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Original Article

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Development of Quantitative Estimates of Wood Dust Exposure in a Canadian General Population Job-Exposure Matrix Based on Past Expert Assessments

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Abstract

Objectives: The CANJEM general population job-exposure matrix summarizes expert evaluations of 31 673 jobs from four population-based case–control studies of cancer conducted in Montreal, Canada. Intensity in each CANJEM cell is represented as relative distributions of the ordinal (low, medium, high) ratings of jobs assigned by the experts. We aimed to apply quantitative concentrations to CANJEM cells using Canadian historical measurements from the Canadian Workplace Exposure Database (CWED), taking exposure to wood dust as an example.

Methods: We selected 5170 personal and area wood dust measurements from 31 occupations (2011 Canadian National Occupational Classification) with a non-zero exposure probability in CANJEM between 1930 and 2005. The measurements were taken between 1981 and 2003 (median 1989). A Bayesian hierarchical model was applied to the wood dust concentrations with occupations as

random effects, and sampling duration, year, sample type (area or personal), province, and the relative proportion of jobs exposed at medium and high intensity in CANJEM cells as fixed effects.
Results: The estimated geometric mean (GM) concentrations for a CANJEM cell with all jobs exposed at medium or high intensity were respectively 1.3 and 2.4 times higher relative to a cell with all jobs at low intensity. An overall trend of −3%/year in exposure was observed. Applying the model estimates to all 198 cells in CANJEM with some exposure assigned by the experts, the predicted 8-hour, personal wood dust GM concentrations by occupation for 1989 ranged from 0.48 to 1.96 mg m^{-3}.
Conclusions: The model provided estimates of wood dust concentrations for any CANJEM cell with exposure, applicable for quantitative risk assessment at the population level. This framework can be implemented for other agents represented in both CANJEM and CWED.

Keywords: job-exposure matrix; occupational exposure database; retrospective exposure assessment; wood dust

Introduction

Retrospective occupational exposure assessment in community-based studies has traditionally relied on expert judgment of individual job descriptions (Gérin *et al.*, 1985) or on job-exposure matrices (JEMs; Hoar *et al.*, 1980). Exposures assigned to individual jobs or JEM cells are often expressed categorically, such as no, low, or high exposure, due to the limited availability of relevant historical workplace measurement data. Some exceptions exist, such as the Finnish job-exposure matrix general-population JEM from Finland (Kauppinen *et al.*, 1998) and Matgéné from France (Févotte *et al.*, 2011), which provide quantitative average exposure levels albeit based on expert judgment.

Recently, a framework to calibrate a semi-quantitative JEM using measurement data, originally developed for an industry-based study (Wild *et al.*, 2002), has been expanded to two population-based studies. One is the Shanghai Women Health Study prospective cohort, with a quantitative JEM for benzene and lead (Friesen *et al.*, 2012; Koh *et al.*, 2014), and the other is the international Synergy case–control study, with estimates for six agents (Peters *et al.*, 2011, 2016). This framework requires the combination of two sources of information. The first is a generic JEM representing a prior opinion of the presence/absence and level of exposure expressed as categorical ratings. The second source is a large sample of measurement data to estimate quantitative exposure levels by occupation and for each categorical JEM rating.

Measurement data collected by governmental agencies for various activities have been identified since the 1990s as a potential useful source of exposure information for population studies (Stewart and Rice, 1990; Lippmann, 1991). For example, the Integrated Management Information System (IMIS) in the USA (Lavoué *et al.*, 2013) and Messdaten zur Exposition gegenüber Gefahrstoffen am Arbeitsplatz in Germany (Koppisch *et al.*, 2012) both contain over 2 million measurements dating back to the 1970s. They have been applied in support of exposure assessment efforts for epidemiological studies (*e.g.* Teschke *et al.*, 1999; Kendzia *et al.*, 2017). Other national databases include COLCHIC and Système de COLlecte des informations des organisme Accrédités from France (Mater *et al.*, 2016), National Exposure Database from the UK (Burns and Beaumont, 1989) and Sistema informativo registro di esposizione e patologie from Italy (Scarselli *et al.*, 2008). The use of such databases to assess exposure in population studies has been limited due to concerns regarding the non-random selection of workers or industries monitored (Olsen *et al.*, 1991), the inconsistent quality of descriptive information (Hall *et al.*, 2002), and the lack of data for some occupations and industries. Combining measurements with a JEM, which represents a prior opinion on exposure in the population across occupations, can adjust for some of these limitations and addresses data gaps by using the calibrated JEM ratings as quantitative estimates for occupations not represented in the measurement data (Peters *et al.*, 2011).

