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Reconstructing Historical Exposures to Respirable Dust and Respirable Silica in the Taconite Mining Industry for 1955–2010

Yuan Shao[1,2], Jooyeon Hwang[3], Richard F. MacLehose[4], Bruce H. Alexander[1], Jeffrey H. Mandel[1], Peter C. Raynor[1] and Gurumurthy Ramachandran[2,*],

[1]Division of Environmental Health Sciences, University of Minnesota, Minneapolis, MN 55455, USA; [2]Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205, USA; [3]Department of Occupational and Environmental Health, University of Oklahoma Health Sciences Center, Oklahoma City, OK 73104, USA; [4]Division of Epidemiology & Community Health, University of Minnesota, Minneapolis, MN 55455, USA

*Author to whom correspondence should be addressed. Tel: +1-6126265428; e-mail: gramach5@jhu.edu

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Abstract

The goal of this study was to reconstruct the historical respirable silica (RS) and respirable dust (RD) exposures of workers in the Minnesota taconite industry from 1955 to 2010 as part of several epidemiological studies for assessing the association between exposure to components of taconite dusts and the development of respiratory diseases. A job-exposure matrix (JEM) was developed that uses 9127 RS and 19 391 RD occupational hygiene historical measurements. Historical RS and RD data were extracted from several sources and were grouped into seven mines and then into eight departments [Concentrating, Crushing, Janitor, Mining, Office/control room, Pelletizing, Shop (mobile), and Shop (stationary)]. Within each department, we applied a two-level random-intercept regression model which assumes that the natural log of Y (RD or RS concentration) changes over time at a constant rate. Among all predicted RD and RS values, we found that larger RD values were located in the following departments: Crushing, Concentrating, Pelletizing, and Shop (mobile). Larger RS values were located only in either Crushing or Shop (mobile). The annual rates of change for historical RD and RS exposures were between −3.3 and 3.2%. The silica percentage in the dust varied by mine/department with the highest value of 29.3% in Mine F (Crushing) and the lowest value of 2.1% in Mine B (Pelletizing). The predicted historical RD and RS arithmetic mean exposures ranged between <0.075 and 3.14 mg m^{-3}, and between <0.005 and 0.36 mg m^{-3}, respectively. The result of this study is a JEM by mine, department, and year for RD and RS for epidemiological studies.

What's Important About This Paper?

Taconite mining in Minnesota generated exposures to hazardous dusts, including respirable dust containing silica and iron, among other hazards. This study is important because it reconstructed workers' historical respirable silica and respirable dust exposures, and developed a job-exposure matrix using an innovative two-level random-intercept regression model. The job-exposure matrix will be used for further epidemiological studies among this worker population.

Keywords: job-exposure matrix (JEM); respirable dust; respirable silica; retrospective exposure reconstruction; taconite mining

Introduction

Taconite mining in northeastern Minnesota began in the 1950s along the Mesabi Iron Range after the depletion of hematite reserves (Berndt and Brice, 2008). Taconite is an iron-bearing and silica-rich rock with an iron content of 15–30% and a silica content of 45–50%. The mining and processing of the taconite ores includes four main steps—mining, crushing, concentrating, and pelletizing—that increase the iron content to as high as 65% in the final product (Hubbell *et al.*, 2001; US EPA, 2012). This process, however, generates significant amounts of hazardous dusts that are released into the air and can result in worker exposure to mixtures of respirable dust (RD) containing iron, silica, and other materials. The Taconite Workers Health Study (TWHS) is by far the most comprehensive occupational epidemiological investigation into the causes of excess mesothelioma, lung cancer, and nonmalignant respiratory disease among taconite workers in Minnesota (University of Minnesota, 2014). A number of studies relating to exposure assessment and health studies within the TWHS have been published in the past decade (Hwang *et al.*, 2014, 2017; Allen *et al.*, 2015a,b; Lambert *et al.*, 2016; Perlman *et al.*, 2018; Odo *et al.*, 2020). But these studies have mainly focused on the exposures to elongate mineral particles and the epidemiological association between this exposure and respiratory diseases like lung cancer and mesothelioma. The levels of historical exposure to the taconite dusts have never been quantitatively evaluated in the past. The main goal of this paper is to describe the reconstruction of the historical exposures of workers and the creation of the job-exposure matrix (JEM) in the taconite industry in Minnesota for respirable silica (RS) and RD using available occupational hygiene (OH) measurements.

Two approaches have been described in the literature for developing JEMs for multiple components of a mixture. The first approach (Gao *et al.*, 2000; Zhuang *et al.*, 2001; Tu *et al.*, 2005; Føreland *et al.*, 2012; Leal *et al.*, 2012) is to construct the JEM for a particular component of the mixture independent of other components. In this instance, this would imply that the RS JEM would be constructed using only RS monitoring data, and the RD JEM would use only RD monitoring data. This method is less likely to lead to multiple-collinearity issues in epidemiologic studies, since the prediction of one component does not rely on information relating to the other components. However, this approach, since it treats each agent separately, could result in JEMs of varying quality due to differences in data quality for the components. Additionally, the two JEMs may not necessarily be consistent with each other. For example, in some extreme cases, a predicted RS concentration could be higher than its corresponding RD concentration due to poor data quality. To prevent these drawbacks, another approach has been used (Zhuang *et al.*, 2001; Føreland *et al.*, 2012) that first develops a 'parent' JEM for one contaminant, typically the one with the best data quality. Conversion factors are derived between other contaminants to the parent contaminant usually based on side-by-side measurements, and these factors are then applied to the parent JEM to develop 'child' JEMs. The drawback of this strategy, however, is that these JEMs could potentially be highly correlated.

