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Mesothelioma Risks and Cumulative Exposure to Elongate Mineral Particles of Various Sizes in Minnesota Taconite Mining Industry

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Abstract

OBJECTIVES: An excess of mesothelioma has been previously observed in iron ore miners in Northeastern Minnesota. This study explored the potential association between mesothelioma and elongate mineral particle (EMP) exposures in the Minnesota taconite mining industry, examining both regulated and non-regulated EMP dimensions.

METHODS: A nested case-control study design within the Mineral Resources Health Assessment Program cohort analyzed 104 mesothelioma cases and 410 controls. Cumulative EMP exposures were assessed across various dimensional definitions, including regulated (NIOSH) and non-regulated EMPs. Conditional logistic regression models were applied to estimate mesothelioma risk linked to employment duration and cumulative EMP exposure, while adjusting for potential confounding variables.

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CONTRIBUTORSHIP STATEMENT

YS led the analysis and interpretation of the data, wrote the first draft of the manuscript, and contributed to its revision. JM contributed to the acquisition of the medical data and provided valuable insights during the analysis. RM assisted with data interpretation and played a key role in refining the statistical analysis, contributing to the manuscript revision. GR was involved in the conception of the study, contributed to the interpretation of the results, and participated in the manuscript editing process. BA, as both the guarantor and corresponding author, ensured the accuracy and integrity of the research. All authors contributed to the planning, execution, and reporting of the work and approved the final version of the manuscript.

ETHICS APPROVAL

The research was reviewed and approved by the University of Minnesota Human Subjects Research Committee. The research was determined as Not Human Subjects Research (0709S16941).

DISCLAIMER

The authors declare that there are no conflicts of interest relating to the material in relation to this article. The opinions expressed in this publication are those of the authors and do not express the views of the State of Minnesota.

RESULTS: Consistent with earlier assessments, mesothelioma was associated with the number of years employed in the taconite industry (RR = 1.02, 95% CI 1.00 to 1.05) and cumulative NIOSH EMP exposure ((EMP/cc)×years) in taconite mining and processing (RR = 1.20, 95% CI 0.99 to 1.46). Positive associations were also observed with mesothelioma and cumulative exposure to non-regulated EMPs.

CONCLUSIONS: This study supported the main conclusions in the previous study, that the data were consistent with an association between mesothelioma and employment duration and with NIOSH EMP exposure in taconite mining and processing. However, the 95%CI indicates the data are also compatible with a null effect. Given the limitations we cite in the manuscript, additional study is needed to clarify the effect. Additionally, this study found possible evidence of a positive association between mesothelioma and cumulative exposure to Chatfield EMP, Suzuki EMP and Cleavage Fragments in the Minnesota taconite worker population.

Keywords

Mesothelioma risk; Cumulative exposure; EMP dimensions; Non-asbestiform EMPs

INTRODUCTION

The mining of taconite (low-grade iron ore) began in the 1950s in northeastern Minnesota Mesabi Iron Range after the depletion of hematite reserves [1]. This region has been a major supplier of iron ore to the North American steel manufacturing industry, accounting for around 75% of the total U.S. iron ore production [2]. The crushing of the taconite ore releases a significant amount of dust that includes Elongate Mineral Particles (EMPs), which pose a potential respiratory threat. In 1983, to study the potential occupational risk, a cohort that included 68,737 individuals who had ever worked in the mining industry in northeastern Minnesota between the 1930s and the end of 1982 was enumerated [3]. In 1997, the Minnesota Department of Health first documented the rates of mesothelioma and other cancers in Northeastern Minnesota [4] and subsequent reports in 2003 and 2007 showed a 2.9-fold increase in the rate of mesothelioma in the mining region compared with all other Minnesota regions [5,6].

To investigate the potential causes of these elevated mesothelioma rates among the taconite miners, the Minnesota State Legislature funded the Taconite Workers Health Study (TWHS) in 2008. A series of investigations, including exposure assessments for taconite dust, pulmonary function testing, and epidemiological analyses have been conducted, and the summary of these investigations can be found elsewhere [7,8]. A case-control study of mesothelioma [9] found that risk of mesothelioma was associated with the number of years employed in the taconite industry (RR=1.03 per taconite year, 95% CI 1.00 to 1.06) and cumulative exposure to EMPs as determined by the NIOSH 7400 method (National Institute for Occupational Safety and Health) with length >5µm and aspect ratio ≥ 3 (RR=1.10 per (EMP/cc)×year, 95% CI 0.97 to 1.24). Risks associated with EMPs of any other dimensions were not evaluated.