Expert evaluations of over 31 000 jobs collected during four large case–control studies in Montreal, Canada, were summarized to form the CANJEM general population JEM (Sauvé *et al.*, 2018; Siemiatycki and Lavoué, 2018). CANJEM features three dimensions: occupation (or industry), agent (n = 258), and employment period. When a job was considered exposed to an agent, the experts rated the intensity of exposure on a three-point scale (low, medium, high). For CANJEM, exposure intensity in cells is represented by the relative proportion of jobs exposed at low, medium, and high level. One issue is that these categories do not directly correspond to quantitative concentration levels. This could be addressed using historical workplace measurement data, such as those from the Canadian Workplace Exposure Database (CWED; Hall *et al.*, 2014; Peters *et al.*, 2015; Hon *et al.*, 2017). CWED comprises exposure measurements for over 300 agents, mostly collected for compliance purposes by provincial governmental agencies in Canada since the 1960s. Both CANJEM and CWED are recently constituted sources of exposure information that have never been linked together in a systematic way.

The objective of this article is to develop quantitative retrospective estimates of exposure for CANJEM cells by combining the distribution of semi-quantitative ratings within occupations in the JEM with the measurement data contained in CWED using Bayesian models. The use of Bayesian models allows for the incorporation of prior information in the analysis, beyond the information contained in the JEM, and can seamlessly handle samples with non-detected concentrations. This article focuses on exposure to wood dust as a first step in the development of a new quantitative dimension of CANJEM that could represent an invaluable source of information in the evaluation of quantitative exposure–response relationships and in the surveillance of occupational diseases in the population, and serve as guidance for future analyses on other agents in CANJEM.

Methods

Data sources

CANJEM

CANJEM is a publicly available (www.canjem.ca) general-population JEM summarizing expert evaluations of occupational histories from four population-based case–control studies conducted in the Montreal metropolitan region in Canada. A detailed description of CANJEM can be found elsewhere (Sauvé *et al.*, 2018; Siemiatycki and Lavoué, 2018), and the expert assessment approach is described in Gérin *et al.* (1985). An application of the expert approach to assess wood dust exposure is presented in Vallières *et al.* (2015).

Briefly, CANJEM is defined by three axes: occupation (or industry), period, and agent. The occupation/industry axis is available in four Canadian and international standardized classifications for occupations and three for industries. The time axis has three levels of resolution, from one global period (1930–2005) split into two (1930–1969; 1970–2005) or four periods (1930–1949; 1950–1969; 1970–1984; 1985–2005). The 258 agents, including wood dust, form the third dimension. In the original studies, no distinction was made between dusts from softwood, hardwood, and/or allergenic species, thus ‘wood dust’ in CANJEM covers all species. Each CANJEM cell indicates the probability of exposure (or proportion of jobs exposed), and provides the distribution of categorical reliability, intensity, and frequency ratings (*e.g.* low, medium, and high for intensity) across jobs for one combination of occupation, period, and agent for which at least one job was evaluated.

Canadian Workplace Exposure Database

CWED was initiated in 2008 to create a centralized repository of historical measurement data from Canadian workplaces from existing data stored in electronic databases and in hard copy (Hall *et al.*, 2014). Applications of CWED have included the surveillance of exposure to carcinogens in the Canadian population for the CAREX Canada project (Peters *et al.*, 2015), estimating the burden of occupational cancer in Canada (Demers *et al.*, 2014), and documenting historical trends in exposure to isocyanates (Hon *et al.*, 2017).

CWED contains approximately 500 000 measurements from 350 agents, collected for purposes of compliance or routine monitoring and research. About 80% of the data originates from the provinces of British Columbia (BC) and Ontario, the latter from the Medical Surveillance database (Lubek, 1991), with the remainder from other provinces and federal administrations. Although the measurements in CWED were collected between the 1960s and the 2010s, most were taken from the mid-1970s to the late 1990s. Ancillary information varies by data source, but the standard set of commonly recorded variables includes sampling date, contaminant sampled, company name, sampling duration, sample type (area or personal), sampling method, occupation title (2006 National Occupation Classification for Statistics, or NOC-S; Statistics Canada, 2007), and industry title (2002 North American Industry Classification System, or NAICS; Statistics Canada, 2003).

Data preparation

Selection of measurement data

A total of 6569 wood dust entries were retrieved from six individual databases of four provinces within CWED (BC, Manitoba, Ontario, and Saskatchewan) and covering the period 1978–2012. The samples contained a mixture of softwood (n = 1673, 24%) and hardwood (n = 2037, 29%), with 3249 (47%) samples being unspecified. A total of 1389 samples (20%) were identified as allergenic species. We retained an initial set of 5428 samples, with 1890 from BC and 3538 from Ontario, after excluding samples with missing occupation title (n = 1003) or a sampling duration missing or under 15 min (n = 74), among others. The exclusion criteria and number of samples affected are listed in Supplementary Figure 1 (available at *Annals of Work Exposures and Health* online). Most measurements from BC were based on the WorkSafeBC method 1150 for ‘Particulate (Total) in Air’ using a 37-mm cassette.