To improve upon these two strategies, a new approach is proposed here for reconstructing RS and RD exposures. This new approach uses a random-intercept regression model to incorporate both RS and RD data during the reconstruction process. In this new approach, annual exposure change rates are predicted using both RS and RD data, increasing the information and size of samples available to use for each prediction model and ensuring the consistency of prediction results between different job-exposure metrices.

At the same time, average percent silica in airborne dust is estimated from each model, yielding additional information that will allow us to understand the impact of taconite processing procedures on the silica content in airborne mining dusts in Minnesota taconite industry.

Methods

Background

The TWHS study comprised seven taconite mines within two geological zones (the eastern zone and the western zone) on the Mesabi Iron Range in Minnesota. For confidentiality purposes, all mine names were replaced with a name code that is consistent with previous study publications (Hwang *et al.*, 2013, 2014, 2017; Shao *et al.*, 2019, 2020). Mines A and G are located in the eastern zone, and Mines B–F are located in the western zone (Table 1). The oldest mine started operating in 1955 and the newest mine in 1977 (Sheehy, 1986). Mine G was closed in 2001. Six out of these seven mines were still in operation in 2010 when a comprehensive exposure monitoring study was conducted (Hwang *et al.*, 2013, 2014, 2017). The mining processes for all the mines were similar, but workers with different tasks were considered to experience different exposures. Hwang *et al.* (2013) grouped all taconite workers into job titles within eight exposure departments: Mining, Crushing, Concentrating, Pelletizing, Shop (mobile), Shop (stationary), Janitor, and Office/control room for each mine. We grouped workers by department and mine; thus there were 56 different mine–department combinations in our study.

Historical RS and RD data were obtained for seven taconite mines from two sources: (i) the Mine Safety and Health Administration (MSHA) has online records for all inspection results since 1978 for study-associated mines with 4303 RD monitoring records with their occupational exposure limits (OELs) (enabling calculation of RS concentrations, see equation (1)); (ii) the mining companies' internal monitoring reports contain 14 417 RD records, each of which has concentration and corresponding OEL information. Specific sampling and analytical methods for the above measurements were not found in the records but were believed to be standard MSHA air sampling and gravimetric dust analysis methods. For each data record, we collected the following information: concentration, sampling year, sampling agent, personal/area sample, and mine/department. As we can see in Table 1, there were no personal samples available in the early operational years of the taconite mines. Sample durations were also missing from these historical records.

To supplement existing historical measurements and better understand mines' current exposure levels, in 2010 the TWHS collected 688 additional 6-h long personal dust sample measurements covering six active mines (Hwang *et al.*, 2017). All dust samples were analyzed by a NIOSH-accredited lab. For each sample, the RD concentration was determined by the NIOSH 0600 (NIOSH, 1998) gravimetric method, and the silica content in the dust collected by that sample was determined by the NIOSH 7500 X-ray diffraction (XRD) method (NIOSH, 2003).

Since 1970s when the XRD method became available, MSHA has been measuring the silica content of

Table 1. Profile of taconite mines and the number of personal and area RD and RS measurements by decade.

#	Taconite mine	Year opened	Status (as of 2010)	OH measurement coverage
1	A	1955	Active	1956–2010
2	B	1974	Active	1976–2010
3	C	1964	Active	1978–2010
4	D	1967	Active	1971–2010
5	E	1967	Active	1979–2010
6	F	1977	Active	1978–2010
7	G	1957	Closed in 2001	1978–2000

RD	1956–1959	1960s	1970s	1980s	1990s	2000–2010[a]
Personal samples	0	0	1926	3850	2356	4244[a]
Area samples	867	1882	2714	1037	295	209

RS	1956–1959	1960s	1970s	1980s	1990s	2000–2010
Personal samples	0	0	1451	3031	1272	1464[a]
Area samples	0	0	480	1035	268	126

[a] Including the 688 pair of personal RS and RD measurements taken by our team in 2010.

dust samples. But instead of reporting this silica content directly, MSHA embeds this information in their OEL calculation equations (MSHA, 1989). The specific equations are listed in equations (1) and (2).

$$\text{The specific OEL value for a RD sample} = \frac{10}{2 + \%\ \text{silica}}\left(\frac{\text{mg}}{\text{m}^3}\right) \tag{1}$$

$$\text{The specific OEL value for a RD sample} = \frac{250}{5 + \%\,\text{silica}}(\text{mppcf}) \tag{2}$$

Because of this formulation, if a historical RD sample had its OEL information reported, we could use equation (1) or (2) to back-calculate the % silica in the sample and then use equation (3) to calculate RS concentration values from the original RD values. In other words, we can back-calculate the RS value only when a sample has an OEL value. In this manner, an additional 8840 RS exposure values were calculated.

$$\text{RS concentration}\left(\frac{\text{mg}}{\text{m}^3}\text{ or mppcf}\right) = \text{RD concentration}\left(\frac{\text{mg}}{\text{m}^3}\text{ or mppcf}\right) \times \%\ \text{silica}/100 \tag{3}$$

The data cleaning process included reviewing original OH reports, checking each measurement's concentration value, sampling date and location information, unit conversion, and zero value replacement. The data cleaning was performed using SAS statistical software (version 9.3, SAS Institute, Cary, NC, USA). A total of 76 RD records and 56 RS records were removed using this process because they lacked specific sampling locations.