In the US, regulatory agencies such as the Occupational Safety and Health Administration (OSHA) regulate six commercial asbestiform minerals (actinolite asbestos, amosite asbestos,

anthophyllite asbestos, chrysotile asbestos, crocidolite, and tremolite asbestos). These asbestos standards do not include regulations for non-asbestiform EMPs. The mining and processing of taconite ore can generate non-asbestiform EMPs (e.g. cummingtonite-grunerite, Langer et al., 1979 [10]). The health effects of non-regulated EMPs, which include both non-asbestiform variants and asbestiform minerals not covered by existing regulations, are not well established, with some research [11,12] indicating some potential risk. For instance, a study conducted by Metintas et al., in 2010 found that the elevated risk of mesothelioma in Karain, Turkey resulted from indoor exposure to erionite, an asbestiform mineral not currently regulated. In another case, in Taiwan [12], stone workers exposed to nephrite (the non-asbestiform counterpart of tremolite asbestos) exhibited pulmonary fibrosis.

The EMP dimension (width and length) is considered a crucial characteristic when assessing health risk with longer EMPs potentially more potent in the development of asbestos-related diseases than shorter EMPs [13–15]. Current regulations in the US (29 CFR 1910.1001) only address EMPs equal to or greater than 5 μm with a minimum aspect ratio of 3:1. In 2003, in the report of the “Peer Consultation Workshop to Discuss a Protocol to Assess Asbestos–Related Risk” [16], panelists agreed that “the available data suggest that the risk for EMPs less than 5 μm in length is very low and could be zero. Some panelists suggested that, for mesothelioma, greater weight should perhaps be assigned to fibers in the 5 to 10 μm length range and to thinner fibers.” However, other researchers have argued EMPs of all sizes, both long and short, should be regarded as potential contributors to asbestos-related diseases [17,18].

To further explore the potential associations between mesothelioma and non-asbestiform EMP exposures in the taconite industry we present a case-control study with updated case ascertainment and assessments of EMP exposure [19,20]. In this analysis we specifically evaluate the mesothelioma risks associated with non-asbestiform EMPs of various dimensions.

METHODS

Study design and population

The Mineral Resources Health Assessment Program (MRHAP) cohort was enumerated by the University of Minnesota in 1983 with the support of the Iron Range Resources and Rehabilitation Board (IRRRB) and the cooperation of the seven mines then in operation and included 68,737 individuals identified in employee records from the mining industry in northeastern Minnesota before 1983. It included workers employed in either the hematite and/or taconite industry. The MRHAP cohort was followed for vital status through 2010 (Allen et al., 2014). Vital status was ascertained using the Social Security Administration, the National Death Index, and the Minnesota Department of Health and state death certificates outside of Minnesota. All deaths were coded to the International Classification of Disease (ICD) codes in effect at the time of death.

Selection of cases and controls

Cases of mesothelioma were identified through the Minnesota Cancer Surveillance System (MCSS) and/or death certificates for out of state mesothelioma cases. In addition to the original 80 mesothelioma cases in the Lambert et al. (2016) study, 24 additional cases were identified with the MCSS through 2016. Mesothelioma in MCSS was histologically confirmed and coded using ICD-O-3 histology codes 9050–9053 and cases from death certificates were identified as ICD 10th Revision code C45. Versions prior to the 10th revision of ICD did not have a code specifically for mesothelioma. Four controls were selected for each case using an incidence density sampling approach from risk sets of cohort members of similar age (years of birth $\pm$ 2 years). Controls for the 80 cases in the Lambert et al. (2016) study were alive and without a diagnosis of mesothelioma on the date of diagnosis or death of the case. The controls for the newly added 24 cases were alive as of the last full vital status ascertainment (2010). All cases and controls had to have clear evidence of employment in the mining industry based on review of work history records obtained when MRHAP cohort was enumerated. The final study population in the current study included 104 cases and 410 controls. The study was approved by the University of Minnesota Human Subjects Research Committee (Reference number 0709S16941).

