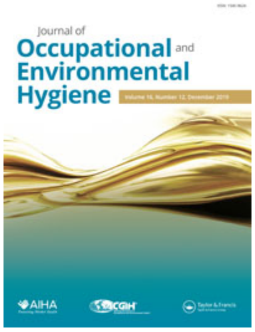

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20

Reconstructing historical exposures to elongate mineral particles (EMPs) in the taconite mining industry for 1955–2010

Yuan Shao, Jooyeon Hwang, Bruce H. Alexander, Jeffrey H. Mandel, Richard F. MacLehose & Gurumurthy Ramachandran

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2019, VOL. 16, NO. 12, 817–826
https://doi.org/10.1080/15459624.2019.1676431

Reconstructing historical exposures to elongate mineral particles (EMPs) in the taconite mining industry for 1955–2010

Yuan Shao[a], Jooyeon Hwang[b], Bruce H. Alexander[a], Jeffrey H. Mandel[a], Richard F. MacLehose[c], and Gurumurthy Ramachandran[d]

[a]Division of Environmental Health Sciences, University of Minnesota, Minneapolis, Minnesota, USA; [b]Department of Occupational and Environmental Health, Hudson College of Public Health, University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma, USA; [c]Division of Epidemiology & Community Health, University of Minnesota, Minneapolis, Minnesota, USA; [d]Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, Maryland, USA

ABSTRACT

As part of ongoing epidemiological studies for assessing the association between exposure to dust from taconite operations and the development of respiratory diseases, the goal of this study was to reconstruct the exposures of workers to elongate mineral particle (EMP) in the Minnesota taconite mining industry from 1955–2010. Historical NIOSH-7400 and equivalent EMP personal exposure data were extracted from two sources: (1) the Mine Safety and Health Administration (MSHA) online database recorded for all inspection results since 1978 with 655 EMP monitoring records from 1978–2010 for 13 MSHA Mine IDs associated with this study; and (2) the mining companies' internal monitoring reports contained 96 personal EMP exposure records. NIOSH-7400 EMP personal exposures were measured for workers in different jobs in all active mines in 2010 by obtaining 1,285 personal samples. After data treatment, all data were grouped into seven mines and eight departments. Within each mine-department, the yearly EMP mean concentration in f/cc for each year of operation was predicted using two approaches. The performance of two approaches varied by situation. The assumptions underlying each approach described in this article have limitations. A linear regression based on limited historical measurements and those made in 2010–2011 (Approach 1) does not yield reasonable and plausible values of the slope. Approach 2 assumes that the EMP and the respirable dust in the same department share the same historical time trend. This approach allowed us to avail of the more reasonable slope estimates from the historical respirable dust data set and yielded more plausible historical exposure estimates for most locations. This work with two different job exposure matrix (JEMs) provides a unique research opportunity to study the potential impact of exposure assessment to epidemiological results. Both JEMs are being used to assess associations between EMP and respiratory disease in epidemiological studies.

KEYWORDS
Elongate Mineral Particles (EMP); job-exposure matrix (JEM); respirable dust; respirable silica; retrospective exposure reconstruction; taconite mining

This peer-reviewed paper was presented at the 2018 International Occupational Hygiene Association meeting.

Introduction

The Taconite Worker Health Study (TWHS), which was funded by the State of Minnesota in 2008, is the most comprehensive occupational epidemiological investigation into the causes of the excess cases of respiratory diseases (mesothelioma, lung cancer, and non-malignant respiratory disease (NMRD)) among taconite workers in Minnesota.[1] Since its inception, a number of studies under the umbrella of this investigation have been published, including occupational exposure assessments,[2–4] a respiratory health survey,[5] a cancer incidence study,[6] retrospective case-control studies,[7,8] and mortality studies.[9–11] The main goal of this article is to report on the reconstruction of the historical exposures to elongate mineral particle (EMP) from 1955–2010 for different departments in each of the taconite mines.

Since the term "fiber" has been controversial in the context of asbestos,[12] the National Institute for Occupational Safety and Health (NIOSH) has recently proposed the use of the term "elongate mineral particles" or EMP to refer to mineral particles with a minimum aspect ratio of 3:1 that are of inhalable, thoracic, or respirable size.[13] The original Occupational Safety

CONTACT Gurumurthy Ramachandran gramach5@jhu.edu Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, Maryland 21205, USA
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.
Supplemental data for this article can be accessed at tandfonline.com/uoeh. AIHA and ACGIH members may also access supplementary material at http://oeh.tandfonline.com/.