Before 1975, measurements were in the now-defunct count metric of millions of particles per cubic foot (mppcf). They constitute about 20% of all measurements in our database. We converted them to mass concentrations using the OSHA-recommended conversion factor of 1 mppcf = 0.1 mg m^{-3} (Occupational Safety and Health Administration, 2017). Since the analytical laboratory limits of detection (LOD) information for historical data are not recorded, censored values and zero values (2264 RD records and 954 RS records) were imputed using the beta-substitution approach (Ganser and Hewett, 2010). The β_{GM} and LOD values used in this substitution are 0.555 and 0.005 mg m^{-3} for the RS data, and 0.580 and 0.075 mg m^{-3} for the RD data (NIOSH, 1998, 2003). After the data cleaning procedures, a total of 9127 RS data and 19 391 RD data were available for subsequent modeling. Each data record is associated with six variables (concentration, year, personal sample or area sample, RD or RS, department, and mine).

Statistical model

The reconstruction strategy used here for reconstructing RS and RD exposures uses both RS and RD data, without assuming that they are independent of each other within a mine/department combination. Rather, they retain some similar characteristics resulting from their common sampling location. For example, they may share the same time trend (slope with respect to time) due to the same dust-control practices being implemented in a given mine/department. We defined a categorical dummy variable—**Group** and assumed this variable has two levels—RS and RD, then constructed a regression-based model to analyze the similarities at the individual datum level as well as the differences between the two agents.

A varying-intercept model (equation (4)), a simple type of the multilevel modeling family, was used in the study. This model assumes that within each mine–department combination, the predicted ln(RS) and ln(RD) mean lines with Year (variation on RS and RD with Year) share the same slope, but with a varying intercept determined by the grouping variable **Group**. In other words, multilevel modeling can be thought of as a regression that includes a categorical input variable representing group membership (Gelman and Hill, 2007).

$$\begin{Bmatrix} \text{Level} \quad 1: \ \text{Ln}\left(\overline{\textbf{Conc}}|\textbf{Mine, Dept}\right) = \beta_{00} + \beta_{10}\textbf{Year} + \beta_{20}\textbf{Type} \\ \text{Level} \quad 2: \ \beta_{00} = \gamma_{00} + \gamma_{01}\textbf{Group} \end{Bmatrix}_{ij} \tag{4}$$

where $\overline{\textbf{Conc}}|\textbf{Mine, Dept}$ is the predicted mean exposure value in mg m^{-3} for a given mine–department combination (mine *i* and department *j*), **Year** is the sampling year, **Type** is the sample type (0 = personal sample, 1 = area sample), and **Group** is the targeted agent (0 = RD, 1 for RS). The default value for variable **Type** is 0, meaning that the final model outputs will be focused on personal samples. From this model, RD and RS will have different intercepts ($\beta_{00} = \gamma_{00}$for RD curves and $\beta_{00} = \gamma_{00} + \gamma_{01}$ for RS curves) but the same slope.

One benefit of this model (equation (4)) is its parameters have physical meanings. Within each mine–department, its annual exposure change rate and the predicted silica percent in the dust can be calculated using equations (5) and (6), respectively.

For a given mine–department:

$$\text{Annual exposure change rate}: \left\{\frac{\overline{\textbf{Conc}}|(\textbf{Year} = n+1)}{\overline{\textbf{Conc}}|(\textbf{Year} = n)} = e^{\beta_{10}}\right\}_{ij} \tag{5}$$

The regression coefficient *P* values were used to decide whether the predicted trends were significantly different from zero (no change over time).

$$\text{Silica percent in the dust}: \left\{\frac{\overline{\textbf{Conc}}|(\textbf{Group} = 1)}{\overline{\textbf{Conc}}|(\textbf{Group} = 0)} = e^{\gamma_{01}}\right\}_{ij} \tag{6}$$

Since Mine G had very few measurements, we used Mine A data for exposure reconstruction in Mine G due to the similarity in their mineralogical characteristics (McSwiggen and Morey, 2008). In addition to the data from each of the eight departments within each of the seven mines, we created an 'all 7 mines' column and an 'all 8 departments' row for potential reconstruction needs (see Table 2). We aggregated data across all departments within a mine (data in the 'all 8 departments' row) for the 'Janitor' exposure reconstruction due to the data sparseness in this department. 'Office/control room' departments relied on aggregating data across all departments within a mine to estimate the time-trend slope, and their intercepts were determined by their Year-2010 measurements to provide estimates of exposure magnitudes.

The model was implemented using the MATLAB 'fitlm' function (MATLAB version R2014b, the MathWorks, Inc., Natick, MA, USA). All model outputs (GMs: geometric means and GSDs: geometric standard deviations) were used to calculate their corresponding arithmetic means (AMs) using the conversion equation shown in equation (7).

$$\mathrm{AM} = \mathrm{GM} \times \exp\left(\frac{1}{2}\ln^2(\mathrm{GSD})\right) \qquad (7)$$

The end result was two JEMs (one for RS, one for RD) that report an AM personal exposure level in mg m^{-3} for each year–department–mine combination. These JEMs, when linked to the working history of individual taconite workers, will allow us to calculate the cumulative exposure for the study population in relevant epidemiologic studies.