Exposure assessment

The detailed exposure assessment work for this study can be found elsewhere [19–21]. In brief, seven taconite mines of the Mesabi Iron Range were associated with this study. For confidentiality purposes, these mines were coded as Mine A to Mine G. Mines A and G were located on the eastern side (Zone 2 and Zone 4) of the range, and Mines B to F were on the western side (Zone 1). The opening year of these mines varied, ranging from 1955 to 1977 [22]. As of 2010, six mines were still in operation and one closed in 2001. The previous TWHS investigations, grouped taconite worker job titles into 28 similar exposure groups (SEG) within eight departments [23] and created a job exposure matrix (JEM) for EMP in these SEGs based on current and historical NIOSH 7400 phase-contrast microscopy (PCM) monitoring.

Four JEMs were used in this updated study. Details about how they were formed can be found elsewhere [19,20]. In brief, all JEMs were for EMP exposures, but each represented a unique EMP dimension range (see Table 1). The NIOSH EMP JEM provided yearly-averaged NIOSH EMP concentration estimates in the workplace for each mine-department combination and calendar year. Concentration estimates were created based upon 2036 historical NIOSH 7400 measurements and the historical reconstruction strategy described in Shao et al., 2019. The NIOSH EMP definition is used for regulatory purposes and is the same criteria used in our previous mesothelioma study. The JEMs for the other three EMP definitions were created by applying the department-level conversion factors to the NIOSH EMP JEM. These conversion factors were estimated based on probability density functions derived from actual dimensional information of 11,147 individual EMPs, which were associated with 1268 personal EMP samples analyzed using the ISO 10312 or 13794 transmission electron microscopy (TEM) methods, collected in the Minnesota taconite mines. The Chatfield EMPs refer to EMPs that meet the dimensional criteria proposed by Chatfield in 2008 [24]. He observed the dimensional difference between pre-

determined asbestiform amphibole fibers and non-asbestiform amphibole fibers, and found that asbestiform ones were more likely to be thinner and longer. The Suzuki EMPs were defined here as the EMPs that were less than or equal to 5µm in length and 0.25µm in width. Suzuki et al. reported in 2005 that the majority of the asbestiform fibers in the human lung and mesothelial tissues examined were within this range. The Cleavage Fragments here were defined as any EMPs with less than 20:1 aspect ratio [25,26].

Work history and cumulative EMP exposure calculation

Work history information for cases and controls, including all job titles and dates of employment, was abstracted from available mining company work records from the 1950s through the end of 1982. All job titles were standardized into 28 SEGs of 8 departments. Some study subjects worked in the earlier hematite industry. Hematite as a “direct shipping ore” did not require the processing and concentrating techniques of taconite and no historical EMP samples were available during the hematite production period. Therefore, EMP exposure levels for the hematite mining period were set to zero. For each study subject, we estimated cumulative exposure values based on each of four EMP JEMs: “NIOSH EMP”, “Chatfield EMP”, “Suzuki EMP”, “Cleavage Fragments.” Cumulative exposure was calculated as the sum of the products of time/location-specific exposure concentrations and the time each individual spent in each exposure category, i.e., in units of (EMP/cc)×years. Commercial asbestos was likely used in some operations of the processing, but no historical measurements were available for commercial asbestos exposure in these operations. The study team and industrial hygienists from the taconite companies assessed the likelihood and frequency of exposure to commercial asbestos within each SEG and assigned a commercial asbestos score (low, medium, or high) accordingly. Ultimately, the number of years worked in an SEG with a high commercial asbestos score was used as a surrogate metric for historical commercial asbestos exposures. A sensitivity analysis was conducted to evaluate how the choice of a commercial asbestos surrogate metric would affect the estimation of mesothelioma risk.