Further details on the specifics of sampling methods for BC were not available as the laboratory closed in 2004 and no remaining contacts with institutional memory were available for comment. However, gravimetric methodologies for total particulate sampling are generally straightforward, and the flow rates recorded (2 l min^{-1}) and filters used (37-mm PVC) are consistent with comparable sampling procedures recommended by agencies such as Occupational Safety and Health Administration and National Institute for Occupational Safety and Health. Sampling methods for the Ontario data were unreported but the occupational exposure limits (OELs) are also based on 'total' dust. Because the data were collected by inspectors to enable comparison to the OEL, all samples retained were assumed to concern the 'total' dust fraction. A total of 248 samples were flagged as non-detects. Of those, 136 samples had a limit of detection (LOD) reported. For the remaining non-detects (n = 112), we assigned an LOD value of 0.1 mg per sample for measurements before 1994, and a value of 0.05 mg per sample from 1994 onwards, based on the information from the 2841 samples (43% of all samples) that had an LOD reported, which all came from BC.

Linkage of CANJEM and CWED

We selected CANJEM defined by the 2011 NOC classification (Statistics Canada, 2012), the most similar to the 2006 NOC-S classification in CWED. Four-digit 2011 NOC codes were assigned for each CWED measurement using official conversion tables (Statistics Canada, 2016). When multiple codes were possible, we selected the occupation with a similar title (maximum difference of five characters); otherwise, the occupation with the largest number of Canadians employed was selected. The following estimates from CANJEM cells in period 1930–2005 were then assigned to each measurement: number of jobs evaluated, number of jobs exposed, exposure probability, and relative proportion of exposed jobs at low, medium, and high intensity.

Statistical analyses

Statistical modelling

The model for combining the CWED measurement data with CANJEM was based on the mixed-effects model framework described in Peters *et al.* (2011) and Friesen *et al.* (2012), in which log-transformed concentrations represent the outcome, with categorical ratings of cells as fixed effects and the occupation titles as random effects. Quantitative exposure levels can then be estimated for each categorical JEM rating as well as specific levels by occupation. With this model, the average concentration levels of occupations with few measurements are pulled toward the average concentration of the JEM rating, resulting in a comparatively higher weight of the JEM ratings on the predicted exposure levels relative to groups with more measurements available (Wild *et al.*, 2002; Peters *et al.*, 2011). We adapted this structure to the multiple intensity categories in CANJEM cells using one term for the proportion of jobs at medium intensity and another for the proportion at high intensity. Other covariates were sample year, duration, and type (area or personal) and province, in the model structure shown later:

$$\ln\left(Y_{ij}\right) = \beta_0 + \sum \beta X_i + \sum \beta I_i + bJ_j + \varepsilon_{ij}$$

where

- $\ln\left(Y_{ij}\right)$ was the natural log-transformed wood dust concentration.
- β_0 was the model intercept.
- X_i were the fixed-effect terms (except for the CANJEM intensity ratings).
- I_i were the continuous variables for the relative proportion of jobs exposed at medium and at high intensity level in CANJEM.
- J_j was a random effect term of the NOC occupation title.
- ε_{ij} was the residual (within-occupation) error.

The estimated model coefficients for sample duration, year, type, and province, and categorical intensity rating, were transformed into relative indices of exposure (RIE; Lavoué *et al.*, 2006) to illustrate their influence on exposure as a percentage of increase or decrease relative to a reference level (taken as 100%). The model was fitted with a Bayesian approach using the JAGS 4.0.0 software (Plummer, 2003), using 12 Markov chain Monte Carlo (MCMC) chains of 13 750 iterations each, discarding the first 1250 iterations per chain and keeping the result of one out of two iterations for inference (75 000 iterations total). The medians of the posterior distribution of the parameters were used as point estimates, with the 5th and 95th percentiles defining the 90% credible intervals (CI). Non-detected concentrations were treated as missing observations in the model. At each MCMC iteration, a log-transformed concentration value between 0 and the LOD was imputed for each sample from a normal distribution truncated at the LOD specific to that sample.

In defining the prior distributions for the fixed effects, we did not expect extreme differences in exposure over time or between provinces, for instance. Prior distributions of fixed effects (except for the intensity ratings) were normal distributions of mean 0 and variance

5.7, representing a 50% interval of the RIEs covering the range 20–500% (*i.e.*, from five times lower to five times higher than the reference).