Results

There are a total of 9127 RS data and 19 391 RD data across all mines and departments as summarized in Table 2. The distribution of the samples, to some extent, reflects overall OH sampling priorities in the taconite industry. Most of OH samples were collected in the four main taconite processes—mining, crushing, concentrating, and pelletizing, while not many historical data are available for the Office/control room departments in the seven mines. Additionally, Mine G has no Year-2010 measurements since it shut down in 2001.

Model outputs

Historical occupational dust levels were reconstructed for each of the 56 mine–department combinations by our regression model with industrial hygiene measurements. While only a few output plots are shown in Fig. 1a (Mine F) and Fig. 1b (Mine B) as example results of the exposure reconstruction, plots for all other locations can be found in Supplementary Fig. S1 (available at *Annals of Work Exposures and Health* online).

Table 2. Numbers of RD and RS measurements in each mine–department combination.

Mine–department	A	B	C	D	E	F	G	All 7 mines
RD								
Mining	643	651	417	294	409	203	145	2762
Crushing	2602	3139	274	165	458	178	101	6917
Concentrating	393	2474	46	425	309	68	31	3746
Pelletizing	1838	1289	191	388	300	176	111	4293
Shop (mobile)	179	205	110	67	240	50	45	896
Shop (stationary)	112	24	84	28	37	48	29	362
Office/control room	16	6	6	6	15	10	0	59
Janitor	43	101	64	48	55	20	25	356
All 8 departments	5826	7889	1192	1421	1823	753	487	19 391
RS								
Mining	104	483	228	242	165	77	65	1364
Crushing	229	2001	197	96	413	125	65	3126
Concentrating	39	856	38	230	237	52	26	1478
Pelletizing	233	1114	137	236	144	114	46	2024
Shop (mobile)	63	148	82	59	173	38	18	581
Shop (stationary)	39	17	67	27	31	24	16	221
Office/control room	15	6	6	6	12	10	0	55
Janitor	33	78	47	42	41	20	17	278
All 8 departments	755	4703	802	938	1216	460	253	9127

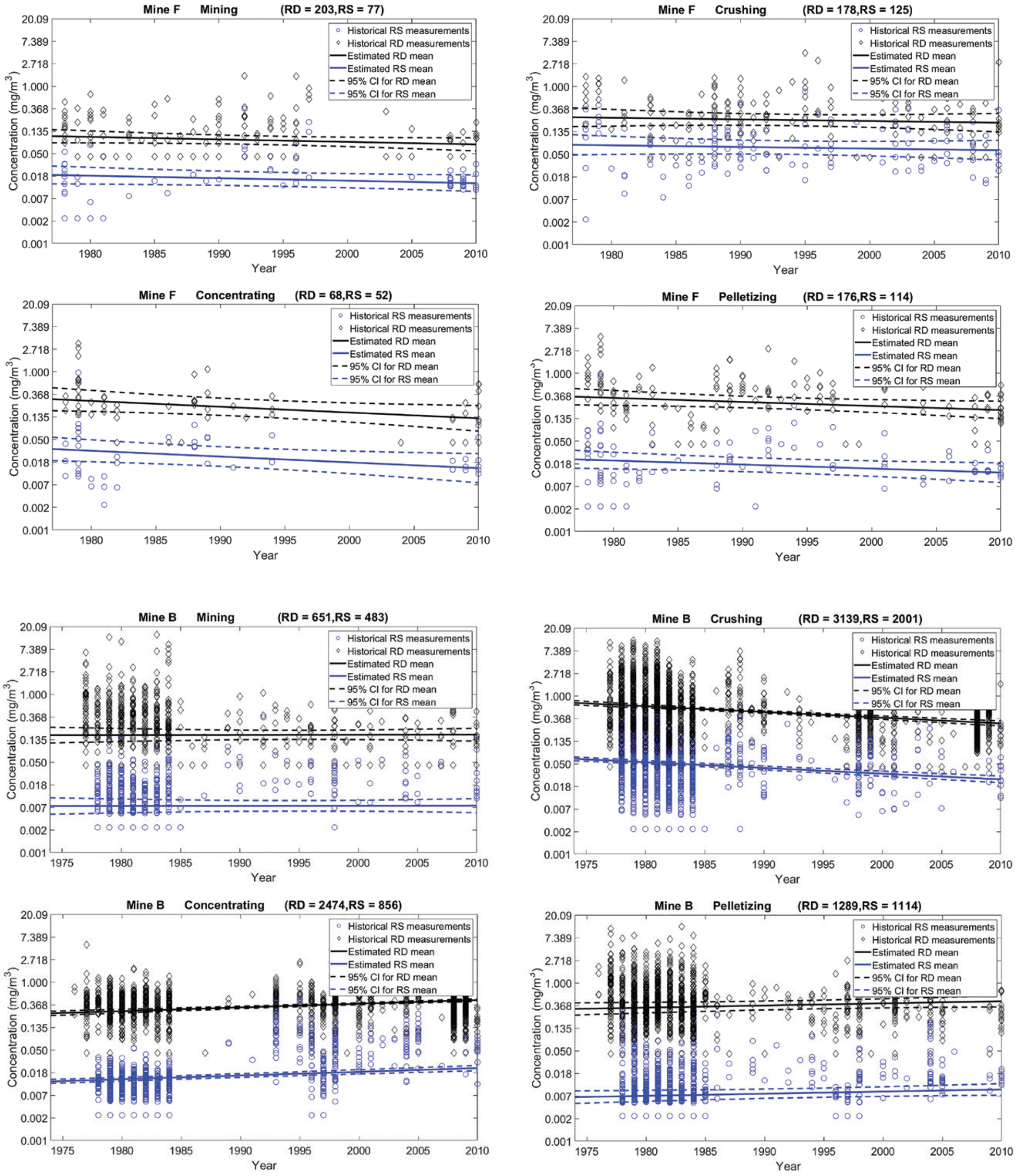

Figure 1. (a) Model outputs for several departments of Mine F (Year 1977–2010). (b) Model outputs for several departments of Mine B (Year 1974–2010).

