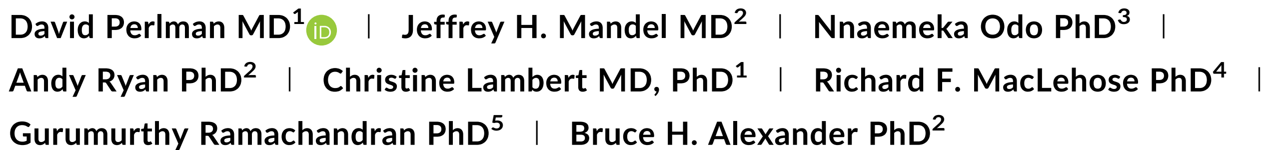
Accepted: 4 February 2018
DOI: 10.1002/ajim.22828

RESEARCH ARTICLE

WILEY AMERICAN JOURNAL OF INDUSTRIAL MEDICINE

Pleural abnormalities and exposure to elongate mineral particles in Minnesota iron ore (taconite) workers



David Perlman MD[1] | Jeffrey H. Mandel MD[2] | Nnaemeka Odo PhD[3] | Andy Ryan PhD[2] | Christine Lambert MD, PhD[1] | Richard F. MacLehose PhD[4] | Gurumurthy Ramachandran PhD[5] | Bruce H. Alexander PhD[2]

[1] Department of Medicine, University of Minnesota School of Medicine, Minneapolis, Minnesota

[2] Division of Environmental Health Sciences, University of Minnesota School of Public Health, Minneapolis, Minnesota

[3] Kaiser Permanente, Oakland, California

[4] Division of Epidemiology and Community Health, University of Minnesota School of Public Health, Minneapolis, Minnesota

[5] Department of Environmental Health and Engineering, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland

Correspondence
Jeffery H. Mandel, MD, Division of Environmental Health Sciences, University of Minnesota School of Public Health, 420 Delaware Street SE, MMC 807, Minneapolis 55455, MN.
Email: mand0125@umn.edu

Funding information
State of Minnesota

Background: Iron ore (taconite) mining and processing are an important industry in northern Minnesota and western Michigan. Concerns around exposures have centered largely on exposure to non-asbestiform amphibole elongate mineral particles (EMPs) found in the eastern portion of the Minnesota iron range.

Methods: A cross sectional survey was undertaken of current and former taconite workers and spouses along with a detailed exposure assessment. Participants provided an occupational history and had a chest radiograph performed.

Results: A total of 1188 workers participated. Potential exposures to non-amphibole EMPs were evident across multiple jobs in all active mines. Pleural abnormalities were found in 16.8% of workers. There was an association of pleural abnormalities with cumulative EMP exposure that was not specific to the eastern portion of the range.

Conclusion: There was evidence of a mild to moderate increase in pleural abnormalities in this population of miners, associated with geographically non-specific cumulative EMP exposure.

KEYWORDS
chest x-ray, elongate mineral particles, pneumoconiosis, taconite

1 | INTRODUCTION

Taconite ore mining and processing have been a significant source of economic activity in Northern Minnesota over the last six decades. Since the 1970s there have been concerns about the health effects of exposure to the dust and tailings produced in the taconite industry. The industry facilities follow iron ore deposits that exist in a narrow band stretching 110 miles across the northeastern portion of the state, known as the Mesabi Iron Range.[1] Concerns have centered largely on the possible effects of exposure to a non-asbestiform amphibole elongate mineral particle (EMP), a fiber-like mineral found in the eastern-most portion of the deposit. There have been EMPs from processing tailings found in the air and water supply of communities near taconite mining and processing facilities.[2,3] Increased rates of mesothelioma have been detected in several Northern Minnesota counties[4] and more recently in taconite miners.[5,6] Furthermore, the risk of mesothelioma has been associated with length of employment in the taconite industry and an imprecise association was observed with cumulative exposure to EMPs.[7]

The National Institute of Occupational Safety and Health (NIOSH) defines an EMP as any mineral with an aspect ratio (length to width) of 3:1 or greater,[8] but only EMPs of at least 5 μm in length are regulated. EMPs in the taconite industry can originate from multiple sources and may be asbestiform (chemically similar to asbestos mineral and capable of cleaving along parallel planes and forming fibers) or non-asbestiform (not cleaving along parallel planes). Because of the inability to easily form fibers, non-asbestiform EMPs are thought to be less toxic and less

Institution at which the work was performed: University of Minnesota.

 © 2018 Wiley Periodicals, Inc.

pathogenic,[9–11] however, the effects of exposure to non-asbestiform EMPs have not been extensively studied. The mining and processing of taconite ore generate dusts that also include cleavage fragments, another type of EMP created when the ore is crushed.[12] The standard NIOSH counting method using phase contrast microscopy (NIOSH 7400 method), that identifies all EMPs longer than 5 µm with a diameter of 0.25 µm or greater and with an aspect ratio ≥ 3:1, does not distinguish between asbestiform and non-asbestiform EMPs.[4,13,14]

The Mesabi iron range has been divided into distinct mineralogical zones. Geologic analysis has suggested that in the eastern part of the range (zone 4) the ore contains higher concentrations of amphibole, non-asbestiform EMPs. Less than 1% of the EMPs in eastern-most portion of the iron range (Zone 4) are thought to be asbestiform, while the western end (zone 1) does not contain asbestiform EMPs. Zone 2 is an intermediate zone, with some asbestiform amphibole EMPs present.[15–17] Occupational exposure levels to total and amphibole EMPs have been found to be higher in the eastern zones, but amphibole EMPs are generally well below the recommended exposure limit (REL) of 0.1 EMP/cc in all geographic areas.[12] The NIOSH REL is intended for regulated asbestiform EMP and for their non-asbestiform analogs.