Analysis

Descriptive analyses were performed to assess the relationship between demographic and occupational factors and case/control status. Conditional logistic regression was used to estimate the effect occupational exposure to EMP and risk of mesothelioma for a unit change in exposure variables (1 taconite year or 1 cumulative exposure value EMP/cc×year). The main exposure was either years of employment in taconite mining or cumulative exposure to EMP (either NIOSH, Chatfield, Suzuki, or Cleavage fragments). When taconite mining was the main exposure, only years in the taconite industry counted toward the number of years. Years in hematite mining were not included in the taconite years exposure. Taconite-year equals to 0 for the hematite only workers. Separate models were fit for each exposure definition (NIOSH, Chatfield, Suzuki, Cleavage) and used cumulative exposure value in EMP/cc×year as the primary exposure. Models that included two EMP exposure terms were used to explore the effects of the Chatfield, Suzuki, Cleavage exposure definitions while controlling for the NIOSH EMP exposure. The conditional logistic regression approach accounted for the person-time matching of cases and controls within risk sets and results are reported as rate ratios and 95% confidence intervals. The final

models incorporated the following two additional confounders: number of years employed in hematite mining, and duration of work in SEGs with a high commercial asbestos score. All statistical analyses were conducted using SAS (version 9.4, SAS Institute, Cary NC).

RESULTS

Characteristics of cases and controls

A total of 104 cases and 410 controls were included in the study (Table 2). All cases and 94% of controls were male. A greater proportion of cases (71 out of 104) were taconite workers compared to the controls (236 out of 410). While the duration of hematite employment was similar for both groups, cases had a higher median number of years working with taconite. Among those who had ever worked in taconite mines, a larger percentage of cases were associated with Zone 2, and they also had a higher median number of years in this zone compared to the controls. The cumulative exposure values of all four EMP types for cases were higher than for controls. Median years spent in SEGs with a high commercial asbestos score were the same between the controls and the cases.

Taconite employment duration

The risk of mesothelioma was associated with the number of years of employment in the taconite mining industry (RR = 1.02, 95% CI 1.00 to 1.05) (Table 3). However, the Model dividing workers into categories based on the median length of employment of cases did not reveal an increased risk associated with longer tenure. The mesothelioma risk increased with duration of employment in both Zone 1 and Zone 2, but was not associated with duration of employment in Zone 4. The associations observed with employment duration were consistent with findings from the previous study.

Cumulative exposure to EMPs of varying dimensions

Cumulative exposure to NIOSH EMP (EMP/cc×years) was associated with an increased risk of mesothelioma (RR=1.20, 95% CI 0.99 to 1.46) (see Table 4). Cumulative exposure to the other three EMPs were all positively associated with the risk of mesothelioma: RR = 2.85 (95% CI of 0.97 to 8.40) for the Chatfield EMP, 1.04 (95% CI of 1.00 to 1.09) for the Suzuki EMP, and 1.03 (95% CI of 1.00 to 1.06) for the Cleavage Fragments. Additionally, a sensitivity analysis was conducted by switching the default commercial asbestos metric from the number of years in SEGs with a high asbestos score to the total number of years in SEGs with a medium or high asbestos score. This change resulted in stronger estimation results: RR = 1.42 (95% CI of 1.06 to 1.90) for the NIOSH EMP, 3.70 (95% CI of 1.11 to 12.27) for the Chatfield EMP, 1.05 (95% CI of 1.00 to 1.10) for the Suzuki EMP, and 1.04 (95% CI of 1.01 to 1.08) for the Cleavage Fragments.

In our study population, all EMP definitions were positively correlated to varying degrees, (Figure 1). The Pearson correlation coefficients (r) between NIOSH EMP and Chatfield EMP, Suzuki EMP, and Cleavage Fragments were 0.53, 0.66, and 0.84, respectively. The correlation between Chatfield EMP and Suzuki EMP was $r=0.88$. The degree of this correlation and the relatively small number of cases made separating the independent effects of the non-NIOSH EMPs challenging. In models adjusting for NIOSH EMP exposure, the

estimates for the Chatfield EMP, Suzuki EMP, and Cleavage Fragments remained positive but were attenuated and less precise (RR = 2.19 (95% CI of 0.69 to 6.96), 1.03 (95% CI of 0.98 to 1.09), and 1.02 (95% CI of 0.98 to 1.07) respectively).