For the intensity ratings, a larger prior variance of 46.6 was used to reflect the possibility of larger effects sizes on the exposure levels. The priors represented a 50% interval over the RIE covering the range 0.0001–10000% (i.e., 100 times lower to 100 times higher than the reference of all jobs at low intensity). We also placed a constraint to associate the medium category with higher exposure relative to low, and the high category with higher exposure than medium, by truncating the prior distributions to the positive domain and setting β_{C_high} to a value greater than β_{C_medium}. This ensured that an increase in the relative intensity ratings of jobs in the cell, as assessed by the experts, would be associated with higher exposure levels. Prior distributions for the between and within occupation variances were Uniform(0,10). Supplementary File 1 (available at *Annals of Work Exposures and Health* online) presents the JAGS code used to fit the model.

Predictions

For each occupation with measurements available, we predicted the geometric mean (GM) of wood dust concentration for 1989 (median year in data set), duration of 480 min, personal sample, relative proportion of measurements by province, relative distribution of intensity ratings in the CANJEM cell, and occupation. These predicted GMs are conceptually similar to best linear unbiased predictions, in frequentist analyses. Predicted GMs for a hypothetical cell with all jobs at low, medium, or high intensity were made using the same combination of sample year, duration and type, and province. We also predicted levels for all occupations with exposed jobs in CANJEM, regardless of measurements being available, using the calibrated ratings.

Sensitivity analyses

We conducted sensitivity analyses to evaluate the impact of alternative model specifications, exposure indices, and data selection. We first tested models without the constraint in the prior distributions forcing a trend of higher exposure levels with higher intensity ratings in cells. Second, we evaluated a model with a single rating per cell by selecting the category with the most jobs. When two categories had the same number of jobs, one category was randomly selected in each MCMC chain prior to fitting the model. Third, we applied different criteria on sample size, with a minimum of one or five measurements per occupation, or restricted to occupations with probability ≥5% in CANJEM. Fourth, we performed analyses restricted to periods 1970–2005 or 1985–2005, using the CANJEM intensity estimates of cells specific to each period. Lastly, we applied the models to personal samples only.

Results

Data selection

CANJEM contained 476 four-digit NOC cells for the period 1930–2005. A total of 198 cells (listed in Supplementary Table 3, available at *Annals of Work Exposures and Health* online) had at least one job exposed to wood dust, with a median probability of exposure of 6.3% (range 0.14–100%). The 5428 CWED samples initially retained represented 78 occupations of which eight (90 samples) had no exposed job in CANJEM. These mainly concerned automobile and boat manufacturing, education, and healthcare. Of the remaining 70 occupations with exposed jobs in CANJEM, 31 had at least 10 samples and were retained in the analysis (n = 5170 samples). Woodworking machine operators (NOC 9437, n = 1616) and sawmill machine operators (NOC 9431, n = 1127) had the largest number of measurements.

Descriptive statistics of the exposure data

Table 1 presents descriptive statistics of wood dust concentrations for selected categorical variables. The overall GM was 1.64 mg m^{-3} [geometric standard deviation (GSD) 4.3], and 127 samples (2.5%) were non-detects. Of the non-detected samples, 60 had no LOD reported and had to be assigned from the other measurements. Sampling duration ranged from 15 to 690 min (median 195 min). Samples were collected between 1981 and 2003 (median 1989), with 13% before 1985.

The number of samples, GM and GSD of wood dust concentrations by occupation, and the probability and intensity of exposure in CANJEM cells for period 1930–2005 are presented in Supplementary Table 1 (available at *Annals of Work Exposures and Health* online). Automotive service technicians, truck and bus mechanics, and mechanical repairers had the highest GM at 4.62 mg m^{-3}, followed by chain saw and skidder operators (GM = 4.59 mg m^{-3}, n = 14). Figure 1 presents the distribution of the exposure probability of all 198 CANJEM cells with at least one exposed job, differentiating between the 31 occupations with at least 10 samples in CWED and the remaining 167 cells. Cells with low exposure probability generally had fewer measurements (if any) than cells with higher probabilities. Sixty-five percent of all measurements came from occupations with a probability greater than 90% in CANJEM.

Modelling

Estimated effects of variables on wood dust exposure levels

Table 2 presents the RIEs for selected determinants included in the model, with the model coefficients being presented in Supplementary Table 2 (available at *Annals of Work Exposures and Health* online).

Table 1. Number of samples and GM and geometric standard deviation (GSD) of wood dust exposure levels, overall and stratified by level of selected categorical variables.

Variable	*N*[a]	%[b]	ND (*n*)[c]	GM (mg m^{-3})[d]	GSD[e]
Overall	5170	100	127	1.64	4.3
Sample type					
Area	1451	28.1	50	1.04	4.0
Personal	3719	71.9	77	1.96	4.3
Province					
British Columbia	1829	35.4	67	0.92	4.2
Ontario	3341	64.6	60	2.25	3.9
CANJEM period					
1970–1984	678	13.1	36	1.21	5.2
1985–2005	4492	86.9	91	1.71	4.2

ND = non-detected.
[a]Number of samples.
[b]Relative percentage of samples by level.
[c]Number of non-detected samples.
[d]Computed with the robust Regression on order statistics (ROS) method for non-detects (Helsel, 2012).
[e]Computed with the robust ROS method.