In addition to EMPs, potential exposures in the taconite industry include respirable dust and it's component, respirable silica.[18] Similar combinations of non-asbestiform EMPs and dust exposures may be seen in gold and talc mining, where excess mortality from non-malignant respiratory disease (NMRD) has been reported.[19,20] Previous studies among Minnesota taconite workers did not show increased deaths due to NMRD.[5,21,22] However one study did show small numbers of miners with silicosis.[23]

A respiratory survey and exposure assessment were undertaken to assess the degree of NMRD among taconite workers. Spouses of participating workers were also recruited to estimate the prevalence of lung disease, which may be elevated in people with community and secondary occupational exposure.[24,25] Here, we report on the relationship between EMP exposure and abnormal chest radiograph findings in a cross-sectional study of workers and spouses.

2 | METHODS

The University of Minnesota Institutional Review Board Human Subjects Research Committee approved the protocol for this study. All participants were guided through an informed consent process and written consent obtained prior to their participation.

2.1 | Study population

The study population was assembled from lists of current and former workers obtained from each of the six active mines and one inactive site. The sampling frame was comprised of workers employed during the late 1980s until 2010 and totaled 16 990 individuals. This group represented the industry as a whole since mines that closed were typically purchased by one of three currently active companies. From this population a random sample of 3310 individuals was selected stratified on age and geographic location on the Mesabi Range. Older individuals were oversampled because of the long latency of pneumoconiosis in some individuals. The geographic representation was intended to represent the potential differences in the geologic determinants of exposure across the entirety of the Mesabi Range. With consideration of the prevalence of outcome abnormalities in the screened group, a sample size of 1200 workers was determined to provide adequate power to explore associations between exposure groups and lung abnormalities. All spouses were invited to participate with their partner to assess prevalence of pneumoconiosis in a population with possible secondary occupational exposure.

2.2 | Study recruitment

The selected individuals were invited to participate in the study by mail. For those individuals who didn't respond to three mailings, attempts were made to contact them by phone. After five attempts to reach people by phone, no further recruitment efforts were undertaken. Only remuneration for mileage reimbursement was provided for participants.

2.3 | Exposure assessment

The exposure assessment process has been described previously and is reviewed briefly here. The approach used work history, current on-site measurements, and historical exposure measurements (below) to estimate the cumulative exposure for each worker.[12,14] Standardized exposure assessment approaches were used to assign each of 181 jobs across the active mines to 28 similarly exposed groups (SEG), common to all plants.[12] Three workers per SEG were selected for the on-site sampling. Each participant wore a personal air-sampler for approximately 6 h of a work shift on three separate occasions. The filter samples were analyzed for EMPs using the NIOSH 7400 method. These measures were used to estimate an 8-h time-weighted average (TWA) concentration for each SEG, which served as an anchoring point in the estimation of cumulative exposures. A total of 233 workers underwent personal exposure monitoring. Since five of the seven (six currently operating) mines were in the western zone, 177 of the workers were from this zone with the remainder from the eastern zone. All mines had some exposure levels for total EMPs that were greater than 0.1 EMP/cc for multiple SEGs.[12]

Work history information in this study was obtained from questionnaires which were reviewed with the participant by the investigative team in advance of medical testing. Information obtained directly from each participant included job titles and description of activity, job locations, and dates of each job. These work histories were used to assign workers to an SEG for the primary analysis.

Historical EMP exposure estimates were based on measurements provided by the companies and measurements taken by the Mining Safety and Health Administration (MSHA). These historical data were used in combination with the current, onsite measurements to estimate yearly EMP exposures for all SEGs from the beginning of the industry (1950s) and to create a job-exposure matrix (JEM).[6] For years when no EMP data were available, imputation was used to

estimate EMP levels. Regression models were fitted for each SEG within each mine, and used to estimate EMP exposure values for all years between 1955 and 2010. For jobs that occurred in 1954 or earlier 1955 exposure levels were used. The work history information for each worker was mapped to a specific SEG and time, using the JEM and standardized mapping terms from the work history. SEG exposures in the JEM were then combined by duration of work in that SEG to give a cumulative exposure estimate measured in (EMP/cc)*years.

2.4 | Clinical assessment

Workers, along with their spouses, were invited to participate in the study with the clinical testing based at a local hospital. Participants were mailed study documents including consent forms and the study questionnaire. At the clinic a research team member reviewed the purposes and procedures for the study, completed the informed consent process and ensured adequate completion of the questionnaire with each individual participant. The data collected included a brief physical examination, a detailed work history, and a brief medical and pharmaceutical history. The participant then underwent a chest radiograph, which was the primary health outcome for this investigation.