DISCUSSION

Similar to the previously published work [9], in this updated analysis with an additional 24 cases of mesothelioma, we observed associations between mesothelioma risk and continuous duration of employment in the taconite industry and cumulative exposure to regulated EMPs as characterized by the NIOSH 7400 method. We also observed associations between mesothelioma risk and cumulative exposure to EMPs with sizes that fell outside the regulated dimensions.

Any particles that have a length to width ratio of no less than 3:1 can be called elongate mineral particles. They can be categorized based on several factors [27]: their chemical composition (organic or inorganic), mineralogical habit (asbestiform or non-asbestiform), and formation (natural or man-made). This complexity makes it challenging to communicate the risks associated with EMP toxicity and to compare findings across different studies. . Although the association between mesothelioma and regulated asbestiform EMPs is well-established, there is limited knowledge regarding the risk posed by non-asbestiform EMPs, including Minnesota taconite EMPs [28]. In March 2024, taconite was listed by the International Agency for Research on Cancer (IARC) Monographs program as one of the agents recommended for high-priority evaluation during 2025–2029 due to its significant evidence of human cancer relevance[29].

The EMP dimensions (width and length) are important characteristics to consider when assessing their health risk. Longer EMPs are often considered more potent in the development of asbestos-related diseases than shorter EMPs. In this case-control study, we selected four metrics of EMP exposures based on different dimensional definitions (NIOSH EMP, Suzuki EMP, Chatfield EMP, and Cleavage Fragments), and estimated the mesothelioma risk for each of them. All EMP metrics were positively associated with mesothelioma, with the long Chatfield EMPs having a stronger association with than other dimensions. While this conforms to the theory of longer EMPs being more toxic, our results do not rule out the potential for a risk associated with shorter EMPs, which are more numerous in this workplace.

One challenge when studying the health risks of EMP is the lack of EMP habit information in historical sample analysis. In mineralogy, fiber habit has a clean definition, and one can easily tell whether a bundle of fibers in a rock sample are asbestiform (thin, hairlike fibers, for example) or non-asbestiform EMPs from their morphology. But in industrial hygiene practice, when single form fibers are often observed under either conventional PCM or advanced TEM, it's nearly impossible to distinguish between asbestos and non-asbestos fibers [30]. For example, the ISO 10312:2019 TEM method explicit states that “The standard’s reference method cannot discriminate between individual fibers of asbestos and elongate fragments (cleavage fragments and acicular particles) from non-asbestos analogues of the same amphibole mineral.” Because of this technical difficulty, researchers in the EMP

field proposed dimension-based approaches to address this issue. For example, Chatfield (2001) [31] proposed that “with the light microscope, the asbestiform habit is generally recognized by the following characteristics: mean aspect ratios ranging from 20:1 to 100:1 or higher for fibers longer than 5 μm .” In our study, we adopted this asbestiform EMP definition to examine the association between mesothelioma and hypothetical “asbestiform” taconite EMPs.

Another challenge encountered in the study of EMP health risks involves the potential for high correlations between different EMP types. Our correlation analysis revealed positive associations among all EMP variables, suggesting the coexistence of both short EMPs and long EMPs in the workplace. This implies that workers were likely exposed to EMPs of varying sizes simultaneously. In addition, we found that commercial asbestos, which was not generated from taconite mining itself, was not correlated with any of the cumulative EMP exposure variables in our study population (Pearson correlation coefficients ranged from 0.12 to 0.21).

Limitations

In this study, we were not able to update the vital status of the entire MRHAP cohort. All new mesothelioma cases were cases identified through MCSS system in Minnesota. It is possible that we missed out-of-state cases this time. Also, some new controls who were alive in 2010 may have died prior to the diagnosis of mesothelioma of the matched case. This would affect the final results if the deceased controls of similar age had an exposure experience that was not representative of the MRHAP cohort. However, no additional exposure was ascertained for either cases or controls after 1982.