An annual decrease in exposure of 3% per year was found, whereas a 50% increase in sampling duration (*e.g.* from 60 to 90 min) decreased concentration levels by 22%. Samples from Ontario were associated with higher exposure compared to BC. Using a cell with all jobs at low intensity as a reference, exposure levels were 1.3 times higher for a cell with all jobs at medium intensity, and 2.4 times higher when all jobs were at high intensity.

Predicted exposure levels by occupation and intensity ratings

The predicted GM for 1989 for a cell with all jobs at low intensity was 0.76 mg m^{-3} (90% CI: 0.56–0.95 mg m^{-3}), compared to 0.97 mg m^{-3} for all jobs at medium intensity (90% CI: 0.77–1.27 mg m^{-3}) and 1.77 mg m^{-3} for high intensity (90% CI: 1.23–2.73 mg m^{-3}). The predicted GMs of all 198 occupations based on the calibrated intensity ratings are presented in Supplementary Table 3 (available at *Annals of Work Exposures and Health* online). For the 31 occupations with measurements, the predicted GMs based on the calibrated ratings and the occupation random effect ranged from 0.48 mg m^{-3} (2252 industrial designers) to 1.96 mg m^{-3} (8421 chain saw and skidder operators), representing a 4.1-fold difference compared to 2.3 for predictions based on the calibrated ratings alone. Occupations with the highest predicted GMs (Table 3) mainly concerned woodworking and furniture manufacturing, logging and forestry, and carpentry.

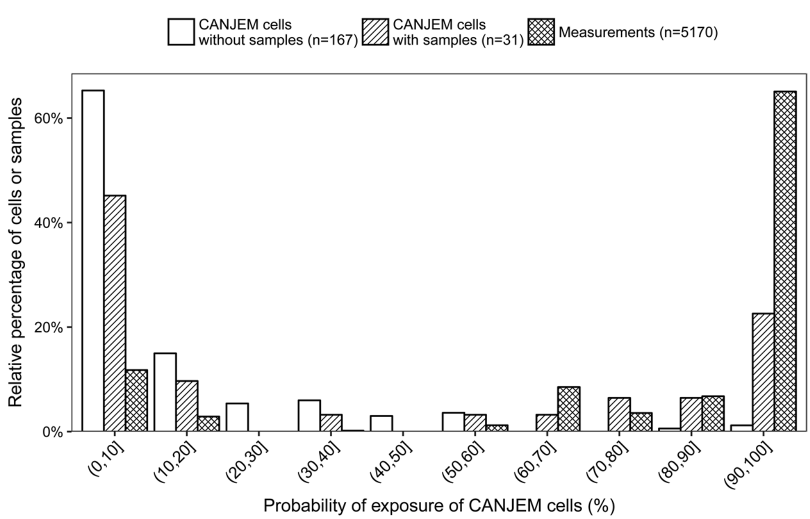

Figure 1. Distribution of the 198 CANJEM cells with at least one exposed job by probability of exposure, stratified by the availability of measurements (minimum of 10 samples per cell), and distribution of the measurements by the probability of exposure of the occupation in the 31 CANJEM cells with samples.

Table 2. Relative effects of selected variables on wood dust exposure levels.

Variable/category	RIE (%) (90% CI)[a]
Sample duration (minutes)[b]	77.8 (76.5–79.2)
Sample year[c]	96.7 (96.0–97.4)
Intensity ratings of cell	
All jobs at low intensity	100 (reference)[d]
All jobs at medium intensity	125.0 (101.9–198.7)
All jobs at high intensity	235.8 (146.4–407.1)
Sample type	
Area	100 (reference)
Personal	171.9 (161.1–183.4)
Province	
British Columbia	100 (reference)
Ontario	167.8 (155.0–181.1)

[a]RIE and 90% CI.
[b]Corresponds to the effect of an increase of 50% in sampling duration. For example, using a reference duration of 60 min (taken as 100%), the exposure level for an increase in duration of 50% (i.e., 90 min) is 77.8% of the reference level (i.e., 22.2% lower).
[c]Corresponds to the effect of an increase of 1 year. Using 1989 as a reference year (100%), the relative level for 1990 would be 96.7% of the reference (i.e., 3.3% lower).
[d]RIE of the reference level is taken as 100%.

Sensitivity analyses

The influence of alternative model specifications and data restriction on the associations between the categorical intensity ratings and the wood dust concentrations are presented in Table 4. Removing the constraint on the model coefficients resulted in lower exposure for medium intensity relative to low when using the proportion of jobs by rating (RIE 92%, 90% CI: 47–180%) or the most frequent category (RIE 96%, 90% CI: 68–136%) in the model. Using a minimum of one or five samples by occupation, or using the most frequent rating in cells, decreased the contrasts in exposure between the intensity categories. On the other hand, restricting the analysis to occupations with an exposure probability ≥5% or using a narrower period resulted in greater contrasts.