2.5 | Chest radiographs

The prevalence of pleural abnormalities and parenchymal opacities was determined with a single hard copy (analog) posteroanterior (PA) chest radiograph consistent with the recommendations of the International Labour Organization (ILO). Each radiograph was interpreted independently by two NIOSH-certified B-Readers using ILO guidelines and standard hard copy images for comparison.[26] The interpretations were recorded on the standard NIOSH chest radiographic classification form and all forms were fully completed. For the purposes of this study, parenchymal abnormalities were defined as the presence of small opacities of ILO profusion category 1/0 or above, and pleural abnormalities were defined as the presence of any classifiable pleural abnormality (minimum width was 3 mm as per ILO standard). When results from the two initial primary readers differed, a third certified B-reader performed an arbitration reading. For parenchymal abnormalities, a third read took place if the two initial readers disagreed by more than one profusion subcategories (eg, 1/0 vs 1/2), one profusion main category (eg, 1/× vs 2/×), disagreement on shape (s,t,u vs p,q,r), or more than one category in size (ie, p vs r or s vs u). For pleural abnormalities a third read was performed if there was disagreement on the presence of any classifiable pleural abnormality (ILO question 3A). A consensus of two B-readers was required for an abnormality to be present. B-readers assessed each film as acceptable or not acceptable, using standard definitions for these terms.[26] 10% of the radiographs were submitted a second time to the two primary B-readers (blindly) to assess internal consistency.

2.6 | Analysis

Baseline and demographic characteristics were assessed in both worker and spouse groups. Poisson regression models with robust standard error estimates were used to estimate prevalence ratios (PR) and 95% confidence intervals for the association between cumulative EMP exposure in workers and pleural and parenchymal abnormalities. Separate Poisson models were estimated to examine the association between years worked in the taconite industry across the entire Iron Range and pleural and parenchymal abnormalities. Cumulative EMP models examined exposure across the Iron Range and included terms for working in the eastern zones (2, 4) and western (zone 1) portions of the range, corresponding to the presence/absence of non-asbestiform EMPs, respectively. There were two plants located in the eastern portion of the range and five in the western portion.

To account for potential commercial asbestos exposure within the industry, each SEG was assigned an asbestos score of low, medium, or high based on the combined likelihood, and frequency of commercial asbestos exposure as determined by a consensus of industrial hygiene experts, and the number of years in SEGs with a high asbestos score was included in the exposure models. Potential occupational asbestos exposure outside the taconite industry was assessed in the questionnaire, and a variable included in the models that indicated whether an individual had ever been employed in an occupation outside the taconite industry with a high potential for asbestos exposure. Years in hematite were important since they preceded taconite mining, represented a higher-grade ore that required less processing than taconite, and had a different exposure profile.

To evaluate for potential for response bias, a comparison between participants, and non-participants was made using information available from company records that formed the Mineral Resources Health Assessment Program (MRHAP) cohort which was assembled by University of Minnesota School of Public Health researchers in the mid-1980s and is the basis for studies of mortality and cancer incidence in this population.[5–7] The MRHAP data contained demographic and work history information on all taconite workers from the origin of industry through 1983. To evaluate the potential for selection bias work histories of all individuals recruited for this study who were also included in MRHAP ($N = 1563$) were abstracted and responders and non-responders were compared with reference to sex, age, distance to clinic, and cumulative exposure. Comparisons were conducted using Student's *t*-test for demographic variables and proportional *t*-test for proportional comparisons. Cumulative exposure based on the work history as described above and time to the testing facility was determined by the use of spatial analysis determined by zip code of the person's home address.

3 | RESULTS

Study enrollment consisted of 1322 workers and 496 spouses (1818 individuals). A total of 1188 workers completed the questionnaire and all clinical examinations over a 14-month period. Acceptable chest radiographs were obtained on 1178 workers and (10 radiographs in workers did not meet standard quality indicators and were excluded from the analysis). The distribution of cumulative exposure uniformly increased both magnitude and variability with increasing duration of employment in the industry (Figure 1). Demographic characteristics

including BMI and smoking status for workers and spouses, along with employment location data for workers, are shown in Table 1. Participating workers were slightly older (66.4 vs 58.1 years), had a similar gender distribution, a shorter mean drive time to the testing facility (62.5 vs 143.3 min) and a higher mean cumulative exposure estimate (1.62 vs 1.27 [(EMP/cc) × years]) when compared to non-participants (Table 2).

Pleural abnormalities were found in 16.8% of workers and 4.4% of spouses. Parenchymal abnormalities were found in 5.4% of workers and 0.6% of spouses (Table 1). On chest radiographs where pleural abnormalities were noted, 97.4% had pleural plaques, 4.1% had diffuse pleural thickening, 8.8% had calcifications, and 47% had bilateral changes. Of the parenchymal abnormalities, most (86.0%) were category 1: 1/0 (57.8%), 1/1 (26.6%) or 1/2 (1.6%). Only one radiograph was category 3 (3/3), and 90% of the abnormalities were characterizes as irregular (categories s,t,u) versus 10% rounded (categories p,q,r,). Both types of chest radiographic abnormalities were more common in smokers and older workers, and mean BMI was higher among those with pleural abnormalities (Table 3—data not shown for spouses due to the very low number of abnormalities). Workers with pleural abnormalities were more likely to work in a job category within the industry with a high possibility of commercial asbestos exposure (Table 3). Of all 1674 films (workers and spouses) 341 (20.4%) met criteria for a third read; of the abnormal films, 257 (70.8%) required a third read. The third reader agreement was evenly distributed between the two primary B-readers for both pleural and parenchymal abnormalities, and our readers showed good internal consistency when radiographs were interpreted twice (kappa values >0.4, data not shown).