Generally speaking, the varying-intercept model is reasonably consistent with the historical data over the reconstruction time periods (adjusted model R^2 values vary by mine–department combination with the overall range of 0.24–1.00 and a median value of 0.56). The reconstruction time period for each mine covers the entire tenure of this mine. Under the natural log scale (y-axis), the RD prediction line parallels its paired RS line but with a different intercept, and the slope of these lines was determined by RS and RD data taken together. The underlining assumption here is that the silica percentage in the taconite ore and in the airborne taconite dust in

Table 3. Mine/department-specific average annual rate of change in exposure levels.

Mine–department		A	B	C	D	E	F	G	All 7 mines
Mining	Mean	0.4%	–0.1%	1.0%	–1.8%	–0.6%	–1.1%	0.4%	–0.4%
	P value	0.25	0.78	<0.05	<0.05	0.25	<0.05	<0.05	<0.05
Crushing	Mean	–0.1%	–2.5%	2.2%	–3.3%	2.3%	–0.8%	–0.1%	–0.7%
	P value	0.67	<0.05	<0.05	<0.05	<0.05	0.20	<0.05	<0.05
Concentrating	Mean	3.2%	1.6%	0.0%	–2.9%	2.2%	–2.7%	3.2%	2.0%
	P value	<0.05	<0.05	0.99	<0.05	<0.05	<0.05	<0.05	<0.05
Pelletizing	Mean	2.3%	0.9%	0.1%	–1.5%	–0.3%	–2.0%	2.3%	0.2%
	P value	<0.05	<0.05	0.80	<0.05	<0.05	<0.05	<0.05	0.07
Shop (mobile)	Mean	–0.4%	–2.1%	–1.4%	–0.3%	–2.5%	–3.0%	–0.4%	–1.0%
	P value	0.53	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Shop (stationary)	Mean	1.5%	1.1%	–2.6%	1.2%	0.3%	0.2%	1.5%	–0.2%
	P value	<0.05	0.36	<0.05	<0.05	0.67	0.78	<0.05	0.55
Office/control room	Mean	0.7%	–1.0%	0.8%	–2.0%	0.5%	–1.8%	0.7%	–0.2%
	P value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Janitor	Mean	0.7%	–1.0%	0.8%	–2.0%	0.5%	–1.8%	0.7%	–0.2%
	P value	<0.05	<0.05	0.07	0.86	0.64	0.52	<0.05	<0.05
All 8 departments	Mean	0.7%	–1.0%	0.8%	–2.0%	0.5%	–1.8%	0.7%	–0.2%
	P value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

P value indicates whether the rate is significantly different from 0% (no annual change).

Table 4. Summary of model estimated median silica content in the airborne dust collected in each mine–department combination.

Mine–department	A	B	C	D	E	F	All 7 mines	G
Mining	15.0%	4.4%	11.3%	12.7%	15.6%	17.7%	9.7%	Same as Mine A
Crushing	17.6%	8.4%	15.7%	19.2%	23.1%	29.3%	13.0%	
Concentrating	7.5%	5.0%	8.3%	14.4%	16.5%	11.3%	7.5%	
Pelletizing	2.6%	2.1%	5.4%	8.7%	5.9%	6.5%	3.3%	
Shop (mobile)	12.6%	11.1%	10.5%	11.6%	14.0%	12.6%	12.0%	
Shop (stationary)	9.5%	12.1%	11.5%	7.1%	7.1%	14.3%	10.3%	
Office/control room	9.7%	10.0%	10.0%	10.0%	11.7%	10.9%	10.4%	
Janitor	Same as 'All 8 departments'							
All 8 departments	8.8%	5.5%	10.7%	11.5%	16.2%	16.0%	8.2%	

each mine/department does not change over time. The assumption appears to be reasonable, given the consistency between the model and the data as well as our understanding of taconite mining process.

Several mines had no measurement records in their first 10 or more years (Table 1). For the years without any measurement data, their dust levels were back-calculated in time using the regression model outputs. Mine G has the greatest data gap: we do not have any exposure information for its early years (1957–1977), and we did not have an opportunity to conduct Year-2010 measurements for this mine because it was shut down in 2001. To model the historical exposure for this mine, we chose to use Mine A's data given their mineralogical proximity. The predicted exposure levels for Mine G, which were predicted using Mine A's data, align well visually with Mine G's original measurements (as shown in Supplementary Fig. S1, available at *Annals of Work Exposures and Health* online).