and Health Administration (OSHA) regulation defined asbestos only mineralogically without specifying the habit or asbestiform nature. The definition also specified length and aspect ratios that were derived from measurement reproducibility considerations rather than health relevance. This was the origin of the regulatory definition that a "fiber" should have a length that exceeds 5 µm and an aspect ratio (length: width) that is at least 3:1. However, in many industries including taconite mining and processing, EMPs are created during mechanical processing of the ore (e.g., crushing and fracturing of the mineral) that are referred to as cleavage fragments. These cleavage fragments could meet the regulatory definition of a "fiber" described above, even if they were not asbestiform in habit. NIOSH has explicitly included EMPs from the non-asbestiform analogs of asbestos in its recommended exposure limit (REL). Their rationale for this decision was three-fold (NIOSH, 2011): (1) the epidemiological evidence from studies where worker populations were exposed to non-asbestiform EMPs (New York talc miners and millers, Homestake gold miners, and taconite miners) was considered inconclusive due to inadequate EMP exposure characterization, not accounting for smoking status, poor reliability of death certificate information, and exposures associated with prior employment; (2) animal studies showed differential toxicity of asbestiform and non-asbestiform EMPs with lower effects of exposure to non-asbestiform EMPs and some evidence that EMP dimensions may be predictors of toxicity; and (3) current analytical methods used for routine analysis of samples, i.e., the NIOSH 7400 phase contrast microscopy (PCM) and NIOSH 7402 transmission electron microscopy (TEM) methods cannot differentiate between asbestiform and non-asbestiform EMPs when present in a heterogeneous mixture. The term "Elongate mineral particle" or "EMP" used throughout this article specifically refers to any particles that is longer than 5 µm and has a minimum aspect ratio of 3:1 on the basis of a Phase contrast microscopic (PCM) analysis of an air sample using the NIOSH method 7400 or an equivalent method. [13] The current NIOSH method 7400 was firstly published in 1989 and is the default method for evaluating the EMP in the US. Prior to this method, some of its equivalent methods had already been existing with the earliest one published around the 1970s. [14]

Historical EMP exposure reconstruction, especially over a long span of time (1955–2010), is challenging. The biggest challenge is that typically industrial hygiene (IH) measurement data are not available for every job for every time point of the study period in the job exposure matrix (JEM). Different quantitative strategies have been proposed to overcome the sparse data problem: (1) data pooling: e.g., in the historical tremolite-actinolite exposure reconstruction work for the vermiculite miners and millers between 1930 and 1980 near Libby Montana. Amandus et al.[15] estimated the 8-hr TWA fiber exposure for different jobs in each year of operation of the Libby facility by pooling arithmetic averages of the fiber concentrations from filter samples for years when production processes and dust controls were assumed to be similar; (2) statistical modeling: e.g., in the historical fiber exposure reconstruction work for the chrysotile asbestos textile workers between 1940 and 1975 in Charleston South Carolina, Dement *et al.*[16] first divided the textile operations into 16 exposure zones according to similarity of processes and exposures, and then applied a linear model to estimate the mean exposure levels over time for each of their exposure zones; (3) hybrid methods: e.g., during the process of reconstructing the historical exposure to Libby vermiculite for the workers between 1972 and 2000, researchers first calculated the natural log-transformed mean for any year with 40 or more sample results, then fitted a smooth curve through these mean values, and finally calculated the yearly fiber exposure levels by exponentiating the value on this curve for each year.[17,18]

Based on sparse IH measurements and other information, this paper uses two statistical modeling approaches to reconstruct the historical EMP exposure profiles from 1955–2010 for Minnesota taconite miners. The exposure estimates will be used for estimating the life-time cumulative EMP exposure values for taconite workers in epidemiological investigations.

Methods

Taconite mines and different exposure groups

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.[2,3] 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.[19] Six out of these seven mines were still in operation in 2010 when a comprehensive exposure monitoring was conducted.[2–4] The mining processes

Table 1. Data availability for the seven taconite mines in the study.

Taconite Mine	Geological Zone	Year Opened	Status (as of 2010)	Available EMP Measurements by Year
A	Eastern	1955	Active	1973–1976, 1978–1980, 1983–1986, 1990–1993, 1995, 2000, 2001, 2003–2010
B	Western	1974	Active	1985, 1986, 1995, 2000, 2001, 2003, 2007, 2010
C	Western	1964	Active	1978, 1979, 1981–1983, 1985–1990, 1995, 2000, 2001, 2003, 2007, 2010
D	Western	1967	Active	1975–1977, 1987, 2000, 2001, 2003, 2004, 2007, 2010
E	Western	1967	Active	1990, 1991, 1994–1998, 2000, 2001, 2003, 2007, 2010
F	Western	1977	Active	1979, 1981, 1983, 1985, 1986, 1988, 1992, 1999–2001, 2003, 2004, 2007, 2010
G	Eastern	1957	Closed in 2001	1979–1992, 2000, 2001

*Mining Companies: http://www.taconite.org/mining-industry/mines

Table 2. Numbers of historical and "Year 2010/2011" EMP measurements for each location.

	Mine							
Department	A	B	C	D	E	F	G	All 7 mines
# of historical measurements								
Mining	84	20	21	15	46	31	14	231
Crushing	109	6	36	5	30	35	19	240
Concentrating	13	4	4	4	29	8	3	65
Pelletizing	8	10	3	2	35	5	2	65
Shop (mobile)	54	3	14	5	17	3	1	97
Shop (stationary)	1	0	12	0	0	1	8	22
Office/control room	0	0	0	0	0	0	0	0
Janitor	10	3	4	0	13	1	0	31
All 8 departments	279	46	94	31	170	84	47	751
# of "Year 2010/2011" measurements								
Mining	21	30	24	42	36	11	0	164
Crushing	54	23	36	18	22	11	0	164
Concentrating	32	24	18	24	24	12	0	134
Pelletizing	60	35	57	54	55	29	0	290
Shop (mobile)	42	52	52	30	76	30	0	282
Shop (stationary)	42	24	22	23	30	18	0	159
Office/control room	15	11	12	12	24	18	0	92
Janitor	0	0	0	0	0	0	0	0
All 8 departments	266	199	221	203	267	129	0	1285

for all the mines were quite similar, but workers with different tasks were considered to experience different exposures. Hwang et al.[3] grouped all taconite worker job titles into eight exposure departments: Mining, Crushing, Concentrating, Pelletizing, Shop (mobile), Shop (stationary), Janitor, and Office/control room. Given this exposure categorization, the specific aim of this study was to create historical EMP reconstruction for each of these mine-department combinations.

