposure matrix (FINJEM), which catalogues occupational exposure to a wide variety of hazards by over 300 occupations over time, have also been produced.⁸ FINJEM has been used for many purposes in Finland and beyond, including risk assessments, evaluating exposure trends and as a source for other JEMs.⁹ A Costa Rican version of CAREX (TICAREX) extended the original model by including estimates of occupational exposure by sex, as well as approaches to estimate exposure to pesticides in agriculture.¹⁰

The CAREX Canada project was founded in 2007 in an effort to create an enhanced and

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Canadian-specific tool for occupational carcinogen exposure assessment. CAREX Canada's occupational component is modelled after the EU CAREX project and was designed to incorporate the strengths of that system, as well as those of FINJEM. CAREX Canada also includes a component that is focused on environmental exposures, described elsewhere.³ The goal of CAREX Canada's occupational component is to *estimate the number of Canadian workers exposed to known and suspected carcinogens, and where possible, to estimate their levels of exposure.*

Unique enhancements in the Canadian project include estimates of occupational exposure by detailed industry and occupation, as well as by sex and province. It is important in Canada to assess exposure by province because workplace health protection is largely administered at the provincial level, and providing exposure estimates at this level allows provinces to set their own priorities. The ability to separate estimates by sex is important for biological reasons (where an exposure leads to a sex-specific cancer) and expansion of CAREX estimates to other purposes (eg, estimating the burden of disease by sex). The CAREX Canada system also created and used a national exposure measurement database to produce estimates of occupational exposure, and the number of agents included was expanded to include more suspected carcinogens. This type of carcinogen exposure surveillance data can be used for the identification of high-risk groups, setting priorities for prevention-related activities, monitoring trends in exposure over time and assessing the impact of changing regulations.¹¹ CAREX Canada does not include the primary collection of exposure data, but rather harvests from existing data sources to guide the exposure estimation process. The purpose of the present article is to highlight the enhancements made to the CAREX process in the creation of CAREX Canada, and summarise the occupational exposure estimate results (both exposure prevalence and level of exposure). This work was approved by the Research Ethics Board at the University of British Columbia.

METHODS

Selection of carcinogens

Known and suspected carcinogens were selected for inclusion in CAREX Canada (where the workplace was identified as a potential source of exposure) from the list of IARC-classified Group 1 (known human carcinogens), Group 2A (probable carcinogens)

and Group 2B (possible carcinogens). The occupationally-related agents were then evaluated based on three criteria: (1) the agent was likely to be present in Canadian workplaces in the year 2006, and exposure was relatively prevalent (>10 000 likely to be exposed); (2) toxic effects, including carcinogenicity (IARC Group 1 agents were given higher priority); and (3) the feasibility of assessing exposure based on available data. Occupational exposure was defined as inhalation and/or dermal exposure at work to levels above environmental background levels. We combined some separate IARC agents into groups for exposure assessment when they were expected to be encountered together in workplaces. This grouping occurred for the polycyclic aromatic hydrocarbons and the antineoplastic agents.

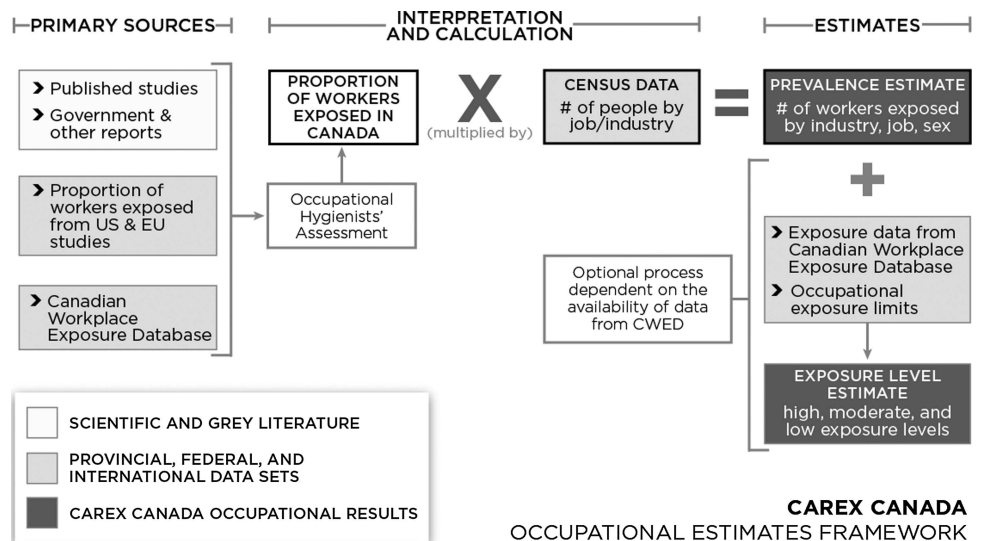
Data gathering

A major component of the CAREX Canada occupational project was the creation of the Canadian Workplace Exposure Database (CWED), a repository of occupational exposure monitoring data from across Canadian jurisdictions. This database was used in two ways: (1) to identify the potential for exposure in particular industries and occupations and (2) to create exposure level estimates among the data-rich priority agents. At the time these estimates were developed, the CWED contained approximately 100 000 exposure measurements for known and suspected carcinogens collected between 1981 and 2004 for regulatory purposes in two of Canada's largest provinces. The CWED has been continuously expanded as other Canadian provinces agree to contribute data, and at time of writing contained 460 000 measures of exposure (carcinogens and non-carcinogens).¹² Other primary sources of data include the EU CAREX project (for proportions of workers exposed and other general methodology), published literature on exposure to carcinogens in the workplace, government reports and grey literature (figure 1). Population data on industry, occupation, province/territory and sex were obtained from Statistics Canada based on their 2006 Census of Population.¹³