Predicted average annual rate of change in exposure levels by mine/department

Table 3 lists the averaged time trends in the RS and RD exposure for all mine–departments. The *P* values are also listed in the table to help determine whether our results are statistically different from 0, i.e. there is a flat trend over time. The predicted annual change rates vary by mine/department, but within a narrow range of –3.3

to 3.2%. Among the 56 mine–departments, 33 combinations show a decreasing or flat RS and RD trend with a maximum rate of decrease of 3.3% per year; 23 mine/department combinations show a trend with a maximum annual increase rate of 3.2%. We however did not find any consistent patterns in these trends. For Mine F, exposures showed decreasing trends in seven of eight its departments whereas Mine A only had two departments where exposures decreased over time. As for departmental trends across mines, we did not find any pattern in the four main departments. But it is notable that the slopes in all eight Shop (mobile) departments were negative. For the overall time trend in each mine (Table 3, last row), three mines shown an uptrend and four mines shown a downtrend. The overall time-trend slope in this study was −0.2%, which suggested that the overall historical dust exposure in the entire taconite industry decreased at a very low rate. All 56 slopes results, whether statistically significant or not, were used for in the exposure reconstruction.

Predicted median silica percentages in different exposure mine/departments

Table 4 lists the predicted median silica content in dust collected in every mine–department combination. These values show high variability across all mines as well as departments within each mine. The overall range of the silica content is from 2.1% in Mine B—Pelletizing to 29.3% in Mine F—Crushing. Mine B has the lowest silica content in all four main departments across all 7 mines (4.4% in Mining, 8.4% in Crushing, 5.0% in Concentrating, and 2.1% in Pelletizing). In contrast, the silica content in Mines E and F are much higher (17.7% in Mine F—Mining, 29.3% in Mine F—Crushing, 16.5% in Mine E—Concentrating). In every mine, we can see that the percent silica changes as the ore moves from mining to crushing to concentrating to the final pelletizing; and these changes follow a similar pattern for all mines: within each mine, the silica percentage increases from mining to crushing, decreases from crushing to concentrating; and falls further to its lowest level from concentrating to pelletizing. For instance, we see the 15.0, 17.6, 7.5, and 2.6% data series in Mine A, or the 11.3, 15.7, 8.3, and 5.4% in Mine C.

Predicted AM of RS and RD exposure by mine/department

As suggested by other researchers (Rice *et al.*, 1984; Seixas *et al.*, 1988; Rappaport, 1991; Berman and Crump, 2008; Verma *et al.*, 2011), the AM is an appropriate exposure metric while creating a JEM for health studies. The range of AM results of the study is listed in Table 5. The GSDs used for this AM calculation are listed in Supplementary Table S2 (available at *Annals of Work Exposures and Health* online).

Historical RD mean exposures ranged between <0.075 and 3.14 mg m^{-3}. This range reflects exposure variations across mines/departments, but also indicates that the historical mean dust exposures in the taconite mining were sometimes higher than the current MSHA 8-h Time Weight Averaged (TWA) concentration limit for the overall RD of 1.5 mg m^{-3}. In ‘All 7 mines’ column, the predicted highest RD value is located in Crushing and the lowest value appears in Office/control room, in accordance with expectations. Within each individual mine, we generally found a similar distribution across departments.

The AMs for historical RS exposures ranged between <0.005 and 0.36 mg m^{-3}. The upper bound of this range has exceeded the current MSHA 8-h TWA concentration limit for the silica of 0.1 mg m^{-3}. This range also reflected exposure variations across mine/department combinations. In ‘All 7 mines’ column, the distribution across departments found for RD is also true for RS. Crushing is the dustiest working space whereas Office/control room is the cleanest space.

Discussion

This paper describes how a retrospective exposure reconstruction was conducted for RS and RD using 9127 RS and 19 391 RD OH monitoring measurements. This is the first time that the historical occupational dust levels were reconstructed for every mine–department combination in the Minnesota taconite mining industry. In this study, we developed a linear regression-based model to overcome the data sparseness issues in our data. The model outputs not only include dust concentrations for each calendar year throughout the entire taconite mining history as offered by traditional exposure reconstruction, but also predictions of the annual rate of change and the silica content. This new information advances our understanding of this industry and the exposure level changes in its history.

The regression models used produce yearly GM and GSD values for each mine–department group. Within each mine/department, changes in yearly RS and RD GMs with time have the same slope. But the slopes of different mines/departments would be different. Therefore, the GMs of RS and RD over all groups would not be correlated. Yearly AM values, which were actually used in the cumulative exposure calculation, were calculated based on these GMs and GSDs. Additionally, the cumulative RS and RD exposure metrics that will be

Table 5. The JEM summary table [first-year and last-year AMs of RD and RS exposure levels in each mine/department (mg m^{-3})].