Construction of historical exposure database

Historical EMP measurements included both personal and area samples In this study, which reconstructs exposures for use in epidemiological analysis of worker respiratory health outcomes, only personal historical EMP samples (collected over an 8-hr period) were considered, and all samples were analyzed using the standard phase contrast microscopy (PCM) method as defined by the National Institute for Occupational Safety and Health (NIOSH).[20]

Historical NIOSH-7400 EMP personal exposure data were extracted from two sources: (1) the Mine Safety and Health Administration (MSHA) online database recorded for all inspection results since 1978 with 655 EMP monitoring records from 1978–2010 for 13 MSHA Mine IDs associated with this study (10 of the post-2008 samples were above the new MSHA PEL of 0.1 fibers/cc, and were likely further corrected by TEM analysis); and (2) the mining companies' internal monitoring reports contained 96 personal EMP exposure records with the earliest record in 1983. In total, there were only 751 historical EMP personal samples—a small number for the seven mines and eight departments over a 50-year time-span. The apportionment of these samples can be found in Table 1 and their location distribution is listed in Table 2. The data gap is significant for several mines, especially during their early years: for instance, the first EMP measurements for Mine G were made in 1979, ~22 years after it started production. Similarly, Mine E, which started operating in 1967, also had no historical EMP measurements until 1990—23 years later.

"Year 2010/2011" EMP measurements

As reported in detail in a previous publication,[3] a total of 1,285 personal samples from a subset of workers in seven of the eight departments (excluding

"Janitor") of each active mine were collected to assess "Year 2010/2011" EMP exposures. This sampling was conducted from January 2010 to May 2011. Mine G, which was closed in 2001, was not covered in this survey. All these samples were analyzed using the NIOSH 7400 PCM method by an American Industrial Hygiene Association-accredited laboratory (EMSL Analytical Inc., Minneapolis, MN, USA).

Handling data below the limit of detection

Among the 2,036 historical and "Year 2010/2011" measurements, 176 historical measurements and 463 "Year 2010/2011" measurements were either below the limit of detection (LOD) or recorded as zero. All zero values and the values below LOD were replaced with a small positive value (0.001 f/cc), which was approximately one-half of the lowest LOD among all study measurements. This substitution method works reasonably well when the percentage of censored data are not too high.

Historical EMP reconstruction strategy

While "Year 2010/2011" measurements enable us to understand the current EMP exposures, historical monitoring data are crucial to estimating how these levels changed over time. However, there were only 751 historical measurements in total in this study that were not uniformly distributed across mine-departments, and 12 locations had no historical data at all (Table 2).

To assess exposures in the face of this data sparseness, two approaches were used. The first one (hereafter referred to as Approach 1) is a regression-based approach. All 2,036 data points were first sorted by mine, and within each mine, a categorical variable for department was created. For each mine, a log-linear regression model was run to obtain a fixed slope estimate (time trend) that is common to all departments (within that mine) and a varying intercept for each department (Eq. (1)). The model was also adjusted for "present-day" vs. "historical" measurements to account for systematic differences in sampling strategies between these two sets of measurement data. The sampling strategy for the "Year 2010/2011" exposure assessment was primarily designed to capture a wide range of exposure levels for epidemiological analyses, while the historical measurements were obtained primarily for compliance purposes. Therefore, the linear regression model for each mine included a categorical variable to explain the potential difference in exposure levels by different measurement type. A fixed slope (time trend) model was used so that estimates for departments with fewer monitoring data could borrow strength from departments with more monitoring data. Mine G had no "Year 2010/2011" measurements and its historical data were very sparse as well. Therefore, given their geographical proximity (western zone) and geological similarity,[21] data from Mine A was used as a surrogate to make predictions for Mine G. The Mining department in Mine G and Janitor departments in each of the other mines had no "Year 2010/2011" measurement (shaded gray in Table 2). In addition to the seven mines and the eight departments within each mine, an "All 8 departments" department category and an "All 7 mines" mine category were created (see Table 2). The results of these two categories would be used to provide exposure estimates for workers with unclear job titles or work histories. The "All 8 departments" department was modeled using all the data within a mine. The "All 7 mines" mine was modelled using all the data within the same department across all mines.

It's worth noting that the term $\beta_{9,i}$ in Eq. (1) was the predicted time-trend for each mine of this study. Its exponentiation, i.e., $\exp\left(\beta_{9,i}\right)$ (in percentage), reflected the fixed annual mean EMP exposure change in a mine:

$$\log\left(\hat{Y}_{j,i}\right) = \beta_{0,i} + \sum_{j=1}^{8} \beta_{j,i} \times Department + \beta_{9,i} \times Year_i + \beta_{10,i} \times Present\,day, \tag{1}$$

where $\hat{Y}_{j,i}$ was the predicted EMP mean concentration value (in f/cc) for department j of mine i. *Department* was a categorical variable that had eight levels corresponding to the eight departments in each mine and $\beta_{j,i}$ ($j = 1–8$) were the model coefficients for the eight departments within each mine. The baseline department was the "Mining" department. $Year_i$ was the time variable, from 1955 or later to 2010, depending on the mine. *Present day* was a binary variable with 0 for "Year 2010/2011" measurements and 1 for historical measurements. When $\hat{Y}_{j,i}$ was predicted, the present day variable was set to '0', i.e., the log EMP level was estimated at a historical time point as if it had been measured the same way as today.