The Poisson regression suggest little evidence of association between duration of employment (PR = 1.01, 95% CI = 0.99-1.02) or for cumulative exposure (PR = 1.02, 95% CI = 0.98-1.05) and pleural abnormalities. When analyzed by quartile of exposure there was a moderate association for cumulative EMP exposure in quartiles two (PR = 1.53, 95% CI = 1.07-2.17) and three (PR = 1.63, 95% CI = 1.14-2.32) versus quartile one (used as the reference quartile) but a more attenuated association in quartile four (PR = 1.25, 95% CI = 0.86-1.82) versus quartile one (Table 4). For parenchymal disease there was no association with either employment duration or cumulative EMP exposure (Table 5). Analysis by working on the east versus west end of the iron range did not reveal meaningful differences in prevalence of

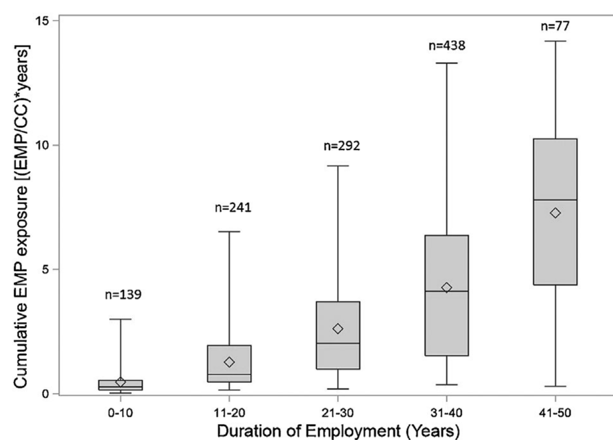


FIGURE 1 Cumulative elongate mineral particle (EMP) exposure measured by the NIOSH 7400 method. Shaded box represents first and third quartiles; line in mid-portion of box represents the median value; the diamond in the box represents the mean value; the lines at the ends of each box represent the 25th and 75th percentiles; the lines beyond the boxes represent the minimum and maximum values

TABLE 1 Baseline demographic characteristics and chest radiograph abnormalities of study participants

	Workers (*n* = 1179)	Spouses (*n* = 495)
Mean age (years)	60.5	59.7
Age groups		
<45	8.7%	7.4%
45-54	19.9%	26.0%
55-64	34.2%	30.8%
65-75	27.5%	30.3%
>75	9.6%	5.5%
Gender		
Male	90.2%	3.1%
Female	9.8%	96.9%
Mean BMI (kg/m^2)	31.4	31.0
Smoking		
Never	37.6%	47.1%
Current	12.3%	10.1%
Former	50.1%	42.7%
Zone ever worked[a]		
Zone 1 (western)	61.3%	
Zone 2 (intermediate)	35.0%	
Zone 4 (eastern)	24.9%	
Mean years of taconite employment		
Overall	25.5	
Zone 1 (western)	21.1	
Zone 2 (intermediate)	19.4	
Zone 4 (eastern)	21.4	
Chest x-ray abnormalities		
Two reader consensus parenchymal abnormality	5.4%	0.6%
Any one reader parenchymal abnormality	10.4%	3.0%
Two reader consensus pleural abnormality	16.8%	4.4%
Any one reader pleural abnormality	23.4%	11.5%

BMI, body mass index.
[a]Some miners worked in more than one zone, no mines were located in Zone 3.

TABLE 2 Comparison of eligible study participants with employment records in MRHAP[a] who enrolled in the respiratory health survey versus those who did not enroll

	Responders (*N* = 680)	Non-responders (*N* = 883)	*P*-value
Mean age (years)	66.4	58.1	<0.001
Gender			
Male	620 (91.3%)	801 (90.7%)	0.168
Female	59 (8.7%)	80 (9.0%)	0.836
Unknown[b]	1 (0.01%)	2 (0.002%)	0.832
Mean time to facility (minutes)[c]	62.5	143.3	<0.001
Mean cumulative EMP exposure (EMP/cc)*years[d]	1.62	1.27	<0.001

EMP, elongate mineral particle.
[a]Mineral Resources Health Assessment Program (MRHAP).
[b]"Unknown" category included people with missing gender information. This category was excluded in calculating *P*-values for gender proportions between groups.
[c]Based on zip codes for residence.
[d]Cumulative exposures were assessed from the Mineral Resources Health Assessment Program (MRHAP) work history database for responders and non-responders.

pleural or parenchymal abnormalities in those who worked in the eastern part of the iron range where naturally occurring non-asbestiform amphibole EMP exposures could occur (data not shown). The multivariate analysis adjusted for age, gender, BMI, smoking status, hematite years, probability of asbestos exposure in taconite industry job category, and potential outside asbestos exposure.

4 | DISCUSSION

This investigation of current and former workers in the taconite industry of Minnesota estimated the prevalence of radiographic abnormalities. There was evidence of an association between cumulative EMP exposure and the prevalence of pleural abnormalities. The results of this study should be interpreted in the context of certain limitations. Though workers were selected randomly, the participation rate was around 40%. As expected, a higher rate of participation occurred in those who lived within one hour of the testing facility, where participation rates approached 60%. However, when limiting the analysis to only participants within 1 h of the testing facility, the association with cumulative EMP exposure, and pleural abnormalities was not meaningfully different compared to the overall result (data not shown). Participants were older than non-respondents and therefore likely had longer duration of employment and higher cumulative EMP exposure.