Exposure reconstruction in this investigation was based on available work history information. This information was available through the end of 1982. It's likely that some study subjects were still working after this point in time. If that were the case, then the life-time exposure values estimated for these subjects could be lower than their actual exposures, but the extent to which this might differ between cases and controls was not known. To partially address this limitation, we ran models with 0, 20 and 30-year latency, thus cases and controls had similar measures of missing data. The associations found in the exposure lagged models were similar to those for non-lagged models. Additionally, there is the potential for a healthy worker survivor bias, however the lack of complete work histories for cohort members employed after 1982 limits the potential for analyses that effectively adjust for such bias.

Uncertainties in historical exposure reconstruction [19,20] may also influence the efficacy of our epidemiological analysis: (1) Our NIOSH EMP JEM was developed using data from about 2000 historical NIOSH 7400 PCM measurements with the earliest measurement dating back to 1978, over two decades after the inception of the Minnesota taconite industry. (2) Historical exposure to other EMP metrics were entirely unknown from historical PCM measurements. To estimate these exposures from NIOSH EMP JEM, we examined up to 11,147 individual TEM EMPs collected from six study mines active in 2010, and applied a bivariate normal distribution assumption to characterize the overall size distribution of EMPs.

CONCLUSION

This study supported the main conclusions in the previous study, that the data were consistent with an association between mesothelioma and employment duration and with NIOSH EMP exposure in taconite mining and processing. However, the 95%CI indicates the data are also compatible with a null effect. Given the limitations we cite in the manuscript, and sensitivity to parameterization of employment duration, additional study is needed to clarify the effect. Additionally, we found possible evidence of a positive association between mesothelioma and cumulative exposure to Chatfield EMP, Suzuki EMP and Cleavage Fragments in the Minnesota taconite worker population, but we were not able to clearly identify the independent effects of the various EMP subtypes.

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- **What is already known on this topic:** Previous research highlighted associations between mesothelioma and employment duration, as well as cumulative exposure to elongate mineral particles (EMPs) as determined by the NIOSH 7400 method. However, the health effects of non-asbestiform EMPs, which are generated during taconite mining, were not clear. This study aimed to fill this gap by evaluating mesothelioma risk associated with non-regulated EMP exposures, focusing on EMPs of different dimensions.
- **What this study adds:** This study adds insights into the association between mesothelioma and various EMP exposures in the taconite mining industry. The findings reaffirm the previous observations regarding the association between mesothelioma and employment duration, as well as NIOSH EMP exposure. Additionally, this study revealed positive associations between mesothelioma and cumulative exposure to non-regulated EMPs of different dimensions, including Chatfield EMP, Suzuki EMP, and Cleavage Fragments. These findings contribute to a better understanding of the health risks posed by EMPs beyond those covered by current regulations.
- **How this study might affect research, practice or policy:** This study underscores the importance of research into potential health effects of non-regulated EMPs, particularly in settings without exposure to the long thin EMPs that are believed to be more toxic.