Occupational estimates approach and simple adaptations

A generalised approach (outlined in figure 1) was developed to ensure comparability among substances, methodological transparency and ease of interpretation. This framework was flexible and was adapted for agents with unique data sources or particular assessment challenges.¹⁴ Primary data sources were reviewed

Figure 1 Generalised methodology used to generate estimates of occupational exposure to known and suspected carcinogens.



for relevance to the Canadian context and the proportion of workers likely to be exposed by industry and occupation in Canada was assigned using expert assessment and agreement by a minimum of two occupational hygienists. All procedures and estimates were externally reviewed by a scientific advisory committee composed of research and practice professionals in occupational hygiene and epidemiology.

These proportions were then linked to the census data to calculate a simple prevalence (number of workers exposed) by agent. Prevalence estimates were generated by industry (North American Industry Classification System or NAICS, 2002 version), occupation (National Occupational Classification—Statistics, 2006 version), province or territory, and sex.

Where data are available in the CWED, exposure levels were also estimated using a semi-quantitative method based on the concepts used by the Institut de recherche Robert-Sauvé en santé et en sécurité du travail in Quebec, Canada (IRSST).¹⁵ We used these criteria for exposure levels to match the methods and reporting structure of the IRSST because Quebec is the largest current exposure data collector in Canada, but these data were publically unavailable. Using their method allowed estimates to be comparable across jurisdictions. Two concentration thresholds were selected for each agent based on workplace exposure limits and cancer-relevant health outcomes. In general, we set high exposure thresholds to current threshold limit values from the American Conference of Governmental Industrial Hygienists (ACGIH), unless the limit was not set for cancer prevention reasons. In these cases (eg, for wood dust, where the current threshold limit value (TLV) is set to prevent non-malignant respiratory disease), we selected a threshold based on the epidemiological literature. We set the moderate thresholds as half of high exposure thresholds. For a given industry/job combination, high exposure was assigned when there were at least 25 samples available for that agent in a particular job and industry, and 20% or more of those samples had concentrations that were at or above the high threshold. The criteria for moderate exposure were met in one of two ways. Either (1) there were at least 25 samples available for that agent in a particular job and industry, and 20% or more of those samples had concentrations above the moderate threshold or (2) there were at least 10, but less than 25 samples, and 20% or more of those samples had concentrations above the high threshold. Workers were assigned into the low category of exposure where there were either no samples (but expert assessment deemed exposure as plausible) or the samples did not meet the criteria for moderate exposure (ie, were typically lower than half the exposure limit).

For some agents, CWED data were not available, but we were able to estimate exposure levels via some simple adaptations to the general framework. Two examples of this are artificial ultraviolet radiation (UVR) and solar UVR exposure to outdoor workers. Since there are no systematic measures of these physical hazards in Canada, we developed modified methods in order to assess both prevalence and level of exposure. The detailed methods and results of the solar UVR exposure assessment have been published elsewhere.¹⁶ Briefly, exposure categories were developed based on expected time spent outdoors. Groups were categorised as having high exposure when $\geq 75\%$ of their workday was expected to be outdoors, and these jobs were identified using skin cancer prevention materials from Australian campaigns.¹⁷ For the moderate and low categories of exposure, Canadian career-selection websites were used to identify jobs with outdoor components.

To develop estimates of the levels of artificial UVR exposure, we used a report by the International Commission of

Non-Ionizing Radiation Protection (ICNIRP).¹⁸ This report classified exposure to artificial UVR into categories of low, medium, high and very high with respect to the potential for overexposure. The only source classified with a low potential was exposure to general lighting, which CAREX Canada defined as environmental exposure (rather than occupational). Therefore, we excluded ICNIRP's low potential for overexposure classification and defined our exposure groups based on their medium, high and very high potential for overexposure categories. A group of workers was considered to have low exposure if the ICNIRP found that there was a medium potential for overexposure, moderate exposure if the ICNIRP classified the job as having a high potential for overexposure and high exposure if the ICNIRP classified the job as having a very high potential for overexposure.

Unique data sources: shift work, antineoplastic agents and ionising radiation

It is relatively simple to adapt the generalised occupational estimates approach to other exposures that either a) are non-traditional from an industrial hygiene perspective or b) have unique challenges or exposure monitoring practices that make the general approach less desirable. The three main exposures where this occurred in CAREX Canada were shift work, ionising radiation and antineoplastic agents.

Briefly for shift work, we used Statistics Canada's Survey of Labour and Income Dynamics public-use micro-data file for the year 2006.¹⁹ This survey was selected because it is a large, nationally representative survey that has information on industry and occupation for all respondents, as well as data on the type of shift that people work in Canada. Exposure was defined as regular work between the hours of 12:00 and 05:00, which was captured by the self-reported shift types of 'A rotating shift' and 'Regular night or graveyard schedule.' Population counts were calculated by using Statistics Canada provided weights for use in their survey data. The granularity of codes available for industry and occupation in the public-use micro-data file was less than that for census-derived exposure estimates. Therefore, in order to compare exposure estimates by industry, some basic assumptions were made, which are noted where applicable in the results tables.