The second approach (Approach 2) used the results from a companion study—*Reconstructing Historical Exposures to Respirable Dust (RD) and Respirable Silica (RS) in the Taconite Mining Industry for 1955–2010*.[22] These two studies are similar: both are historical exposure reconstructions for the same taconite worker population, and they share the same mine-department combinations with the same reconstruction time period. The only difference between these two studies was the pollutant of interest: one was for EMP exposure, the other was for RS and RD exposure. In the RS-RD study, thanks to the abundant measurements (19,408 respirable dust (RD) measurements and 9,128 respirable silica (RS) measurements), the annual percentage change in RSRD exposure levels over time in each mine-department combination was easier to reconstruct. Since this study to reconstruct EMP exposures has a much sparser data set, respirable dust exposure levels and EMP exposure levels for a given mine-department combination were assumed to have the same annual percentage change over time. For example, a yearly 1% increase/decrease in respirable dust exposure would lead to the same 1% annual change in EMP exposure. The advantage of this assumption was that time-trend slopes from the respirable dust study were more precise given the large number of respirable dust measurements (19,408 respirable dust (RD) measurements and 9,128 respirable silica (RS) measurements) and may better reflect the overall exposure changes over time in the taconite mining industry. EMP exposures, being a subset of the overall dust exposures, might reasonably be assumed to follow the same general time-trends. However, sufficient historical EMP measurement data were not available for us to validate this assumption.

The modeling procedure for Approach 2 was as follows: (1) For each mine-department combination, the mean exposure level at Year 2010 was defined as the log of the geometric mean all "Year 2010/2011" measurements of this location; (2) the mean exposure levels for other years were calculated using Eq. (2); and (3) the variance around the mean exposure in each year was assumed to be constant over the entire time period, and was defined as the variance of all "Year 2010/2011" measurements of this location ($\log(GSD_{i,j,2010})$):

$$\log\left(\hat{Y}_{i,j,k}\right) = \log(GM_{i,j,2010}) - \beta_{i,j,dust} \times (2010-k), \tag{2}$$

where $\hat{Y}_{i,j,k}$ was the predicted mean exposure level (f/cc) for department j of mine i in year k; $GM_{i,j,2010}$ was the geometric mean (GM) of all "Year 2010/2011" measurements taken in the year 2010 at department j of mine i; $\beta_{i,j,dust}$ was the estimated annual change for department j of mine i listed in Table 3 under the Approach 2 subtitle.

Similar to the Approach 1, Mine G was modelled based on the "Year 2010/2011" data in Mine A. The 'All 8 departments' grouping was modelled using all the "Year 2010/2011" data within each mine. The "All 7 mines" grouping was modeled using all the "Year 2010/2011" data within the same departments across all mines. Janitor departments were modeled using "All 8 departments" data.

Geometric Mean (GM) to Arithmetic Mean (AM) conversion

Both reconstruction approaches were conducted in the log scale, and their model outputs after exponentiation (GMs and geometric standard deviations (GSDs)) were used to calculate the corresponding arithmetic means using Eq. (3):

$$AM = GM \times \exp\left(\frac{1}{2}\log^2(GSD)\right). \tag{3}$$

Each of the two reconstruction approaches led to the development of a separate EMP JEM (See Supplementary Materials). Each table contains annual arithmetic mean EMP exposure values (in f/cc) for each possible year-department-mine combination. These two JEMs, when linked to taconite workers' employment histories, allow us to calculate the cumulative exposure (in f/cc-year) for the study population for epidemiological studies.

Data cleaning was performed in SAS (Version 9.3, SAS Institute, Cary NC). EMP reconstruction was performed in MATLAB R2014b (MATLAB e MathWorks, Inc., Natick, MA).

Results and discussion

There was a total of 2,036 EMP measurements available across all mines and departments as summarized in Table 2. The distribution of these samples, to some extent, reflects overall IH sampling priorities in the taconite industry. Most IH samples were collected in the four main taconite processes—mining, crushing, concentrating, and pelletizing. In contrast, there were no historical data available for all seven office/control room departments ("Year 2010/2011" measurements did greatly supplement the database for these departments).

Model outputs

Some of the predicted historical EMP exposure values using the two different reconstruction approaches are shown side by side in Figure 1. The three pairs of plots in this figure demonstrate three typical scenarios in the study. The first scenario is when a mine-department