Discussion

In this article, we combined two recent sources of exposure information to develop quantitative estimates of historical wood dust concentrations in a general-population JEM. We extended an existing framework for calibrating a JEM to account for the multiplicity of intensity ratings in CANJEM cells, and by using Bayesian models to easily integrate prior information on determinants of exposure and to handle non-detected concentrations.

Comparison of occupations represented in CWED and in CANJEM

There was a good concordance overall between the availability of measurements for an occupation and the presence of exposure in CANJEM. Only 8 of the 78 occupations with measurements had an exposure probability of 0% in CANJEM, and these had a relatively small number of measurements in CWED. On the other hand, most samples were in occupations with a high probability of exposure in CANJEM. For instance, woodworking machine operators and sawmill machine operators, which together represented 53% of all samples, had an exposure probability ≥95%. These occupations are also related to some of the industrial sectors (sawmills, furniture, and other wood product manufacturing) with the largest number of workers exposed to wood dust in Canada, after construction (CAREX Canada, 2015). Construction occupations had comparatively fewer measurements, a trend also observed in CWED for other prevalent exposures in this sector such as silica or diesel exhaust (Peters *et al.*, 2015). Lastly, 120 out of the 198 occupations with a non-null probability of exposure in CANJEM were not represented in CWED. The use of a JEM can therefore provide a better indicator of the presence or absence of exposure across the spectrum of occupations in the population, compared to an exposure database alone.

Exposure levels by occupation and categorical intensity ratings

Compared to the calibration of a JEM based on a single rating per cell, the use of a distribution of intensity ratings in CANJEM cells allows for a greater variability in exposure between occupations. The predicted levels of the 198 cells with exposure in CANJEM varied from 0.76 mg m^{-3} (all jobs at low intensity) to 1.77 mg m^{-3} (all jobs at high intensity) based on the calibrated ratings. The predicted GMs represent a product of the expert judgment of jobs in CANJEM cells, the exposure levels in the measurement data, and the relative sample size from the use of random effects. Integrating expert judgment from the CANJEM ratings also adjusted some more outlying estimates. For example, administrative assistants, with all jobs at low intensity in CANJEM, had the third highest descriptive GM based on 13 samples (3.53 mg m^{-3}), whereas its predicted GM from the model only ranked 15th (1.11 mg m^{-3}), suggesting that the few measurements available may have represented unusual exposure circumstances for this occupation.

This study constitutes the first exercise to estimate empirical concentration levels to the intensity categories used in the Montreal case–control studies. In the absence

Table 3. Ten occupations with the highest predicted 8-hour GM wood dust concentration for year 1989.

4-digits NOC occupation code and title	N[b]	Distribution of intensity in CANJEM cells, period 1930–2005[a]			Predicted wood dust GM (90% CI) for year 1989 (mg m^{-3})	
		Low intensity (%)	Medium intensity (%)	High intensity (%)	CANJEM cell ratings and occupation mean[c]	CANJEM cell ratings only[d]
8421: Chain saw and skidder operators	14	52.1	46.7	1.2	1.96 (1.24–3.17)	0.86 (0.71–1.03)
7232: Tool and die makers	13	40.0	20.0	40.0	1.77 (1.13–2.81)	1.12 (0.94–1.34)
9534: Furniture finishers and refinishers	41	14.3	57.1	28.6	1.77 (1.31–2.40)	1.12 (0.95–1.33)
7272: Cabinetmakers	279	3.9	36.3	59.8	1.71 (1.50–1.95)	1.38 (1.11–1.78)
9619: Other labourers in processing, manufacturing, and utilities	97	38.5	26.9	34.6	1.61 (1.31–1.97)	1.09 (0.92–1.29)
9227: Supervisors, other products manufacturing and assembly	10	0.0	0.0	100.0	1.58 (0.95–2.62)	1.77 (1.23–2.73)
9437: Woodworking machine operators	1616	5.6	24.1	70.4	1.58 (1.47–1.70)	1.47 (1.14–1.97)
9224: Supervisors, furniture and fixtures manufacturing	14	23.8	38.1	38.1	1.48 (0.96–2.30)	1.15 (0.98–1.38)
9532: Furniture and fixture assemblers and inspectors	143	32.4	32.4	35.3	1.47 (1.24–1.75)	1.11 (0.94–1.31)
7321: Automotive service technicians, truck and bus mechanics, and mechanical repairers	14	100.0	0.0	0.0	1.33 (0.84–2.16)	0.76 (0.56–0.95)