For ionising radiation, we consulted complementary data available in the 2007 and 2008 annual reports from the National Dose Registry (NDR)^{20 21} in order to reconstruct exposure estimates for 2006. The NDR is a centralised Canadian registry of occupational radiation doses which contains records for over 100 000 currently monitored Canadians.

We calculated a range in the number of workers exposed to ionising radiation to account for uncertainties in how regulations are administered across different Canadian jurisdictions. The low end of the range is the number of monitored workers with a whole-body dose above the limit of detection (ranges from 0.1 to 0.2 mSv (millisievert)) over 1 year. The high end of the range is an extrapolation based on a detailed review of each NDR defined job title with respect to the number of workers likely to be missing from the population of monitored workers. We also examined the proportions of workers exposed from European CAREX projects where we were unable to estimate the proportion of exposed workers directly. For levels of exposure, workers were classified as having low exposure if their annual whole-body radiation dose was between the limit of detection and 1 mSv; moderate exposure if their dose was >1 to <20 mSv; and high if their dose was >20 mSv (which is also the ACGIH occupational exposure limit for an annual dose).

For antineoplastic agents, a varied expert-based approach was used depending on the job/industry being considered. Data sources included: (1) peer-reviewed literature, (2) human resources databases, (3) reports on industry practices, (4) unpublished reports on the potential for antineoplastic agent exposure and (5) personal communication with experts in academia and industry.²² Estimates were produced separately for hospital nurses and physicians, hospital pharmacy staff, community pharmacy staff and veterinary workers.

Data quality definitions

After we calculated prevalence and level of exposure estimates, we assigned a data quality score to each agent. We classified agents as having high quality data where we were able to produce quantitative estimates of the levels of exposure using at least 1000 CWED observations per agent across a variety of industries. An important limitation to this classification is that much of our data are over 10 years old. For agents where we had evidence of stable exposures over that time period (ie, silica), this is less of an issue; however, for agents like tetrachloroethylene, where regulations have changed substantially in the last 5–10 years, we are less convinced that our historic data truly reflect current exposure in the workplace.

We classified agents as having moderate data quality when there were few data available, but where other proxy information on exposure allowed us to assign exposure levels. A good example of this situation is the antineoplastic agents, where few objective exposure measures are available since regulatory exposure monitoring does not occur in Canada. Moderate data quality was also assigned for substances with less than 1000 (but greater than 200) exposure data points available.

We classified agents as having low data quality where we had insufficient exposure data points (<200) to attempt to assign exposure levels, and also in the case of asbestos, where exposure situations have changed significantly in past decades so that assigning accurate exposure levels was difficult.

RESULTS

General results: prevalence and level of exposure, and data quality in Canada

Overall, CAREX Canada produced occupational prevalence estimates for 44 known and suspected carcinogens, and semiquantitative estimates of exposure levels for 18 of these agents. [Table 1](#) outlines the results, categorised by IARC classifications. The data quality variable for each agent is also noted.

Overall, the most prevalent exposure in Canada was shift work (1.9 million exposed), followed by solar UVR exposure to outdoor workers (n=1.5 million), diesel engine exhaust (n=781 000) and benzene (n=374 000). In terms of data quality, 24 (55%) of the 44 agents had low quality data (not enough information to assign exposure levels, or data too outdated to use) and 8 (18%) had moderate data quality (200–1000 workplace samples in the CWED or good quality qualitative data on exposure levels). Only 12 of the agents reviewed (27%) were classified as having high quality data (quantitative exposure level estimates possible, with >1000 samples available in the CWED). More men than women were exposed to carcinogens; the mean percentage of men exposed by carcinogen was 79%, ranging from 27% for antineoplastic agents to 97% for polychlorinated biphenyls (see online supplementary table S1 for more details).

Results are shown in [table 2](#) for the 18 agents where exposure level estimates were calculated. For most agents, the greatest proportion of exposure tends to be located in the low exposure

category. However, agents such as solar radiation, wood dust and artificial UV radiation display large proportions of workers in the high category of exposure.

Exposure prevalence by two-digit NAICS 2002 industry codes is shown in [table 3](#). The total number of workers employed in each industry is also presented, as well as the top three exposure agents (ordered by prevalence). The number of exposures column indicates occurrences of exposure as opposed to individuals exposed. Although one person may very well be exposed to more than one agent, the exposures-per-worker metric gives an indication of the overall prevalence of exposure to known and suspected carcinogens. The mining and oil and gas extraction industry (NAICS 21) along with the construction industry (NAICS 23) are two notable instances where the exposures-per-worker exceed 1.0.

By way of an illustration, [table 4](#) shows the same information as [table 3](#), focusing in a more detailed level on a single sector (manufacturing). This table does not include exposures from ionising radiation or shift work, since the industry classifications systems used for these agents were not available at a sufficient level of detail to link directly to the other estimates. Therefore, in many cases, one of these two exposures could be in the top three, but we cannot address this for the manufacturing industry. The exposures-per-worker metric here is highest in primary metal manufacturing and wood product manufacturing. A similar table with results presented by occupation (job title) is available in the online supplementary table S2. In addition, results for the 12 most prevalence exposures in Canada are presented by province in the online supplementary table S3.