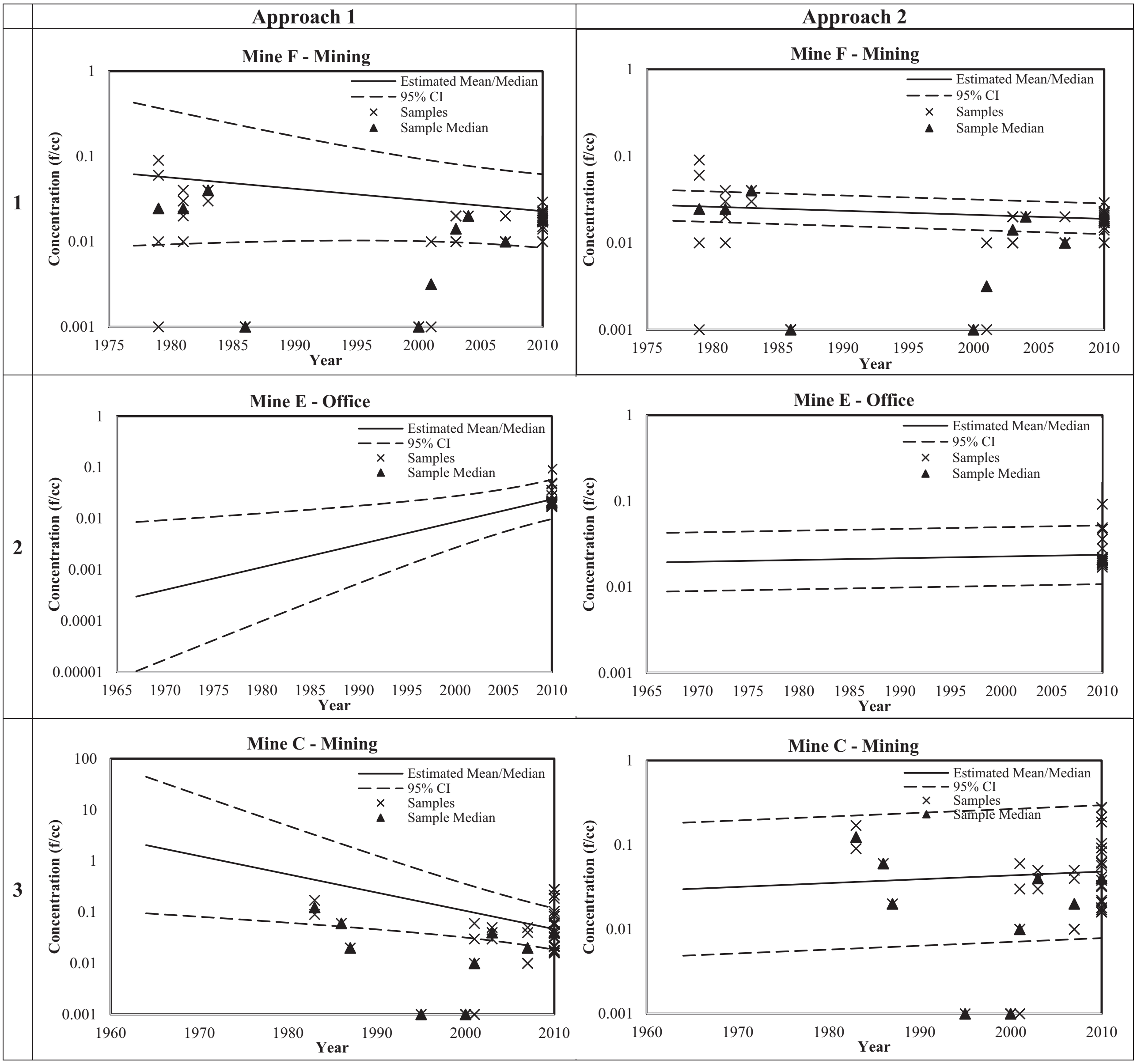

Figure 1. Historical EMP exposure reconstruction results for each of three selected mine-department combinations using two approaches.

location has a fairly good exposure data coverage over its entire time period. Specifically, data are available for the first 10 years and last 10 years in the history of this time. In this scenario, as shown in the two first-row plots, the two approaches provide comparable prediction curves. The predicted EMP exposure slopes by Approach 1 were consistent with the borrowed dust exposure slopes in Approach 2. This result can also be interpreted as the borrowed slope, derived from a separate dust reconstruction work, fitted the EMP data in this study well. The second scenario is when a location only had "Year 2010/2011" measurements. In this scenario, as shown in the two second-row plots, Approach 2 is clearly more reasonable than Approach 1 for the following reason: when the historical EMP data were not available for this department, the slope provided by Approach 1 for this department was determined by other departments that also had little EMP historical data. Due to their sparse nature, these data may not adequately reflect the EMP level change in this department. In Approach 2, this slope was determined by the respirable dust measurements for this mine-department. For almost all departments, many more historical respirable dust measurements were present compared to EMP measurements (19,408 respirable dust (RD) measurements and 9,128 respirable silica (RS) measurements vs. 2,036 EMP measurements). Therefore,

Table 3. The annual percent change in historical EMP exposures estimated by Approach 1, and the location-specific annual percent change for historical exposure to airborne dusts used in Approach 2.

Mine-Department	A	B	C	D	E	F	G	All 7 mines
Approach 1								
All 8 departments	−4.5%	2.1%	−8.2%	−1.8%	10.2%	−3.0%	−4.5%	−3.9%
Approach 2								
Mining	0.4%	−0.1%	1.0%	−1.8%	−0.6%	−1.1%	0.4%	−0.4%
Crushing	−0.1%	−2.5%	2.2%	−3.3%	2.3%	−0.8%	−0.1%	−0.7%
Concentrating	3.2%	1.6%	0.0%	−2.9%	2.2%	−2.7%	3.2%	2.0%
Pelletizing	2.3%	0.9%	0.1%	−1.5%	−0.3%	−2.0%	2.3%	0.2%
Shop (mobile)	−0.4%	−2.1%	−1.4%	−0.3%	−2.5%	−3.0%	−0.4%	−1.0%
Shop (stationary)	1.5%	1.1%	−2.6%	1.2%	0.3%	0.2%	1.5%	−0.2%
Office/control room	0.7%	−1.0%	0.8%	−2.0%	0.5%	−1.8%	0.7%	−0.2%
Janitor	0.7%	−1.0%	0.8%	−2.0%	0.5%	−1.8%	0.7%	−0.2%
All 8 departments	0.7%	−1.0%	0.8%	−2.0%	0.5%	−1.8%	0.7%	−0.2%

Table 4. The predicted arithmetic mean (AM) range of historical EMP exposure levels by location (f/cc)—Approach 1.