TABLE 3 Characteristics of workers based on chest radiograph abnormality

Characteristic	Parenchymal abnormality[a]			Pleural abnormality[b]		
	Yes (63)	No (1115)	*P* value	Yes (198)	No (980)	*P* value
Mean Age (years)	67.9	60.1	<0.001	65.6	59.5	0.001
Mean BMI (kg/m^2)	30.5	31.4	<0.001	34.3	30.8	0.001
Smoking status						
Current	15.9%	11.7%	0.310	8.1%	12.7%	0.069
Former	61.9%	48.3%	0.036	66.7%	45.5%	0.011
Never	22.2%	40%	0.005	25.2%	41.8%	<0.001
Outside asbestos occupation[c]	73.4%	64.1%	0.131	71.2%	63.4%	0.036
SEG asbestos score[d]						
Low	20.3%	29.1%	0.133	21.8%	29.9%	0.021
Medium	64.1%	47.2%	0.009	48.7%	48.0%	0.857
High	15.6%	23.8%	0.135	29.4%	22.1%	0.027

BMI, body mass index; SEG, similarly exposed group.
[a]Defined as profusion category 1/0 or greater by consensus of two B-readers.
[b]Defined as consensus of two B-readers for any pleural abnormality.
[c]Obtained from worker questionnaire.
[d]SEG categorized based on the combined likelihood and frequency of commercial asbestos exposure within the taconite industry as determined by a consensus of two industrial hygiene experts.

Pleural abnormalities were present in 16.8% of workers. Since our study did not include a control population, historical controls, including general, and exposed populations, were examined. General population surveys looking for pleural plaques have shown prevalence rates as high as 6.8%. However, most surveys show rates around 2.5% or less and rates have been found as low as 0.21%.[27–30] Surveys of exposed populations have shown varying rates of pleural plaques, as high as 49%.[31] In the case of Libby, Montana, in which there was widespread exposure to asbestiform EMP contaminated vermiculite,[32] a radiographic survey showed an overall prevalence of pleural abnormalities of 17.8% in the community, with a range of 6.7-34.6% depending on the number of potential pathways of exposure.[33] A survey of community exposure to the Libby vermiculite in northeast Minneapolis, including low, and high intensity exposures, found a prevalence of pleural abnormalities of 15.4%.[34] A high proportion (53%) of the pleural abnormalities in our study were unilateral. While bilateral changes are considered more strongly associated with asbestos exposure,[35] unilateral changes can be seen as well and can be a significant portion of abnormalities.[36] The finding of 4.4% pleural abnormalities in spouses is within previously reported ranges for nonworking populations and thus not elevated in this population.[28]

Using the first quartile as a reference, cumulative EMP exposure was associated with pleural abnormalities in quartiles two and three, with a tendency in quartile four that was not statistically significant (CI includes 1.0), though the prevalence of abnormalities was highest in that group. Of interest is that a similar pattern of association between cumulative EMP exposure and mesothelioma was reported in another analysis of taconite workers.[7] The lack of an association with parenchymal changes in the lung suggests the EMP exposure in taconite mining may be sufficient to contribute to the formation of pleural abnormalities, but likely at concentrations too low to induce parenchymal disease.

Chest radiograph abnormalities were strongly correlated with smoking, which is not unexpected, and the effect was more prominent in current smokers compared with former. Although most previous studies have not shown an association between pleural abnormalities and smoking,[28,33,37] pleural abnormalities were significantly more common in smokers (current and former) in our study (20.9% vs 10.2%, $P < 0.001$). Although we include a smoking term in the pleural and parenchymal models, it is possible that there is some degree of residual, uncontrolled confounding by smoking that is contributing to the pleural abnormality-exposure association.

Most of the plants were built in the 1950s or 1960s, a time when commercial asbestos was commonly employed. However, a gap in historical measurements, particularly in the early years of the industry when use of asbestos was likely to have been higher, is a complicating factor. We attempted to control for commercial asbestos exposure within the industry, however it is possible that there was incomplete control for this exposure. As the work history data used for this study were collected from worker questionnaires, there is the potential for recall bias. In addition, our population had a high prevalence of outside occupations with potential asbestos exposure (64.6% for the overall population). While the general population prevalence of occupational asbestos exposure is not well-known, previous case-control studies have shown a lower prevalence.[38,39] There was a minimal difference in the frequency of possible outside asbestos exposure between the participants with and without radiographic abnormalities, and the group with pleural abnormalities had a slightly higher prevalence of potential outside asbestos exposure compared to those without pleural abnormalities. We did attempt to adjust for this exposure in the analysis, including 30 jobs with potential asbestos exposure; however the true level of outside exposure is difficult to estimate.

BMI was crudely associated with pleural abnormalities in workers, though we did attempt to control for this in the analysis. The relationship between BMI and pleural abnormalities in an asbestos exposed population has been shown previously.[40] In a study on the Libby, Montana population (including workers and household contacts); using high-resolution computed tomography as a gold standard, BMI was significantly associated with false positive findings.[41] The possibility of false positives causing misclassification and contributing to the overall rates of pleural abnormalities exists, but the extent to which this biased the results is not known. While there is variation among B-readers on the interpretation of pleural abnormalities, the good internal agreement, and the even distribution of agreement of the third reader with the two primary readers suggest there was not consistent over- or under-interpretation by either of the B-readers.