Mine–department	A		B		C		D		E		F		G[a]		All 7 mines	
Year	1955	2010	1974	2010	1964	2010	1967	2010	1967	2010	1977	2010	1957	2001	1955	2010
RD																
Mining	0.36	0.45	0.62	0.59	0.35	0.57	0.55	0.26	0.36	0.28	0.28	0.20	0.36	0.43	0.56	0.45
Crushing	0.50	0.48	3.14	1.25	0.84	2.27	1.70	0.42	0.36	0.93	1.12	0.86	0.50	0.48	2.03	1.44
Concentrating	0.12	0.64	0.46	0.83	0.67	0.60	2.00	0.59	0.36	0.89	1.08	0.44	0.12	0.48	0.41	1.20
Pelletizing	0.57	1.99	1.20	1.65	0.75	0.78	1.32	0.70	0.71	0.61	1.52	0.80	0.60	1.61	1.19	1.35
Shop (mobile)	0.81	0.56	1.44	0.67	0.93	0.48	0.49	0.42	2.03	0.66	0.95	0.32	0.80	0.58	1.16	0.66
Shop (stationary)	0.17	0.36	0.38	0.49	0.80	0.24	0.17	0.28	0.30	0.32	0.31	0.34	0.17	0.31	0.41	0.37
Office/control room	0.15	0.14	0.12	0.12	0.12	0.11	0.12	0.11	0.03	0.15	0.11	0.12	0.15	0.15	0.00	0.13
Janitor	0.52	0.77	2.46	1.72	0.72	1.03	1.25	0.52	0.62	0.75	1.17	0.64	0.53	0.72	1.53	1.36
All 8 departments	0.52	0.77	2.46	1.72	0.72	1.03	1.25	0.52	0.62	0.75	1.17	0.64	0.53	0.72	1.53	1.36
RS																
Mining	0.05	0.07	0.03	0.03	0.04	0.06	0.07	0.03	0.06	0.04	0.05	0.04	0.06	0.06	0.05	0.04
Crushing	0.09	0.08	0.26	0.11	0.13	0.36	0.33	0.08	0.08	0.22	0.33	0.25	0.09	0.08	0.27	0.19
Concentrating	0.01	0.05	0.02	0.04	0.06	0.05	0.29	0.08	0.06	0.15	0.12	0.05	0.01	0.04	0.03	0.09
Pelletizing	0.01	0.05	0.03	0.03	0.04	0.04	0.12	0.06	0.04	0.04	0.10	0.05	0.02	0.04	0.04	0.04
Shop (mobile)	0.10	0.07	0.16	0.07	0.10	0.05	0.06	0.05	0.29	0.09	0.12	0.04	0.10	0.07	0.14	0.08
Shop (stationary)	0.02	0.03	0.05	0.06	0.09	0.03	0.01	0.02	0.02	0.02	0.05	0.05	0.02	0.03	0.04	0.04
Office/control room	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.01	0.00	0.01
Janitor	0.05	0.07	0.13	0.09	0.08	0.11	0.14	0.06	0.10	0.12	0.19	0.10	0.05	0.06	0.13	0.11
All 8 departments	0.05	0.07	0.13	0.09	0.08	0.11	0.14	0.06	0.10	0.12	0.19	0.10	0.05	0.06	0.13	0.11

[a] Mines A and G have different reconstruction periods, which results in the difference in the ranges of their historical exposure results.

used in the epidemiological analysis would be even less correlated due to different times spent in different locations and mines by different workers and lengths of employment. Thus, multiple data conversions are been done from the model outputs (yearly GM values) to cumulative exposure values used in the epidemiological models.

Exposure reconstructions in many industries have typically shown downward trends over time that have been attributed to increased and better exposure controls as well as more stringent occupational regulations over time (Symanski *et al.*, 1998b; Chen *et al.*, 2001; Coble *et al.*, 2001; Creely *et al.*, 2007). Our findings, however, are mixed. The predicted annual change rates vary by mine/department, but within a narrow range of −3.3 to 3.2%. Mathematically, this result means if the annual change rate is constant at 3 or −3%, a mine's first-year dust exposure value is at most four times higher ($1.03^{50} = 4.4$) to one fifth ($0.97^{50} = 0.22$) of its final-year's value over a 50-year period. These results are consistent with our knowledge and expectations for this industry where dust levels have not changed much over time.

Table 4 results suggest that taconite mining and processing procedures can affect the silica content in airborne dusts. When the ore is mined from open pits, silica is released into the air. During the crushing process, the ore is crushed to small pieces, and more silica inside the raw ore can become airborne; during the concentrating process, airborne dust and silica levels are reduced due to the wet process that removes the slag containing much of the non-iron silica material. The reduction in silica percent becomes more apparent in the final pelletizing process where limestone powders are added to the taconite ore (the reported silica content in taconite pellets varied from 4.0 to 5.3% (Hubbell *et al.*, 2001). The measured silica percentage values from all historical dust samples taken in each study mine/department are summarized in Supplementary Table S1 (available at *Annals of Work Exposures and Health* online). To check whether the predicted values listed in Table 4 are comparable with their corresponding actual measurements in the four main process departments, we created a predicted versus measured plot shown in Supplementary Fig. S2 (available at *Annals of Work Exposures and Health* online). There are 28 data points on the plot, each representing a mine–department combination in the study. A slope of 1 would be expected if for each data point, if its predicted RS/RD value (x-axis) matched its measured RS/RD value (y-axis). The actual slope of 0.92 (95% confidence interval: 0.65–1.12) and R^2 of 0.64 suggests a good one-on-one correspondence.

Mine G had much fewer historical data (only 740 measurements for RS and RD combined) compared with the other mines and no measurements available for the first 21 years of its history. To overcome this problem, we decided to use the Mine A data for exposure reconstruction in Mine G. The assumption underlying this decision was that the mining and processing procedures for all study mines are similar and both Mines A and G are located in the eastern zone of the Mesabi Iron Range in Minnesota, and ores from these two mines have similar mineral composition. In Supplementary Table S1 (available at *Annals of Work Exposures and Health* online), although the average percent silica in Mine G is approximately half of the average percent silica in Mine A for the mining and crushing departments, we also notice that there is large variability around these means (i.e. mean = 24% and SD = 32% for Mine A—mining). Despite this limitation, this approach performs well, as the predicted exposure levels for Mine G match well with Mine G's original measurement data (as shown in Supplementary Fig. S1, available at *Annals of Work Exposures and Health* online).