Mine-Department	A		B		C		D		E		F		G		All 7 mines	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
Mining	0.08	2.1	0.02	0.07	0.05	7	0.03	10.89	0	0.04	0.03	0.1	0.13	1.82	0.04	0.41
Crushing	0.13	2.87	0.03	0.07	0.03	3.09	0.02	6.56	0	0.06	0.04	0.15	0.2	2.51	0.06	0.60
Concentrating	0.18	4.17	0.02	0.05	0.05	6.21	0.06	15.22	0	0.07	0.05	0.2	0.28	3.64	0.05	0.47
Pelletizing	0.08	1.81	0.03	0.07	0.03	3.61	0.11	30.89	0	0.06	0.02	0.08	0.12	1.58	0.04	0.45
Shop (mobile)	0.08	1.92	0.03	0.08	0.04	4.2	0.05	14.01	0	0.06	0.03	0.12	0.13	1.67	0.05	0.49
Shop (stationary)	0.08	1.82	0.02	0.06	0.04	3.69	0.03	9.14	0	0.04	0.02	0.09	0.12	1.58	0.04	0.41
Office/control room	0.02	0.5	0.02	0.06	0.03	3.17	0.02	7.42	0	0.03	0.03	0.12	0.03	0.44	0.02	0.23
Janitor	0.08	1.82	0.02	0.03	0.03	1.93	0.05	3.32	0	0.05	0.03	0.09	0.13	1.61	0.04	0.45
All 8 departments	0.08	1.82	0.02	0.03	0.03	1.93	0.05	3.32	0.00	0.05	0.03	0.09	0.13	1.61	0.04	0.45

the slope used in Approach 2 (that assumes that EMP concentration and RS/RD concentration track each other over time) is more reasonable (and plausible) than the one in Approach 1. The Approach 1's slope, if it is true, will be against the 3% to 3% slope range that learned from the dust reconstruction study in Minnesota taconite industry. The third scenario is shown in the two third-row plots in Figure 1. Essentially, Approach 1 is a random-intercept model, meaning every department of the same mine shares a common slope but different intercepts. Most times, this assumption should work as each department may have different exposure magnitudes, but their over-time change trend should be in the same direction: all getting better or all getting worse. But sometimes there are exceptions as well as shown in Scenario 3. The common slope used in Mine C mining department does not fit the data as good as the one used in Approach 2. The slope in Approach 2, which was derived from historical dust measurements, has a very good fitness compared to that of Approach 1.

Predicted annual exposure level change rate by exposure location

Approach 1 made time-trend predictions for the historical exposure change in each mine based on historical and "Year 2010/2011" EMP measurements. The results of these time trends are listed on the last row of Table 3. Compared to the time trends in historical respirable dust exposure used in Approach 2 (first 9 rows in Table 3), the predicted EMP trends based on limited EMP data tended to be significantly steeper, and some of the annual percent changes seem unrealistic, ranging from -8.2% to 10.2%. Time-trend results from historical respirable dust exposures suggest that the historical exposure change in taconite mining environment should not be excessive, and in most cases, this change should be within -3% to 3% per year.

Predicted arithmetic mean of EMP exposure by exposure location

The arithmetic mean (AM) is a more appropriate exposure metric in creating a job-exposure matrix (JEM) for health studies than the geometric mean (GM).[23–27] The predicted AM range for every mine-department combination are listed in Table 4 for Approach 1, and Table 5 for Approach 2. The full set of predicted AMs can be found in the Supplementary Materials.

For Approach 1, some of the upper bound AM estimates are unrealistically high (e.g., 30.89 f/cc in Mine D). This might be due to several reasons

Table 5. The predicted arithmetic mean (AM) range of historical EMP exposure levels by location (f/cc)—Approach 2.

Mine-Department	A		B		C		D		E		F		G		All 7 mines	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
Mining	0.07	0.08	0.02	0.02	0.05	0.07	0.04	0.08	0.03	0.04	0.02	0.03	0.07	0.08	0.04	0.05
Crushing	0.21	0.22	0.03	0.07	0.01	0.03	0.03	0.13	0.03	0.08	0.04	0.05	0.22	0.22	0.09	0.13
Concentrating	0.04	0.2	0.01	0.02	0.05	0.05	0.07	0.23	0.02	0.05	0.04	0.1	0.04	0.15	0.03	0.08
Pelletizing	0.03	0.09	0.03	0.04	0.04	0.04	0.12	0.23	0.13	0.15	0.02	0.05	0.03	0.07	0.07	0.08
Shop (mobile)	0.16	0.2	0.04	0.08	0.05	0.1	0.06	0.07	0.07	0.22	0.03	0.08	0.16	0.2	0.06	0.11
Shop (stationary)	0.05	0.11	0.02	0.03	0.03	0.09	0.02	0.03	0.05	0.05	0.02	0.02	0.05	0.09	0.05	0.05
Office/control room	0.01	0.02	0.02	0.03	0.01	0.02	0.02	0.05	0.02	0.03	0.03	0.05	0.01	0.02	0.02	0.03
Janitor	0.09	0.14	0.03	0.04	0.03	0.04	0.06	0.15	0.06	0.07	0.03	0.05	0.09	0.13	0.06	0.07
All 8 departments	0.09	0.14	0.03	0.04	0.03	0.04	0.06	0.15	0.06	0.07	0.03	0.05	0.09	0.13	0.06	0.07