DISCUSSION

CAREX Canada used a well-established model for exposure surveillance developed for and applied across the workforces of many countries in Europe⁵ and specifically Finland.⁸ We expanded on these models by modifying the programme to focus on the Canadian context (adding exposure estimation for many suspected carcinogens that were not initially included, updating proportions exposed to reflect variability in Canadian industries, etc). In addition, we used a more detailed set of labour force data, allowing us to examine exposure at a finer level of detail with respect to industry and occupation titles, as well as jurisdiction (province or territory), and sex. We also created and used a CWED to increase the accuracy and robustness of our exposure estimates. These enhancements together provide a repository of data and other information on occupational exposure to known and suspected carcinogens in Canada, and could serve as a model for expanding CAREX-type systems to other jurisdictions, particularly in the Americas. These enhancements could be applied in other countries with available labour force data, and could be improved further by the addition of age as a dimension in the system. We were not able to include age in our assessment because the extra dimension made some cells in the census data too small for release from Statistics Canada.

CAREX EU estimates of exposure have been used for other purposes, notably for estimating the burden of occupational cancer in various countries. For example, a recent study in the UK by Rushton *et al* used CAREX EU data to complete the exposure assessment portion of the project.²³ CAREX Canada estimates are being used in a similar fashion in a study, currently underway, to estimate the burden of occupational cancer in Canada. Having country-specific estimates of exposure that use measured data is an improvement to burden studies that could be employed in the future.

Table 1 Workplace exposure to known and suspected carcinogens, Canada, 2006

IARC group	Agent	Data quality	n Exposed at work	% Of total workforce	Exposure levels available	
Carcinogenic agents (IARC 1)	Solar radiation	Moderate	1 476 000	8.8	Yes	
	Diesel engine exhaust	Low	781 000	4.6	No	
	Silica (crystalline)	High	382 000	2.3	Yes	
	Benzene	High	374 000	2.2	Yes	
	Wood dust	High	338 000	2.0	Yes	
	Asbestos	Low	151 000	0.90	No	
	Formaldehyde	High	151 000	0.90	Yes	
	Ultraviolet radiation (artificial sources)	Moderate	141 000	0.83	Yes	
	Chromium (hexavalent)	High	104 000	0.61	Yes	
	Ionising radiation	Moderate-high	37 000–78 000	0.22–0.46	Yes	
	Cadmium	High	31 000	0.18	Yes	
	Arsenic	Moderate	25 000	0.15	No	
	Trichloroethylene	Moderate	9800	0.06	Yes	
	Polychlorinated biphenyls	Low	8200	0.05	No	
	Coal tar and coal tar pitches	Low	7600	0.05	No	
	Beryllium	Low	3900	0.02	No	
	1,3-Butadiene	Low	3900	0.02	No	
	Ethylene oxide	Moderate	2400	0.01	Yes	
	Probable carcinogenic agents (IARC 2A)	Shift work with potential for circadian disruption	High	1 900 000	11.6	Yes
Tetrachloroethylene		High	15 000	0.09	Yes	
Acrylamide		Low	9300	0.05	No	
Epichlorohydrin		Low	6600	0.04	No	
Creosotes		Low	4800	0.03	No	
Possible carcinogenic agents (IARC 2B)	Ethylbenzene	Low	208 000	1.2	No	
	Styrene	High	89 000	0.53	Yes	
	Bitumens	Low	44 000	0.26	No	
	Dichloromethane	Moderate	25 000	0.15	Yes	
	Toluene diisocyanates	Low	24 000	0.14	No	
	Chloroform	Low	15 000	0.09	No	
	Antimony trioxide	Low	9700	0.06	No	
	Acetaldehyde	Low	8600	0.05	No	
	Naphthalene	Low	7700	0.05	No	
	Vanadium pentoxide	Low	7100	0.04	No	
	Acrylonitrile	Low	5900	0.04	No	
	Pentachlorophenol	Low	4300	0.03	No	
	1,4-Dioxane	Low	3700	0.02	No	
	Refractory ceramic fibres	Low	3200	0.02	No	
	1,2-Dichloroethane	Low	2000	0.01	No	
	Nitrobenzene	Low	500	<0.01	No	
Mixed carcinogenic exposures	Possible/probable carcinogenic agent (IARC 2B and 2A)	Polycyclic aromatic hydrocarbons	Low	350 000	2.1	No
	Possible/probable carcinogenic agent (IARC 2B and 2A)	Lead	High	277 000	1.6	Yes
	Possible/carcinogenic agent (IARC 2B and 1)	Nickel	High	117 000	0.69	Yes
	Probable/carcinogenic agents (IARC 2A and 1)	Antineoplastic agents	Moderate	58 000	0.34	Yes
	Possible/probable carcinogenic agents (IARC 2B and 2A)	Cobalt	High	33 000	0.19	Yes

IARC, International Agency for Research on Cancer.

Each substance was reviewed in detail by job and industry with potential exposure; design of assessment techniques and reporting of each exposure estimate was reviewed by a scientific advisory committee. Another feature of the CAREX Canada estimates is that they were developed using measured exposure data from Canada; a database created during this process is now being adapted and expanded to include other jurisdictions and non-carcinogenic substances of interest.