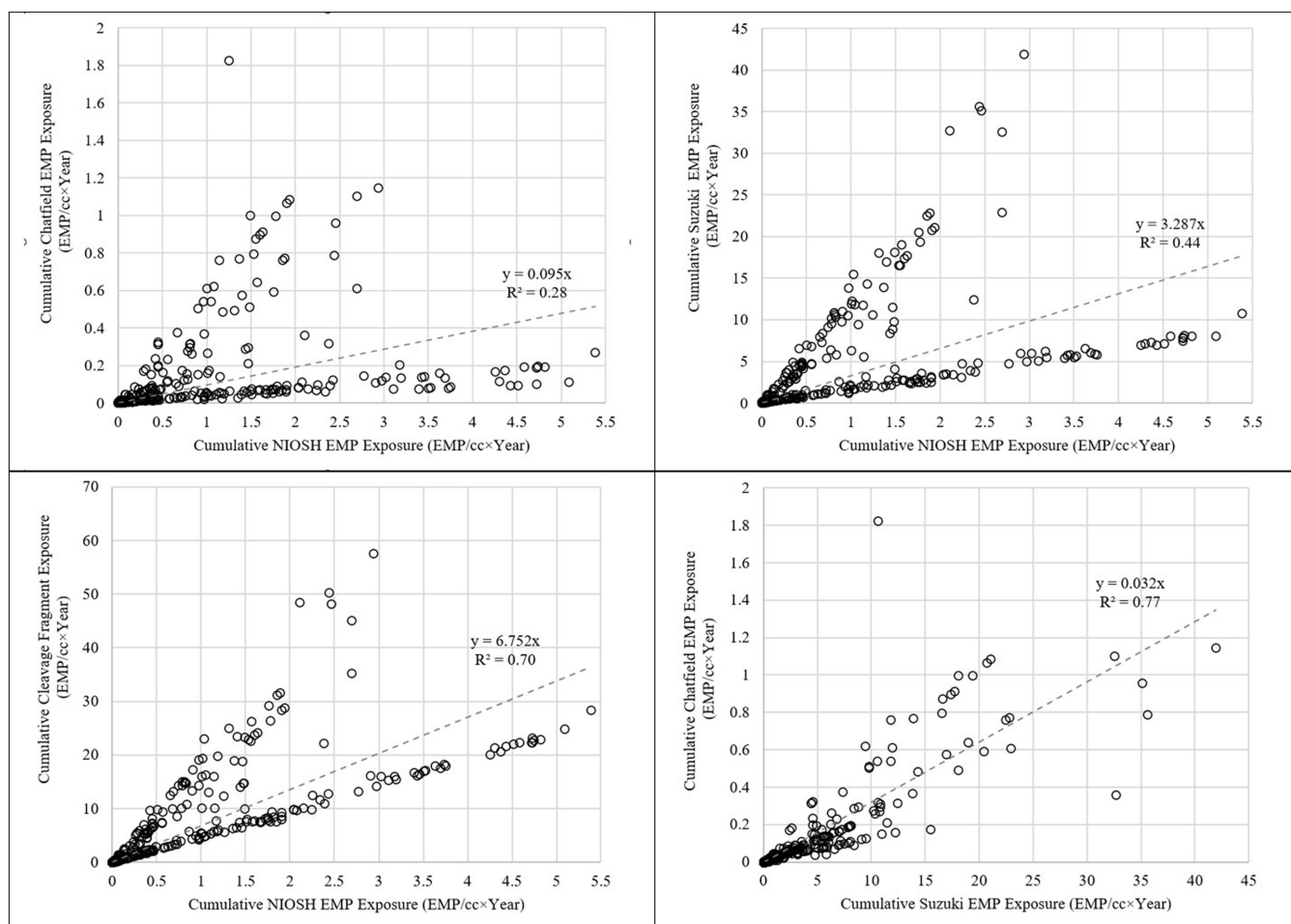


Figure 1.
Correlation Plots for EMP Variables (study population: 514)

Table 1

EMP definitions considered in this study

#	EMP definitions	Width (µm)	Length (µm)	Aspect Ratio (AR)
1	NIOSH EMP	NA *	>5	≥3
2	Chatfield EMP	0.04–1.5	NA	20–1000
3	Suzuki EMP	≤0.25	≤5	NA
4	Cleavage Fragments	NA	NA	<20

* EMP less than approximately 0.25 µm in diameter will not be detected by PCM

Table 2

Characteristics of all cases and controls in study population, and cases and controls who worked in taconite mines