including: some predicted slopes were too steep, no historical data were available for several departments, and there were huge variances in model outputs for some departments. In contrast, predictions from Approach 2 were much more stable. Its overall predicted AM range was 0.01–0.23 f/cc. This narrower range suggests that borrowing time-trend information from the dust exposure study greatly reduced the uncertainties in prediction. Given the sparseness of the historical EMP measurements, the predictions of Approach 2 (that relies solely on "Year 2010/2011" EMP data and a borrowed slope) seem more plausible than Approach 1 in reconstructing the historical EMP exposure profiles in this study.

Historical exposure reconstruction relying on limited information is always challenging, and the assumptions underlying each approach have limitations. A linear regression based on limited historical data (Approach 1) does not yield reasonable and plausible values of the slope. Approach 2 assumes that the EMP and the respirable dust in the same department share the same historical time trend. While this approach allowed us to avail of the more reasonable slope estimates from the historical respirable dust data set and yielded more plausible historical exposure estimates for most locations, the assumption is hard to validate. Such a validation would require both EMP and respirable dust data to be available for each year of the study time period for each mine-department combination.

The results presented here were used for several epidemiological analyses[5–8] and reviews by others,[28,29] These epidemiological analyses used the reconstruction of exposures presented here for non-asbestiform EMP (a number of previous studies have shown that there are no asbestiform EMP in the ore body[3,30,31]) as well as exposures to commercial asbestos reported previously.[6–8] This work is the first time EMP exposures have been reconstructed using information of other exposures in the same mine-department and shows the feasibility of this approach when data are very sparse.

Conclusion

Historical exposure reconstruction often relies upon limited information and is a challenging but important component of epidemiological investigations. In this study, a comprehensive reconstruction of the historical EMP exposures of all study mine-department combinations was completed, using two different reconstruction approaches. The reconstruction approaches resulted in two distinct EMP estimates for each mine, department, and year. Each approach has advantages and disadvantages, but overall, the approach that incorporated borrowed time-trend information from a companion study might provide more plausible exposure estimates. However, both JEMs can be used to assess associations with EMP and respiratory disease in future epidemiological studies to assess the effect of these assumptions.

Disclaimer

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

Funding

This research was made possible by funding under NIOSH 1R01OH010418-01A1 - Respiratory Diseases and Exposure to Elongated Mineral Particles in Taconite Ore. We would also like to thank the State of Minnesota for funding the original TWHS study.

References

[1] **University of Minnesota:** "Public Meeting and Final Report December 1, 2014." Available at http://taconiteworkers.umn.edu/news/documents/Taconite_FinalReport_120114.pdf. (accessed June 11, 2016).

[2] **Hwang, J., G. Ramachandran, P. C. Raynor, B. H. Alexander, and J. H. Mandel**: The relationship

between various exposure metrics for elongate mineral particles (EMP) in the taconite mining and processing industry. *J. Occup. Environ. Hyg. 11(9)*:613–624 (2014).

[3] **Hwang, J., G. Ramachandran, P. C. Raynor, B. H. Alexander, and J. H. Mandel**: Comprehensive assessment of exposures to elongate mineral particles in the taconite mining industry. *Ann. Occup. Hyg. 57(8)*:966–978 (2013).

[4] **Hwang, J., G. Ramachandran, P. C. Raynor, B. H. Alexander, and J. H. Mandel**: A comprehensive assessment of exposures to respirable dust and silica in the taconite mining industry. *J. Occup. Environ. Hyg. 14(5)*:377–388 (2017).

[5] **Odo, N.U., J. H. Mandel, D. M. Perlman, B. H. Alexander, and P. D. Scanlon**: Estimates of restrictive ventilatory defect in the mining industry. Considerations for epidemiological investigations: A cross-sectional study. *BMJ Open. 3(7)*:1–8 (2013).

[6] **Allen, E.M., B.H. Alexander, R.F. MacLehose, H.H. Nelson, G. Ramachandran, and J. H. Mandel**: Cancer incidence among Minnesota taconite mining industry workers. *Ann Epidemiol. 25(11)*:811–815 (2015).

[7] **Lambert, C.S., B.H. Alexander, G. Ramachandran, et al:** A case-control study of mesothelioma in Minnesota iron ore (taconite) miners. *Occup. Environ. Med. 73(2)*:1–7 (2016).

[8] **Allen, E.M., B.H. Alexander, R.F. MacLehose, et al:** Occupational exposures and lung cancer risk among Minnesota taconite mining workers. *Occup. Environ. Med. 72(9)*:633–639 (2015).

[9] **Mandel, J.H., B.H. Alexander, and G. Ramachandran**: A review of mortality associated with elongate mineral particle (EMP) exposure in occupational epidemiology studies of gold, talc, and taconite mining. *Am. J. Ind. Med. 59(12)*:1047–1060 (2016).