CAREX Canada's estimates of exposure can be presented by any available dimension, including industry, occupation, province, sex and exposure level; this ability is a key enhancement to previous CAREX projects. The original platform for the

European CAREX was strictly driven by a broad industry category, and so this system increases flexibility of use. The CAREX Canada system defines exposure very broadly (any exposure above the expected environmental background). In this way, it is intended to estimate the number of workers potentially exposed above background, rather than the number exposed at a level that might confer a risk of developing cancer. For this reason, there are inherently large proportions of workers who fall into the low category of exposure in our estimates. The benefit of a system that estimates all potential exposure, rather than precise estimates of people at risk, is largely a cost and effort benefit. Precise estimates would require regular

Table 2 Exposure to known and suspected carcinogens by exposure level, Canada, 2006

CAREX agent	High exposure (n) (%)	Moderate exposure (n) (%)	Low exposure (n) (%)	Total
Shift work	1 900 000 (100%)*	–	–	1 900 000
Solar radiation	896 000 (61%)	391 000 (26%)	190 000 (13%)	1 476 000
Silica (crystalline)	53 000 (14%)	147 000 (39%)	182 000 (48%)	382 000
Benzene	1400 (<1%)	32 000 (9%)	341 000 (91%)	374 000
Wood dust	93 000 (28%)	166 000 (49%)	79 000 (23%)	338 000
Lead	60 000 (22%)	81 000 (29%)	136 000 (49%)	277 000
Formaldehyde	3700 (2%)	46 000 (30%)	102 000 (68%)	151 000
Ultraviolet radiation (artificial sources)	87 000 (62%)	34 000 (24%)	20 000 (14%)	141 000
Nickel	8100 (7%)	12 000 (10%)	97 000 (83%)	117 000
Chromium (hexavalent) compounds	500 (<1%)	13 000 (12%)	90 000 (87%)	104 000
Styrene	38 000 (43%)	28 000 (32%)	23 000 (26%)	89 000
Ionising radiation†	<100	10 000–18 000	26 000–60 000	36 000–78 000
Antineoplastic agents	5000 (9%)	40 000 (70%)	13 000 (21%)	58 000
Cobalt	1800 (6%)	9500 (29%)	21 000 (65%)	33 000
Cadmium	2200 (7%)	21 000 (66%)	8300 (27%)	31 000
Dichloromethane (methylene chloride)	3400 (13%)	8300 (33%)	14 000 (54%)	25 000
Tetrachloroethylene	700 (5%)	2200 (15%)	12 000 (80%)	15 000
Trichloroethylene	300 (3%)	5400 (55%)	4100 (42%)	9800

*Only those working regular night and rotating night shifts are reported as exposed.

†Results presented as a range due to the assumption that fewer workers are monitored for ionising radiation exposure than are actually exposed; see methods section for more details.

surveys across Canada to identify individual workers at risk of exposure. Certainly, this would produce more accurate counts of workers exposed, but at a much higher cost. CAREX Canada's estimates provide a more accessible and less costly way to identify workplaces with large workforces potentially exposed, and perhaps more importantly, to identify those who are at risk of high exposure (through the use of quantitative data).

The process of creating a CAREX system has inherent uncertainty. For substances that were initially reviewed by the EU CAREX project, we had a starting point to estimate proportions of workers exposed and apply them to Canadian Labour Force statistics. However, even in these cases, exposure proportions in the EU CAREX were more broadly classified than the systems used in Canada, and Canadian proportions required inference for particular industry and occupation combinations. For

Table 3 Exposure to CAREX agents by broad industry group

Industry subsector (two-digit NAICS code)	Total employed (n)	Number of exposures	Exposures per worker	Top three exposures
31-Manufacturing	2 006 000	1 479 000	0.74	SHIFT, WOOD, BENZ
23-Construction	1 069 000	1 188 000	1.11	SOL, SILI, WOOD
48-Transportation and warehousing	820 000	764 000	0.93	DEE, SOL, SHIFT
44-Retail trade	1 917 000	553 000	0.29	SHIFT, PAH, BENZ
62-Health care and social assistance	1 716 000	468 000	0.27	SHIFT, ANTI, IRAD
11-Agriculture, forestry, fishing and hunting	524 000	441 000	0.84	SOL, DEE, WOOD
91-Public administration	979 000	403 000	0.41	SOL, SHIFT, DEE
72-Accommodation and food services	1 127 000	400 000	0.35	SHIFT, PAH, SOL
81-Other services (except public administration)	820 000	398 000	0.49	BENZ, PAH, ETHB
56-Administrative and support, waste management and remediation services	723 000	269 000	0.37	SOL, SHIFT, DEE
21-Mining and oil and gas extraction	239 000	261 000	1.09	SHIFT, SOL, DEE
41-Wholesale trade	739 000	175 000	0.24	DEE, SHIFT, SOL
71-Arts, entertainment and recreation	346 000	118 000	0.34	SOL, SHIFT, CHLF
54-Professional, scientific and technical services	1 122 000	86 000	0.08	SOL, SHIFT, SILI
51-Information and cultural industries	417 000	77 000	0.18	SHIFT, SOL, BENZ
61-Educational services	1 151 000	73 000	0.06	SHIFT, SOL, FORM
22-Utilities	133 000	55 000	0.41	SOL, SHIFT, IRAD
52-Finance and insurance	689 000	32 000	0.05	SHIFT, SOL, DEE
53-Real estate and rental and leasing	304 000	28 000	0.09	SOL, DEE, BENZ
55-Management of companies and enterprises	21 000	3900	0.19	SHIFT, SOL, DEE
Total	16 861 000	7 298 000	0.43	SHIFT, SOL, DEE

ANTI, antineoplastic agents; BENZ, benzene; CHLF, chloroform; DEE, diesel engine exhaust; ETHB, ethylbenzene; FORM, formaldehyde; IRAD, ionising radiation; NAICS, North American Industry Classification System; PAH, polycyclic aromatic hydrocarbons; SHIFT, shift work; SILI, silica; SOL, solar radiation; WOOD, wood dust.