Results suggest a possible mildly increased prevalence of parenchymal abnormalities on chest radiographs among workers. This analysis did not evaluate silica and respirable dust exposures, which could be important contributors to parenchymal abnormalities. Also, we did not find an association of irregular opacities with EMP exposure. However, the majority of the parenchymal abnormalities were irregular versus rounded, which would not be typical for silica exposure. Reports of parenchymal abnormalities in unexposed populations range from 0.21% to 11.7%. Most healthy North American populations show <5%.[27,42] Our finding of 5.4% parenchymal abnormalities could represent a low rate of mixed dust pneumoconiosis similar to that seen in other open-pit mining settings.[43,44]

The survey was cross-sectional, thus only representing the experience of workers who were alive, and chose to participate. As with many cross-sectional studies a key concern is selection bias. Based on the characteristics from the non-responder analysis, our study reflects a prevalence of these conditions in a somewhat older population as older workers are more likely than younger workers to have radiographic findings. However it is also possible that our study underestimates disease level, as sick workers are less likely to travel to the clinic especially across longer distances. Since age and cumulative EMP exposure are highly correlated, it is more difficult to interpret the association of cumulative EMP exposure, and pleural abnormalities. When we excluded age as a covariate in our analysis the association between EMP exposure and pleural abnormalities in quartiles two and three remained significant (data not shown).

The exposure assessment that was done in conjunction with this investigation included current, onsite measurements with personal

TABLE 4 Pleural abnormality associated with duration of employment and EMP exposure

	Abnormalities[a] yes/no	Prevalence ratio[b]	95% CI[b]
Employment (years)			
Taconite employment duration	198/981	1.01	0.99-1.02
Hematite employment duration	24/43	1.01	0.97-1.05[c]
Cumulative exposure			
(EMP/cc)*years	198/981	1.02	0.98-1.05
Taconite employment duration quartile			
0< years <21	47/378		Ref
21< years <30	44/223	1.09	0.76-1.56
30< years <35	56/215	1.22	0.87-1.72
35+ years	51/165	1.21	0.84-1.73
Exposure quartile			
0< (EMP/cc)*years <1.16	48/415		Ref
1.16< (EMP/cc)*years <3.29	50/240	1.53	1.07-2.17
3.29< (EMP/cc)*years <5.89	51/174	1.63	1.14-2.32
5.89 + (EMP/cc)*years	49/152	1.25	0.86-1.82

CI, confidence interval; EMP, elongate mineral particle.
[a]Defined as consensus of two B-readers for any pleural abnormality.
[b]Results adjusted for age, gender, BMI, smoking status, hematite years, probability of asbestos exposure in taconite industry job category, and potential outside asbestos exposure.
[c]With adjustment for taconite employment years; without adjusting for taconite employment years, $P = -1.00$ (0.96-1.05).

samples, and historical measurements done within the companies or by the Mining Safety and Health Administration. The latter data were limited in scope, particularly prior to the regulatory era (mid-1970s). This likely introduced some exposure misclassification although the direction of bias of prevalence ratio estimates is uncertain. In the assessment of pleural abnormalities, it is known that the interpretation of chest radiographs may be influenced by such factors as body habitus and the presence of sub-pleural fat. We attempted to control for these factors but without confirmatory testing by additional imaging the amount of diagnostic error is uncertain.

TABLE 5 Parenchymal abnormality associated with duration of employment and EMP exposure

	Abnormalities[a] yes/no	Prevalence ratio[b]	95% CI[b]
Overall employment (years)			
Taconite employment duration	64/1118	1.01	0.98-1.03
Hematite employment duration	11/96	1.03	0.97-1.09[c]
Cumulative exposure			
(EMP/cc)*years	64/1118	0.98	0.91-1.06
Taconite employment duration category			
0< years <21	14/412		Ref
21+ years	50/706	1.14	0.64-2.02
Exposure category			
0< (EMP/cc)*years <3.29	35/719		Ref
3.29 + (EMP/cc)*years	29/399	0.79	0.48-1.30[d]

EMP, elongate mineral particle.
[a]Defined as profusion category 1/0 or greater by consensus of two B-readers.
[b]Results adjusted for age, gender, BMI, smoking status, hematite years, probability of asbestos exposure in taconite industry job category, and outside job with risk of asbestos exposure.
[c]With adjustment for taconite employment years; without adjusting for taconite employment years, PR = 1.02 (0.97-1.08).
[d]With cutoff of 1.16 (Q1 as reference quartile), PR = 0.97 (0.57-1.64).

5 | CONCLUSION

In this study of chest x-rays in Northern Minnesota taconite workers and their spouses, we found increased rates of pleural abnormalities in workers when compared to general population studies, and other surveys of exposed populations, and some evidence of an association with cumulative EMP exposure. This association was not specific to the geographic region where amphibole non-asbestiform EMPs exist naturally. We found no evidence of radiographic abnormalities related to secondary domestic exposures. Further study is needed to clarify the nature and source of the EMP exposure due to taconite mining and processing.

AUTHORS' CONTRIBUTIONS

Dr JHM was the principal investigator of the Taconite Workers Health Study and participated in all aspects of the study including design, data acquisition, and analysis as well as the drafting and revising the manuscript. Dr DP was involved in the design, oversaw implementation of the respiratory health survey and was principally responsible for drafting and revising the manuscript. Drs NO, CL, BHA, AR, and RFM were responsible for creating the exposure matrix models, creating the population sampling parameters, and for the statistical analysis of the data. Dr GR is an expert in industrial hygiene and oversaw the planning and execution of the exposure assessment. All authors had final approval of the manuscript prior to submission.