[10] **Mandel, J.H., G. Ramachandran, and B.H. Alexander**: Increased lung cancer mortality in taconite mining: the potential for disease from elongate mineral particle exposure. *Chem. Res. Toxicol. 29(2)*:136–141 (2016).

[11] **Perlman, D., J.H. Mandel, N.U. Odo, et al**: Pleural abnormalities and exposure to elongate mineral particles in Minnesota iron ore (taconite) workers. *Am. J. Ind. Med. 61(5)*:391–399 (2018).

[12] **Eastern Research Group, Inc.:** "Report on the Expert Panel on Health Effects of Asbestos and Synthetic Vitreous Fibers: The Influence of Fiber Length." (March 17, 2003). Available at https://www.atsdr.cdc.gov/HAC/asbestospanel/finalpart1.pdf.

[13] **National Institute for Occupational Safety and Health:** *Current Intelligence Bulletin 62: Asbestos Fibers and Other Elongate Mineral Particles: State of the Science and Roadmap for Research*, DHHS (NIOSH) Publication No. 2011–159. Department of Health and Human Services, April 2011.

[14] **National Institute for Occupational Safety and Health**: *USPHS/NIOSH Membrane Filter Method for Evaluating Airborne Asbestos Fibers*, DHEW(NIOSH) Publication No.79-127, U.S. Department of Health, Education and Welfare, February 1979.

[15] **Amandus, H.E., R. Wheeler, J. Jankovic, and J. Tucker**: The morbidity and mortality of vermiculite miners and millers exposed to tremolite-actinolite: Part I. Exposure estimates. *Am. J. Ind. Med. 11(1)*:1–14 (1987).

[16] **Dement, J.M., R.L. Harris, M.J. Symons, and C. Shy**: Estimates of dose-response for respiratory cancer among chrysotile asbestos textile workers. *Ann. Occup. Hyg. 26(8)*:869–887 (1982).

[17] **Borton, E.K., G.K. LeMasters, T.J. Hilbert, J.E. Lockey, K.K. Dunning, and C.H. Rice**: Exposure estimates for workers in a facility expanding Libby vermiculite. *J. Occup. Environ. Med. 54(11)*:1350–1358 (2012).

[18] **US Environmental Proection Agency:** *Toxicological review of Libby amphibole asbestos in support of summary information on the integrated risk information system (IRIS) (Final)*. EPA/635/R-11/002F (December 2014). Available at https://cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/1026tr.pdf (accessed March 1, 2019)

[19] **Sheehy, J.W.**: "Reconstruction of occupational exposures to silica containing dusts in the taconite industry (mining, iron ore, respirable, job class)." Ph.D. diss., School of Public Health, University of Minnesota, Minneapolis, MN, 1986.

[20] **National Institute for Occupational Safety and Health (NIOSH):** *Asbestos and other fibers by PCM* (NMAM 7400). [Standard] Morgantown, WV: NIOSH, 1994.

[21] **McSwiggen, P.L., and G.B. Morey**: Overview of the mineralogy of the Biwabik Iron Formation, Mesabi Iron Range, northern Minnesota. *Regul. Toxicol. Pharmacol. 52(1 SUPPL.)*:S11–S25 (2008).

[22] **Shao, Y.**: "Respiratory diseases and exposures to taconite dust components." Ph.D. diss., School of Public Health, University of Minnesota, Minneapolis, MN, 2018.

[23] **Rappaport, S.M**: Assessment of long-term exposures to toxic substances in air. *Ann. Occup. Hyg. 35(1)*:61–121 (1991).

[24] **Seixas, N.S., T.G. Robins, and L.H. Moulton**: The use of geometric and arithmetic mean exposures in occupational epidemiology. *Am. J. Ind. Med. 14(4)*:465–477 (1988).

[25] **Rice, C., R.L. Harris Jr., J.C. Lumsden, and M.J. Symons**: Reconstruction of silica exposure in the North Carolina dusty trades. *Am. Ind. Hyg. Assoc. J. 45(10)*:689–696 (1984).

[26] **Verma, D.K., P.M. Vacek, K. des Tombe, et al.**: Silica exposure assessment in a mortality study of vermont granite workers. *J. Occup. Environ. Hyg. 8(2)*:71–79 (2011).

[27] **Crump, K.S**: On summarizing group exposures in risk assessment: Is an arithmetic mean or a geometric mean more appropriate? *Risk Anal. 18(3)*:293–297 (1998).

[28] **Boffetta, P., K.A. Mundt, and W.J. Thompson**: The epidemiologic evidence for elongate mineral particle (EMP)-related human cancer risk. *Toxicol. Appl. Pharmacol. 361*:100–106 (2018).

[29] **Garabrant D.H., and S.T. Pastula**: A comparison of asbestos fiber potency and elongate mineral particle (EMP) potency for mesothelioma in humans. *Toxicol. Appl. Pharmacol. 361*:127–136 (2018).

[30] **Wilson, R., E.E. McConnell, M. Ross, C.W. Axten, and R.P. Nolan**: Risk assessment due to environmental exposures to fibrous particulates associated with taconite ore. *Regul. Toxicol. Pharmacol.* RTP; *52(*1 Suppl*)*:S232–S245 (2008).

[31] **Zanko, L.M., H.B. Niles, and J.A. Oreskovich**: Mineralogical and microscopic evaluation of coarse taconite tailings from Minnesota taconite operations. *Regul. Toxicol. Pharmacol.* RTP; *52(*1 Suppl*)*:S51–S65 (2008).