[a]Relative percentage of jobs by intensity rating in CANJEM cells.
[b]Number of samples by occupation.
[c]Predicted wood dust concentration for year 1989, sampling duration of 480 min, personal sample type, relative proportion of measurements in each province, relative proportion of jobs by intensity rating of occupation, and occupation random intercept.
[d]Predicted wood dust concentration for year 1989, sampling duration of 480 min, personal sample type, relative proportion of measurements in each province, and relative proportion of jobs by intensity rating of occupation.

of measurement data, expert judgment has been used to assign generic quantitative weights to the intensity levels such as 1 (low), 5 (medium), and 25 (high) (Lavoué *et al.*, 2012). The ratios between GMs for all jobs at low, medium, and high in this study were comparatively smaller, being on the order of 1, 1.3, and 2.4. These contrasts were comparable to those observed in other studies combining expert ratings with measurement data (Peters *et al.*, 2011; Friesen *et al.*, 2012; Koh *et al.*, 2014; Peters *et al.*, 2016). For example, the predicted benzene concentrations by rating for 1980 in Friesen *et al.* (2012) corresponded to ratios of 1:1.6:3.0.

In sensitivity analyses, the use of a single rating per cell in the model, based on most frequently assigned category, yielded lower contrasts between categories. This selection method did not differentiate between a cell with 51% of jobs at medium intensity and another with 100% at the same level. The use of relative distributions of ratings in the model, providing information on the within-occupation heterogeneity in intensity of jobs, may have therefore led to larger contrasts in exposure. Greater contrasts were also found in analyses restricted to occupations with a probability of exposure of at least 5% and with more samples in CWED, suggesting an influence of specificity in CANJEM and precision in CWED.

Determinants of exposure

The annual decrease in exposure of 3% per year between 1978 and 2008 is comparable, albeit smaller, to trends observed in the USA (7% per year between 1979 and 1997; Teschke *et al.*, 1999;) and the UK (8% per year between 1985 and 2005; Galea *et al.*, 2009), despite some differences in the overall GMs between countries (1.9 mg m^{-3} for the USA and 5.2 mg m^{-3} for the UK, compared to 1.6 mg m^{-3} in CWED). Associations between lower exposure levels and longer sampling durations have also been observed in other analyses

Table 4. RIEs for a theoretical cell with all jobs at medium or high intensity, relative to a cell with all jobs at low intensity, in sensitivity analyses.

	Medium intensity	**High intensity**
Analysis	RIE% (90% CI)[a]	RIE% (90% CI)[b]
Main analysis[c]	125.0 (101.9–198.7)	235.8 (146.4–407.1)
No constraint on intensity categories		
Proportion of jobs by rating in cell	90.4 (46.1–173.3)	199.9 (107.2–367.9)
Most frequent rating in cell[d]		
Most frequent rating, with constraint	112.3 (101.1–144.4)	168.7 (122.9–236.8)
Most frequent rating, no constraint	96.3 (68.2–135.9)	151.1 (101.7–222.9)
Alternative minimum sample size and probability of exposure by occupation		
Minimum of 5 samples/occupation and probability >0%	115.4 (101.2–160.9)	221.4 (138.3–375.2)
Minimum of 1 sample/occupation and probability >0%	118.6 (101.6–167.2)	199.1 (129.2–339.9)
Minimum of 10 samples/occupation and probability ≥5%	255.6 (126.8–542.9)	384.7 (202.5–781.0)
Minimum of 5 samples/occupation and probability ≥5%	205.8 (116.0–399.6)	330.9 (187.5–625.2)
Minimum of 1 sample/occupation and probability ≥5%	163.8 (107.8–284.5)	258.5 (155.8–446.1)
Specific CANJEM period		
Period 1970–2005[e]	141.8 (105.2–217.1)	353.2 (194.9–640.1)
Period 1985–2005[f]	138.9 (104.9–209.6)	244.0 (157.9–381.7)
Personal samples only[g]	143.7 (103.6–263.9)	249.8 (143.1–497.3)

[a]RIE and 90% CI for all jobs at medium intensity, relative to a reference of all jobs at low intensity (taken as 100%).
[b]RIE and 90% CI for all jobs at high intensity, relative to a reference of all jobs at low intensity (taken as 100%).
[c]Main analysis with the CANJEM ratings based on the relative proportions of jobs at medium and at high intensity in the cell in period 1930–2005, with a constraint on the order of the coefficients for the intensity ratings, and occupations entered as random effects. Restricted to occupations with at least 10 samples and at least 1 exposed job in CANJEM (probability >0%).
[d]The intensity category with the highest proportion of jobs in the cell was included in the model instead of the relative proportions of jobs at medium and high intensity.
[e]Based on 4029 samples from 29 occupations with at least one exposed job in period 1970–2005.
[f]Based on 3114 samples from 19 occupations with at least one exposed job in period 1985–2005.
[g]Based on 3685 samples from 26 occupations with at least 10 personal samples.

of administrative databases (*e.g.*, Lavoué *et al.*, 2006; Peters *et al.*, 2011; Kendzia *et al.*, 2017). Samples with a shorter duration may reflect an evaluation of specific tasks in compliance testing, or to avoid filter overloading during very high exposure, whereas samples with a longer duration may have included periods without exposure. Restricting the analysis to measurements with a duration greater than 60 or 120 min did not markedly change the trend between sampling duration and the exposure levels.