ACKNOWLEDGMENT

Thanks are extended to Leslie Studenski and Diane Kampa for their assistance in the conduct of this investigation.

FUNDING

Grant sponsor: State of Minnesota; Grant Title: Minnesota Taconite Workers Health Study.

ETHICS APPROVAL AND INFORMED CONSENT

The University of Minnesota Institutional Review Board Human Subjects Research Committee approved the protocol for this study. All participants were guided through an informed consent process and written consent obtained prior to their participation.

DISCLOSURE (AUTHORS)

The authors declare no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

Rodney Ehrlich declares that he has no competing or conflicts of interest in the review and publication decision regarding this article.

DISCLAIMER

None.

ORCID

David Perlman http://orcid.org/0000-0001-7055-0970

REFERENCES

1. Berndt ME, Brice WC. The origins of public concern with taconite and human health: reserve Mining and the asbestos case. *Regul Toxicol Pharmacol*. 2008;52:S31–S39.
2. Axten CW, Foster D. Analysis of airborne and waterborne particles around a taconite ore processing facility. *Regul Toxicol Pharmacol*. 2008;52:S66–S72.
3. Cook PM, Glass GE, Tucker JH. Asbestiform amphibole minerals: detection and measurement of high concentrations in municipal water supplies. *Science*. 1974;185:853–855.
4. Case BW, Abraham JL, Meeker G, Pooley FD, Pinkerton KE. Applying definitions of "asbestos" to environmental and "low-dose" exposure levels and health effects, particularly malignant mesothelioma. *J Toxicol Environ Health B Crit Rev*. 2011;14:3–39.
5. Allen EM, Alexander BH, MacLehose RF, Ramachandran G, Mandel JH. Mortality experience among Minnesota taconite mining industry workers. *Occup Environ Med*. 2014;71:744–749.
6. Allen EM, Alexander BH, MacLehose RF, et al. Occupational exposures and lung cancer risk among Minnesota taconite mining workers. *Occup Environ Med*. 2015;72:633–639.
7. Lambert CS, Alexander BH, Ramachandran G, et al. A case-control study of mesothelioma in Minnesota iron ore (taconite) miners. *Occup Environ Med*. 2016;73:103–109.
8. NIOSH. Asbestos fibers and other elongate mineral particles: state of the science and roadmap for research. In: *Health NIfOSa*. eds. Vol 62. Cincinnati, Ohio: Department of Health and Human Services; 2011.
9. Addison J, McConnell E. A review of carcinogenicity studies of asbestos and non-asbestos tremolite and other amphiboles. *Regul Toxicol Pharmacol*. 2008;52:S187–S199.
10. Gamble JF, Gibbs GW. An evaluation of the risks of lung cancer and mesothelioma from exposure to amphibole cleavage fragments. *Regul Toxicol Pharmacol*. 2008;52:S154–S186.
11. Mossman BT. Assessment of the pathogenic potential of asbestiform vs. nonasbestiform particulates (cleavage fragments) in in vitro (cell or organ culture) models and bioassays. *Regul Toxicol Pharmacol*. 2008;52:S200–S203.
12. Hwang J, Ramachandran G, Raynor PC, Alexander BH, Mandel JH. Comprehensive assessment of exposures to elongate mineral particles in the taconite mining industry. *Ann Occup Hyg*. 2013;57:966–978.
13. Harper M, Lee EG, Doorn SS, Hammond O. Differentiating non-asbestiform amphibole and amphibole asbestos by size characteristics. *J Occup Environ Hyg*. 2008;5:761–770.
14. Hwang J, Ramachandran G, Raynor PC, Alexander BH, Mandel JH. The relationship between various exposure metrics for elongate mineral particles (EMP) in the taconite mining and processing industry. *J Occup Environ Hyg*. 2014;11:613–624.
15. Jirsa MA, Miller JD Jr, Morey GB. Geology of the biwabik iron formation and duluth complex. *Regul Toxicol Pharmacol*. 2008;52:S5–s10.
16. McSwiggen PL, Morey GB. Overview of the mineralogy of the biwabik iron formation, mesabi iron range, northern minnesota. *Regul Toxicol Pharmacol*. 2008;52:S11–S25.