In this study, we assumed that silica percent in taconite ore varied from mine to mine, but within each mine, the silica percent was constant over time. We unfortunately did not have enough data to prove this assumption. But under this assumption, our predicted silica % values were very close to actual measured values listed in Supplementary Table S1 (available at *Annals of Work Exposures and Health* online).

Retrospective exposure reconstruction can be challenging because it usually has to rely on sparse historical OH measurements (Symanski *et al.*, 1998a). In our study, the data sparseness issue has two dimensions:

(1) Unbalanced data coverage across calendar years. As we see in Table 1, there were few personal samples available in the early operational years of the taconite mines. For example, Mine G started its operation in 1957, but it did not have any dust level record until 1978.
(2) Unbalanced data coverage across job titles. In our study, 93% of historical RD data and 90% of historical RS data were obtained in four main departments: 'Mining', 'Crushing', 'Concentrating', and 'Pelletizing'. As a result, measurements for the other four departments were very limited: only five historical measurements were available for the entire 'Office/control room' departments across all 7 mines.

Because of this data sparseness issue, we chose to aggregate our OH data at the mine–department level to increase the sample size and year coverage of each mine–department combination. This aggregation, however, prevents us from identifying any differences in exposure trends across different similar exposure groups (SEGs) within the same department. To assess the potential impact of this data aggregation on exposure misclassification, we revisited the measurements data collected in 2010, and calculated the between-department (BG), within-department (WG), and within-worker (WW) variance components of the log-transformed exposure concentrations using a two-way nested random-effects analysis of variance model (Hwang *et al*., 2017). The results from this analysis are listed in Supplementary Table S3 (available at *Annals of Work Exposures and Health* online). A comparison of this table with Table 4 in Hwang *et al.* (2017) shows that the between-group, within-group, and WW variabilities do not change appreciably. For example, for Mine A, the between SEG, within SEG, and WW variance components were 45.6, 3.7, and 50.7% in Hwang *et al.* (2017). In Supplementary Table S3 (available at *Annals of Work Exposures and Health* online), the between-department, within-department, and WW variance components are 46.1, 5.6, and 48.3%.

Random sampling versus worst-case sampling are two common sampling strategies used in OH practice. OH measurements used in this study came from multiple sources, and because of this, it is possible that the measurement data were also obtained from different sampling strategies. All Year-2010 samples were from random sampling. For the historical samples, there is no information to indicate whether they were worst-scenario sampling or random sampling. While MSHA inspections could have focused on worst-case scenarios, we have assumed that the samples from MSHA inspections were from random sampling. This assumption could result in underestimation of variability as well as mean estimated exposures.

Limitations

In this exposure reconstruction, we made several assumptions, i.e. the annual rate of change of exposure level is constant over time in each mine–department combination, there are no repeated measurements, and area monitoring results were as useful as health-based personal monitoring results. While these assumptions made predictions possible with limited monitoring results, they may also bring some level of bias in the predictions. For example, if there had been repeated measurements of all or most workers in the cohort at each time point, this would have enabled the estimation of within- and between-worker variability, and the estimation of potential bias in the epidemiological analysis. Given that this was an occupational study where worker exposures were determined by the exposure group to which they belonged, the dominant type of expected error would be Berkson error (Heederik and Attfield, 2000; Zeger *et al*, 2000). This would not lead to bias in the dose–response relationship although it may lead error using bootstrapping methods such as those used by Levin *et al.* (2000).

The OH measurement data used in the study came from three different sources: The median RD levels (in mg m^{-3}) of the OH data from different sources are 0.23 for MSHA, 0.13 for Hwang *et al.* (2013) and 0.34 for the companies. The year coverage for each data source is also different: 1978–2010 for MSHA, 2010 for Hwang *et al*., and 1956–2009 for the companies' internal data. Thus, it is difficult to compare the median values for these three sources directly as the sampling year is a confounder in this comparison. Measurements collected in recent years, in general, were lower than historical measurements included in other two data sources.

In our study, about 10% of the overall measurements were below their LOD values. Censored values and zero values were imputed using the beta-substitution. We understand that analytical methods may have changed over the past 50 years, along with the LOD values of these methods. But no information was available regarding the LOD of the sampling/analytic methods used for most of the historical OH measurements.

Conclusions

The study uses a multiple linear regression approach to exposure modeling that avoids problems of collinearity as well as unrealistic estimates by jointly modeling both RS and RD exposures. Data from both personal and area measurements and count as well as mass concentration measurements are used in a unified framework. This approach is powerful as it allows us to predict not only how the RD and RS exposure change over time for each mine–department, but also how the percent silica changes from department to department. The predicted annual change rates vary by mine/department, but within a narrow range of −3.3 to 3.2%. The predicted historical RD and RS AM exposures ranged between <0.075 and 3.14 mg m^{-3}, and between <0.005 and 0.36 mg m^{-3}, respectively. The findings reported in this paper are consistent with previous exposure assessments for present-day levels (Hwang *et al*., 2013, 2017). The result of this study is a JEM by mine, department, and year for RD and RS that forms the basis for several future epidemiological studies.

Supplementary Data

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

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Conflict of interest

The authors declare that there are no conflicts of interest relating to the material in relation to this article.

Data availability

The data underlying this article will be shared on reasonable request consistent with protections for the privacy of study participants and existing multiparty agreements.

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