Regarding sample type, personal samples were associated with exposure levels 72% higher than area samples. As discussed in Friesen *et al.* (2012), the relationship between personal and area measurements depends on factors such as the location of the sampling equipment relative to the source of exposure. Although personal samples are preferred for this reason, we retained information from area samples, representing approximately 30% of the data, and adjusted for sample type in the model instead. The restriction to personal samples in sensitivity analyses provided similar contrasts (Table 4) while the predicted GMs of occupations were comparable to those obtained with all samples and adjusted for personal sample type (results not shown).

We also found differences between provinces, where exposure levels from Ontario were approximately 1.7 times higher relative to BC. In contrast, an analysis of isocyanate exposure levels in CWED found higher levels in BC compared to Ontario (Hon *et al.*, 2017). The between-province differences could result from differences in industries, regulations, or sampling strategies. For the former, most measurements from sawmills came from BC, whereas a higher proportion of data from manufacturing were from Ontario. However, most occupations in our analysis were associated with a single sector (*e.g.* sawmill machine operators), which should account for these differences. As for differences in regulations, the current OELs for hardwood are 1 mg m^{-3} for both provinces, but the OEL for softwood in BC of

2.5 mg m^{-3} (non-allergenic species) is twice lower than in Ontario (5 mg m^{-3}), which may factor in the higher levels found for the latter. Before 1988, however, the OELs in BC were higher (10 mg m^{-3} for non-allergenic species and 5 mg m^{-3} for allergenic species), yet the average concentrations of samples from Ontario were generally higher throughout this period, which could be due to differences in sampling strategies.

Limitations

As observed in previous studies involving CWED (Hall *et al.*, 2002; Hon *et al.*, 2017), missing data were prevalent for several key variables such as the use of control methods or protective equipment that represented some of the factors used by the Montreal experts when assigning exposures based on job descriptions. Sampling methods, such as the size fraction of dust particles collected, were also inconsistently recorded. However, the OELs in BC and Ontario were based on total dust during the period covered by the data, which limits the possibility of the time trend being confounded by changes in the dust fraction sampled (*e.g.* from total to inhalable dust).

In addition, administrative databases such as CWED may not represent a random sample of the exposure levels encountered in the underlying population because the measurements could have been collected under different objectives. For instance, samples from follow-up inspections and from facilities with a history of non-compliance were associated with higher exposure levels in the IMIS database (Sarazin *et al.*, 2016). In our case, no information was available to evaluate how representative exposure levels in CWED might be. One of the potential biases concerns the representativeness of CWED samples in occupations associated with lower intensity levels in CANJEM. These could reflect more frequently incidental situations of higher exposure compared to samples from occupations associated with higher ratings in CANJEM, a situation also observed by Peters *et al.* (2016) with occupations classified as unexposed by experts. Hence, measured levels in low-exposure occupations would tend to overestimate truth compared to measured levels in higher exposed occupations. This phenomenon would have reduced the observed contrast between exposure rating categories.

Lastly, for the compatibility of the quantitative exposure data with CANJEM, no measurements prior to the 1980s were available, which constitutes a significant source of uncertainty in applying the calibrated JEM estimates to jobs held more than 40 years ago. Assigning quantitative exposure levels to such jobs would require a more detailed study of time trends in wood dust exposure using external information (which may not be readily available) to adjust the estimates. We also did not have measurements from the province of Quebec, where the job information used to create CANJEM was sourced, which represents an additional source of uncertainty.

Conclusions

In this study, we developed quantitative wood dust exposure estimates for a general-population JEM summarizing expert assessments of exposures in individual jobs using a recent database of historical workplace measurements and Bayesian models adapted to the distribution of intensity ratings in CANJEM cells. The quantitative estimates in CANJEM could be applied for the surveillance and prevention of wood-dust-related diseases such as sinonasal cancers (IARC, 2012), and to estimate quantitative exposure–response relationships in etiologic studies, such as for the associations observed in previous case–control studies with lung and colorectal cancer (Siemiatycki *et al.*, 1986; Vallières *et al.*, 2015). Moreover, the framework presented here represents a starting point for future applications to other agents common to CANJEM and CWED, such as silica and formaldehyde with over 5000 measurements each. Lastly, this framework could also be implemented by combining other large, national exposure databases with the information available in CANJEM to develop quantitative estimates for other countries.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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