Table 4 Exposure to CAREX agents in the manufacturing sector (excluding ionising radiation and shift work), Canada, 2006

Industry subsector: three-digit NAICS code	Total employed (n)	# Exposures	Exposures per worker	Top three exposures
321-Wood product manufacturing	146 000	160 000	1.10	WOOD, FORM, SOL
336-Transportation equipment manufacturing	264 000	134 000	0.51	PB, NI, BENZ
332-Fabricated metal product manufacturing	187 000	131 000	0.70	PB, NI, UV
331-Primary metal manufacturing	84 000	100 000	1.19	SILI, BENZ, PB
326-Plastics and rubber products manufacturing	125 000	91 000	0.73	BENZ, STYR, TDI
337-Furniture and related product manufacturing	111 000	89 000	0.80	WOOD, FORM, BENZ
333-Machinery manufacturing	131 000	71 000	0.54	PB, UV, NI
327-Non-metallic mineral product manufacturing	61 000	56 000	0.92	SILI, DEE, SOL
323-Printing and related support activities	91 000	48 000	0.53	BENZ, CR6, PERC
325-Chemical manufacturing	92 000	34 000	0.37	BENZ, SILI, FORM
322-Paper manufacturing	90 000	33 000	0.37	FORM, WOOD, SOL
339-Miscellaneous manufacturing	76 000	29 000	0.38	SILI, NI, BENZ
311-Food manufacturing	251 000	26 000	0.10	SOL, DEE, BENZ
324-Petroleum and coal products manufacturing	15 000	14 000	0.93	NAPH, BENZ, ETHB
335-Electrical equipment, appliance and component manufacturing	49 000	14 000	0.29	PB, STYR, NI
334-Computer and electronic product manufacturing	90 000	11 000	0.12	PB, FORM, NI
315-Clothing manufacturing	68 000	5900	0.09	FORM, TCE, DEE
312-Beverage and tobacco product manufacturing	31 000	5400	0.17	DEE, SOL, BENZ
313-Textile mills	18 000	4900	0.27	FORM, PERC, ACRY
314-Textile product mills	18 000	4500	0.25	PERC, ANT, FORM
316-Leather and allied product manufacturing	7500	1400	0.19	BENZ, CR6, NAPH
Total	2 006 000	1 479 000*	0.74	SHIFT, WOOD, BENZ

*Includes the numbers listed here, in addition to 419 000 manufacturing workers doing shift work, who are not included in any totals due to limited detail on industry in the data source used to produce shift work estimates.

ACRY, acrylamide; ANT, antimony trioxide; BENZ, benzene; CR6, hexavalent chromium; DEE, diesel engine exhaust; ETHB, ethylbenzene; FORM, formaldehyde; NAICS, North American Industry Classification System; NAPH, naphthalene; NI, nickel; PB, lead; PERC, tetrachloroethylene; SHIFT, shift work; SILI, silica; SOL, solar radiation; STYR, styrene; TCE, trichloroethylene; TDI, toluene diisocyanates; UV, artificial ultraviolet; WOOD, wood dust.

substances that were not estimated by the EU CAREX, our group would start from scratch, using peer-reviewed and grey literature, data from the CWED, and information from the National Occupational Exposure Survey from the USA.²⁴ Coupled with expert assessment, these are the best available methods, though they have inherent uncertainty associated with them. For transparency, we applied a flag in the database for low confidence in all cases to document this occurrence.

Our estimates reflect *instances* of exposure that cannot be added, and so we are not able to calculate a total number of occupationally-exposed Canadians. This is a by-product of lack of individual-level data to account for situations where one worker may be exposed to a number of agents. In addition, we are not able to account for additive effects of either included agent exposures or other lifestyle effects (such as smoking) that could increase a worker's risk of cancer. Other methods have been used to assess exposure to carcinogens on a national level, most recently in Australia, where telephone interviews of randomly-selected households in that country asked a series of questions about workplace exposure.²⁵ This study was able to assess exposure overall due to the study design. In general, the proportion of Australians exposed to carcinogens was higher than in Canada, especially for solar UVR exposure (unsurprisingly given climate differences), diesel exhaust (17% exposed vs 4.6% in Canada) and silica (6% vs 2.3% in Canada). This is not unexpected given that the Australian study relied on self-reporting of tasks, which could be subject to bias. Alternatively (or in addition), Australia could truly have more prevalent exposure than Canada. The main limitation of our results centres on exposure data quality. To increase the sensitivity of our exposure level estimates, we applied conservative criteria when identifying a high exposure group. Therefore, if a group

of workers is flagged as having high exposure, we are relatively confident that high exposure is occurring. If exposure data were not available for a particular job and industry combination, this group was automatically placed in the low exposure category for that substance. While this increases the robustness of our estimates in our use of quantitative exposure data, it means that there are likely to be groups of workers flagged in low exposure categories who actually could be at risk of high exposure. This is of particular importance for an industry such as construction. Here we know that high exposure is likely occurring (to agents such as wood dust, silica, diesel exhaust, etc) but since little monitoring data are included in the CWED (eg, none at all for diesel exhaust), we cannot confidently assign varying exposure levels for these workers. For diesel exhaust in particular, more studies have been done recently on exposure levels, and these could be used to enhance our estimates in the future.²⁶

Further to the point on data quality, the CWED data used to create the CAREX Canada estimates cover the time period of 1981–2004, with the bulk of the data being collected in the late 1980s and early 1990s. If exposure circumstances have changed substantially, our estimates could be improved by adding current exposure data to the CWED.¹²

CAREX Canada's estimates of the numbers of workers exposed to known or suspected carcinogens, and the simple system and tools used to enter and extract data, offer enhancements to previous CAREX projects. These data could be used to identify groups at risk of high exposure, assess the impact of changing regulations, identify gaps and research priorities, and account for occupational exposure on the burden of cancer.