All workers	Cases N (%)	Controls N (%)
Total	104	410
Female	0 (0.0)	23 (5.6)
Male	104 (100.0)	387 (94.4)
Type of ore mining		
Hematite only	33 (31.7)	174 (42.4)
Hematite and Taconite	28 (27.0)	96 (23.4)
Taconite only	43 (41.3)	140 (34.2)
Years of employment (years)[†]	Median (Range)	Median (Range)
Taconite employment	1.8 (0–27.6)	0.2 (0–36.3)
Hematite employment	0.2 (0–27.7)	0.4 (0–27.7)
Total employment	3.9 (0–35.2)	2.3 (0–37.3)
Taconite workers	Cases N (%)	Controls N (%)
Total	71	236
Female	0 (0.0)	12 (5.0)
Male	71 (100.0)	224 (95.0)
Geological zone-ever worked *		
Zone 1	24 (32.0)	93 (37.5)
Zone 2	37 (49.3)	69 (27.8)
Zone 4	14 (18.7)	86 (34.7)
Years of employment (years)	Median (Range)	Median (Range)
Total employment	8.4 (0.0–35.2)	8.4 (0.0–37.3)
Hematite employment	0.0 (0–22.3)	0.0 (0–27.7)
Taconite employment		
All workers	7.7 (0–27.6)	6.0 (0–36.3)
Zone 1	8.5 (0.5–19.3)	8.0 (0.0–17.7)
Zone 2	6.0 (0.1–26.0)	2.9 (0.0–26.0)
Zone 4	5.3 (0.0–27.6)	5.4 (0.0–36.3)
Cumulative EMP exposure (EMP/cc)×year	Median (Range)	Median (Range)
NIOSH EMP	0.8 (0.0–4.7)	0.4 (0.0–5.4)
Chatfield EMP	0.0 (0.0–1.8)	0.0 (0.0–1.1)
Suzuki EMP	2.2 (0.0–41.9)	1.8 (0.0–35.6)
Cleavage Fragments	5.7 (0.0–57.6)	4.1 (0.0–50.3)
	Median (Range)	Median (Range)
Employment in SEGs with high commercial asbestos ** (years)	0 (0, 16.4)	0 (0, 22.0)

[†] Employment records were only available till the end of 1982.

* Cases and controls may have worked in multiple zones. The Mesabi Iron Range contains four lateral mineralogical zones. Mines A and G are situated on the eastern side (Zones 2 and 4), while Mines B through F are located on the western side (Zone 1). There are no study mines in Zone 3.

** SEGs with a high asbestos score are crusher maintenance, furnace operator, electrician, carpenter, auto mechanic, pipefitter/plumber, and lubricate technician.

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Table 3

Overall and zone-specific rate ratio estimates for mesothelioma by taconite years

	Cases	Controls	Rate Ratio [†]	95% CI
Taconite years [*]	104	410	1.02	1.00 to 1.05
Hematite years ^{**}	104	410	0.99	0.94 to 1.04
Long vs. Short taconite employment [‡]				
< 7.70 and >0 year	36	128	1	
≥ 7.70 years	35	108	1.04	0.58 to 1.86
0 year (hematite-only workers)	33	174	0.62	0.35 to 1.11
Exposure by geological zone ^{***}				
Zone 1 taconite years	104	410	1.05	0.99 to 1.11
Zone 2 taconite years	104	410	1.05	1.02 to 1.08
Zone 4 taconite years	104	410	0.98	0.94 to 1.02

[†] adjusted for age, employment in hematite, and potential for commercial asbestos exposure.

^{*} include entire study population, taconite-year equals to 0 for the hematite only workers.

^{**} include entire study population, hematite-year equals to 0 for the taconite only workers.

[‡] High group represents workers with employment duration greater than the taconite case median duration.

[§] Based on the lower, middle and upper third of the taconite case employment duration distribution.

^{***} include entire study population, zone-specific year equals to 0 for those who never worked in this zone. The Mesabi Iron Range contains four lateral mineralogical zones. Mines A and G are situated on the eastern side (Zones 2 and 4), while Mines B through F are located on the western side (Zone 1). There are no study mines in Zone 3.

Table 4

Mesothelioma risk estimates for cumulative EMP exposures

			Model adjusting for years of employment in SEGs with a high asbestos score		Model adjusting for years of employment in SEGs with a medium/high asbestos score	
Cumulative EMP exposure ((EMP/cc)×year) *	Cases	Controls	Rate Ratio [†]	95% CI	Rate Ratio [†]	95% CI
NIOSH EMP	104	410	1.20	0.99 to 1.46	1.42	1.06 to 1.90
Chatfield EMP	104	410	2.85	0.97 to 8.40	3.70	1.11 to 12.27
Suzuki EMP	104	410	1.04	1.00 to 1.09	1.05	1.00 to 1.10
Cleavage Fragments	104	410	1.03	1.00 to 1.06	1.04	1.01 to 1.08

* Adjusted for age, employment in hematite, and potential for commercial asbestos exposure. Include entire study population, the cumulative EMP exposure equals to 0 for the hematite only workers.

[†] The rate ratios presented in the table correspond to a one-unit change in cumulative EMP exposure, measured in (EMP/cc)×year.