17. Ross M, Nolan RP, Nord GL. The search for asbestos within the Peter Mitchell Taconite iron ore mine, near Babbitt, Minnesota. *Regul Toxicol Pharmacol*. 2008;52:S43–S50.
18. Hwang J. *A comprehensive assessment of present-day exposures to respirable dust and silica in the taconite mining industry*. Minneapolis, MN: Division of Environmental Health Sciences, School of Public Health, University of Minnesota; 2013.
19. Honda Y, Beall C, Delzell E, Oestenstad K, Brill I, Matthews R. Mortality among workers at a talc mining and milling facility. *Ann Occup Hyg*. 2002;46:575–585.
20. Steenland K, Brown D. Mortality study of gold miners exposed to silica and nonasbestiform amphibole minerals: an update with 14 more years of follow-up. *Am J Ind Med*. 1995;27:217–229.
21. Cooper WC, Wong O, Trent LS, Harris F. An updated study of taconite miners and millers exposed to silica and non-asbestiform amphiboles. *J Occup Med*. 1992;34:1173–1180.
22. Higgins IT, Glassman JH, Oh MS, Cornell RG. Mortality of Reserve Mining Company employees in relation to taconite dust exposure. *Am J Epidemiol*. 1983;118:710–719.
23. Clark TC, Harrington VA, Asta J, Morgan WK, Sargent EN. Respiratory effects of exposure to dust in taconite mining and processing. *Am Rev Respir Dis*. 1980;121:959–966.
24. Ferrante D, Bertolotti M, Todesco A, Mirabelli D, Terracini B, Magnani C. Cancer mortality and incidence of mesothelioma in a cohort of wives of asbestos workers in casale monferrato, Italy. *Environ Health Perspect*. 2007;115:1401–1405.
25. Magnani C, Dalmasso P, Biggeri A, Ivaldi C, Mirabelli D, Terracini B. Increased risk of malignant mesothelioma of the pleura after residential or domestic exposure to asbestos: a case-control study in Casale Monferrato, Italy. *Environ Health Perspect*. 2001;109:915–919.
26. ILO. *Guidelines for the use of the International Labor Organization International Classification of Radiographs of Pneumoconioses*. Revised Eds. Vol 22. Geneva, Switzerland: International Labor ORganization; 2000.
27. Castellan RM, Sanderson WT, Petersen MR. Prevalence of radiographic appearance of pneumoconiosis in an unexposed blue collar population. *Am Rev Respir Dis*. 1985;131:684–686.
28. Hillerdal G. pleural plaques: incidence and epidemiology, exposed workers and the general population: a review. *Indoor Built Environ*. 1997;6:86–95.
29. Miller JA, Zurlo JV. Asbestos plaques in a typical Veteran's hospital population. *Am J Ind Med*. 1996;30:726–729.
30. Muller JG, Bohnker BK, Philippi AF, Litow FK, Rudolph G, Hernandez JE. Trends in pleural radiographic findings in the navy asbestos medical surveillance program (1990–1999). *Mil Med*. 2005;170:375–380.
31. Paris C, Martin A, Letourneux M, Wild P. Modelling prevalence and incidence of fibrosis and pleural plaques in asbestos-exposed populations for screening and follow-up: a cross-sectional study. *Environ Health*. 2008;7:30.
32. Dixon G, Doria J, Freed J, et al. *Exposure Assessment for Asbestos-Contaminated Vermiculite*. In: Agency EP, eds. Washington, DC: Office of Toxic Substances; 1985.
33. Peipins LA, Lewin M, Campolucci S, et al. Radiographic abnormalities and exposure to asbestos-contaminated vermiculite in the community of Libby, Montana, USA. *Environ Health Perspect*. 2003;111: 1753–1759.
34. Alexander BH, Raleigh KK, Johnson J, et al. Radiographic evidence of nonoccupational asbestos exposure from processing libby vermiculite in minneapolis, minnesota. *Environ Health Perspect*. 2012;120:44–49.
35. Peacock C, Copley SJ, Hansell DM. Asbestos-related benign pleural disease. *Clin Radiol*. 2000;55:422–432.
36. Gevenois PA, de Maertelaer V, Madani A, Winant C, Sergent G, De Vuyst P. Asbestosis, pleural plaques and diffuse pleural thickening: three distinct benign responses to asbestos exposure. *Eur Respir J*. 1998;11:1021–1027.
37. Yano E, Tanaka K, Funaki M, Maeda K, Matsunaga C, Yamaoka K. Effect of smoking on pleural thickening in asbestos workers. *Br J Ind Med*. 1993;50:898–901.
38. Uibu T, Oksa P, Auvinen A, et al. Asbestos exposure as a risk factor for retroperitoneal fibrosis. *Lancet*. 2004;363:1422–1426.
39. Villeneuve PJ, Parent M, Harris SA, Johnson KC. Occupational exposure to asbestos and lung cancer in men: evidence from a population-based case-control study in eight Canadian provinces. *BMC Cancer*. 2012;12:595.
40. Lee YC, Runnion CK, Pang SC, de Klerk NH, Musk AW. Increased body mass index is related to apparent circumscribed pleural thickening on plain chest radiographs. *Am J Ind Med*. 2001;39:112–116.
41. Larson TC, Franzblau A, Lewin M, Goodman AB, Antao VC. Impact of body mass index on the detection of radiographic localized pleural thickening. *Acad Radiol*. 2014;21:3–10.
42. Meyer JD, Islam SS, Ducatman AM, McCunney RJ. Prevalence of small lung opacities in populations unexposed to dusts. A literature analysis. *Chest*. 1997;111:404–410.
43. Hughes JM, Weill H, Checkoway H, et al. Radiographic evidence of silicosis risk in the diatomaceous earth industry. *Am J Respir Crit Care Med*. 1998;158:807–814.
44. Koskinen HO, Nordman HL, Zitting AJ, et al. Fibrosis of the lung and pleura and long-term exposure to wollastonite. *Scand J Work Environ Health*. 1997;23:41–47.

How to cite this article: Perlman D, Mandel JH, Odo N, et al. Pleural abnormalities and exposure to elongate mineral particles in Minnesota iron ore (taconite) workers. *Am J Ind Med*. 2018;61:391–399. https://doi.org/10.1002/ajim.22828