We have shown that millions of Canadian workers are at risk of exposure to known and suspected carcinogens, some at high levels of exposure. We have also highlighted where issues of

data quality impacted our ability to provide robust estimates of exposure, which could be used to guide future priority setting activities in Canada, and lead to better occupational cancer prevention at both Canadian and international levels.

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Contributors PAD conceptualized the CAREX Canada project with CEP, and both designed the components of the exposure assessment (CEP completed many of them). CBG and ALH performed several of the exposure assessments. HWD participated in data gathering and creation and expansion of the CWED, as well as in critical review of the exposure assessments. All authors critically reviewed and revised the manuscript.

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Supplementary (online only) data for:

“CAREX Canada: An enhanced model for assessing occupational carcinogen exposure.”

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Table S1: Proportion of men exposed by agent in CAREX Canada

Agent	% men	n exposed at work
Antineoplastic Agents	27.0	58,000
Ethylene oxide	37.7	2,400
Chloroform	49.0	15,000
Shift work with potential for circadian disruption	55.6	1,900,000
1,4-Dioxane	56.8	3,700
Ionizing radiation	57.0	37,000 – 78,000
Tetrachloroethylene	60.4	15,000
Trichloroethylene	63.9	9,800
Formaldehyde	66.1	151,000
Acrylonitrile	67.8	5,900
Acetaldehyde	68.4	8,600
Epichlorohydrin	73.2	6,600
Toluene diisocyanates (TDIs)	75.1	24,000
Nitrobenzene	76.3	500
1,2-Dichloroethane	76.3	2,000
Polycyclic aromatic hydrocarbons (PAHs)	76.7	350,000
UV radiation (artificial sources)	78.3	141,000
Antimony trioxide	78.9	9,700
Pentachlorophenol	81.5	4,300
Solar radiation	82.4	1,476,000
Dichloromethane	82.7	20,000
Styrene	83.7	89,000
1,3-Butadiene	83.8	3,900
Cobalt	85.2	33,000
Beryllium	86.0	3,900
Refractory ceramic fibers (RCFs)	86.5	3,200
Benzene	87.4	374,000
Lead	89.6	277,000
Acrylamide	89.7	9,300
Cadmium	90.0	31,000
Arsenic	90.5	25,000
Naphthalene	90.6	7,700
Nickel	91.1	117,000
Chromium (hexavalent)	91.7	104,000
Diesel engine exhaust	91.7	781,000
Wood dust	92.7	338,000
Silica (crystalline)	92.8	382,000
Vanadium pentoxide	93.1	7,100
Creosotes	93.4	4,800
Coal tar and coal tar pitches	93.4	7,600
Ethylbenzene	93.5	208,000
Bitumens	95.0	44,000
Asbestos	96.3	151,000
Polychlorinated biphenyls (PCBs)	96.7	8,200

Table S2: Exposure to CAREX agents by broad occupational category

Occupational groups: NOC-S 2006 codes	Total employed (n)	Number of exposures	Exposures per worker	Top exposures
Transport and equipment operators: H611 - H737	678,000	1,176,000	1.74	DEE, SOL, BENZ
Other trades occupations: H211 - H535	908,000	1,125,000	1.24	PB, PAH, UV
Occupations unique to primary industry: I011 - I216	648,000	704,000	1.09	SOL, DEE, SHIFT
Machine operators and assemblers in manufacturing, including supervisors: J011 - J228	726,000	684,000	0.94	SHIFT, BENZ, FORM
Construction trades: H111 - H145	436,000	583,000	1.34	WOOD, SOL, SILI
Trades helpers, construction and transportation labourers: H811 - H832	402,000	481,000	1.20	SOL, SILI, SHIFT
Sales and service occupations: G013 - G016, G711 - G732, G911 - G983	1,474,000	316,000	0.21	SHIFT, PAH, SOL
Occupations in protective services: G611 - G631	277,000	304,000	1.10	SHIFT, PB, SOL
Chefs and cooks, and servers: G012, G411-G513	551,000	284,000	0.52	SHIFT, PAH, FORM
Retail salespersons, sales clerks, cashiers: G011, G211 - G311	1,123,000	269,000	0.24	SHIFT, PAH
Labourers in processing, manufacturing, and utilities: J311 - J319	267,000	211,000	0.79	SHIFT, WOOD, FORM
Technical, assisting, and related occupations in health: D211 - D313	478,000	193,000	0.40	SHIFT, UV, FORM
Natural and applied sciences and related occupations: C011 - C183	1,108,000	183,000	0.17	SOL, SHIFT, SILI
Clerical occupations, including supervisors: B411 - B576	1,733,000	181,000	0.10	SHIFT, SOL
Professional occupations in health, nurse supervisors, nurses: D011 - D112	472,000	176,000	0.37	SHIFT, ANTI, FORM
Contractors and supervisors in trades and transportation: H011 - H022	125,000	83,000	0.66	ASB, SILI, SOL
Other management occupations: A111 - A392	1,375,000	75,000	0.05	SHIFT, SOL, UV
Occupations in art, culture, recreation, sport: F011 - F154	502,000	72,000	0.14	SHIFT, SOL, CHLF
Occupations in social science, government service, religion: E011 - E039, E211 - E217	746,000	65,000	0.09	SHIFT, SOL
Teachers and professors: E111 - E133	668,000	37,000	0.05	FORM, SHIFT, WOOD
Financial, Secretarial, Admin occupations: B111 - B318	865,000	17,000	0.02	SHIFT, SOL
Childcare and home support workers: G811 - G814	260,000	16,000	0.06	SHIFT, SOL
Wholesale, technical, insurance, real estate sales specialists, and retail, wholesale and grain buyers: G111 - G134	353,000	8,600	0.02	SHIFT
Professional occupations in business/finance: B011 - B022	428,000	5,400	0.01	SHIFT
Senior management Occupations: A011 - A016	219,000	0	0.00	n/a

*DEE: diesel engine exhaust, SOL: solar radiation, WOOD: wood dust, SHIFT: shift work, BENZ: benzene, PAH: polycyclic aromatic hydrocarbons, SILI: silica, FORM: formaldehyde, ANTI: antineoplastic agents, IRAD: ionizing radiation, CHLF: chloroform, ETHB: ethylbenzene, UV: artificial ultraviolet radiation, PB: lead compounds

Table S3: Top 12 prevalent exposures in Canada by province [n (% of workforce by region)]

	Canada	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	NU, NT, YT
Shift work	1,900,000 (11.3)	263,000 (12.0)	213,000 (11.1)	56,000 (10.8)	65,000 (10.8)	833,000 (12.9)	283,000 (7.2)	51,000 (13.6)	74,000 (15.8)	13,000 (17.7)	47,000 (19.4)	n/a*
Solar radiation	1,476,000 (8.8)	214,000 (9.7)	225,000 (11.7)	83,000 (16.1)	62,000 (10.3)	449,000 (6.9)	291,000 (7.4)	42,000 (11.2)	53,000 (11.2)	13,000 (17.3)	35,000 (14.5)	6,000 (11.0)
Diesel engine exhaust	781,000 (4.6)	106,000 (4.9)	106,000 (5.5)	32,000 (6.1)	30,000 (5.0)	263,000 (4.1)	177,000 (4.5)	23,000 (6.2)	22,000 (4.7)	3,500 (4.7)	14,000 (5.7)	3,800 (6.9)
Silica, crystalline	382,000 (2.3)	52,000 (2.3)	54,000 (2.8)	12,000 (2.3)	13,000 (2.1)	142,000 (2.2)	78,000 (2.0)	9,700 (2.6)	9,900 (2.1)	1,700 (2.3)	6,600 (2.7)	1,800 (3.3)
Benzene	374,000 (2.2)	40,000 (1.8)	45,000 (2.3)	11,000 (2.2)	14,000 (2.3)	147,000 (2.3)	93,000 (2.4)	7,100 (1.9)	10,000 (2.2)	1,100 (1.5)	4,200 (1.7)	1,000 (1.9)
Polycyclic aromatic hydrocarbons (PAH)	350,000 (2.1)	48,000 (2.2)	43,000 (2.2)	13,000 (2.5)	14,000 (2.4)	120,000 (1.8)	85,000 (2.2)	8,800 (2.3)	9,700 (2.1)	1,600 (2.2)	5,400 (2.2)	1,400 (2.6)
Wood dust	338,000 (2.0)	66,000 (3.0)	35,000 (1.8)	8,000 (1.5)	11,000 (1.8)	92,000 (1.4)	92,000 (2.3)	12,000 (3.2)	11,000 (2.4)	1,700 (2.3)	6,100 (2.5)	1,300 (2.4)
Lead and lead compounds	277,000 (1.6)	30,000 (1.4)	41,000 (2.1)	9,000 (1.7)	9,500 (1.6)	102,000 (1.6)	66,000 (1.7)	6,100 (1.6)	7,100 (1.5)	900 (1.2)	4,100 (1.7)	800 (1.5)
Ethylbenzene	208,000 (1.2)	23,000 (1.0)	32,000 (1.7)	8,300 (1.6)	7,800 (1.3)	77,000 (1.2)	46,000 (1.2)	5,000 (1.3)	5,700 (1.2)	800 (1.0)	3,000 (1.2)	900 (1.6)
Formaldehyde	151,000 (0.9)	19,000 (0.9)	12,000 (0.6)	2,900 (0.6)	5,800 (1.0)	63,000 (1.0)	40,000 (1.0)	3,200 (0.8)	3,400 (0.7)	400 (0.6)	1,300 (0.6)	200 (0.4)
Asbestos	151,000 (0.9)	26,000 (1.2)	22,000 (1.1)	4,200 (0.8)	4,800 (0.8)	52,000 (0.8)	48,000 (0.7)	3,700 (1.0)	5,400 (1.1)	800 (1.1)	3,200 (1.3)	600 (1.1)
Ultraviolet radiation, artificial	141,000 (0.8)	15,000 (0.7)	25,000 (1.3)	5,300 (1.0)	5,000 (0.8)	48,000 (0.7)	32,000 (0.8)	3,000 (0.8)	3,600 (0.8)	400 (0.6)	2,300 (0.9)	200 (0.4)

*Data for the Territories was not collected in the Survey of Labour and Income Dynamics, therefore no estimate for shift work prevalence is available.