Radiographic Abnormalities and Exposure to Asbestos-Contaminated Vermiculite in the Community of Libby, Montana, USA

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Mining, handling, processing, and personal or commercial use of asbestos-contaminated vermiculite have led to widespread contamination of the Libby, Montana, area. We initiated a medical testing program in response to reports of respiratory illness in the community. The purpose of this analysis was to identify and quantify asbestos-related radiographic abnormalities among persons exposed to vermiculite in Libby and to examine associations between these outcomes and participants' self-reported exposures. A cross-sectional interview and medical testing were conducted in Libby from July through November 2000 and from July through September 2001. A total of 7,307 persons who had lived, worked, or played in Libby for at least 6 months before 31 December 1990 completed the interview. Of those, 6,668 participants ≥ 18 years of age received chest radiographs to assess the prevalence of pleural and interstitial abnormalities. We observed pleural abnormalities in 17.8% of participants and interstitial abnormalities in < 1% of participants undergoing chest radiography. We examined 29 occupational, recreational, household, and other exposure pathways in the analysis. The prevalence of pleural abnormalities increased with increasing number of exposure pathways, ranging from 6.7% for those who reported no apparent exposures to 34.6% for those who reported ≥ 12 pathways. The factors most strongly associated with pleural abnormalities were being a former W.R. Grace worker, being older, having been a household contact of a W.R. Grace worker, and being a male. In addition to being a former W.R. Grace worker, environmental exposures and other nonoccupational risk factors were also important predictors of asbestos-related radiographic abnormalities. *Key words:* asbestos-related disease, medical screening, pleural plaques, radiographic opacities, radiography, tremolite-actinolite, vermiculite. *Environ Health Perspect* 111:1753–1759 (2003). doi:10.1289/ehp.6346 available via *http://dx.doi.org/* [Online 2 July 2003]

Mining and processing of vermiculite from the world's largest deposit near Libby, Montana, began in the early 1920s and continued for 70 years. In 1963, W.R. Grace acquired the mine from Zonolite Company and operated it until it was closed in 1990. These operations included open-pit mining and on-site milling of the mineral; transporting the raw material by truck and rail to two processing plants in Libby and to plants throughout the United States and Canada, where it was heated and expanded (exfoliated); and finally, shipping the finished product by truck and rail to distribution centers nationally (Myers 1960). Vermiculite is a silicate mineral with the unique property of expanding 8- to 12-fold in volume upon heating (Meisinger 1980; Myers 1960; Otis 1960). Because of its fire-resistant and absorptive properties, vermiculite is used commercially in the construction industry as insulation and filler material, and in agriculture as a soil additive and carrier agent for fertilizers and other chemicals (Lockey 1981; Meisinger 1980). Vermiculite from Montana has been shown to be contaminated with tremolite, actinolite, and other forms of the amphibole series of asbestos, ranging from 2 to 26% in the raw form (Amandus et al. 1987b; Atkinson et al. 1982; Bank 1980; Dixon et al. 1985; Moatmed et al. 1986).

Thus, mining, handling, processing, and personal or commercial use of vermiculite have led to widespread contamination of the Libby area with asbestos-contaminated vermiculite (Dixon et al. 1985).

Although no serious health effects from vermiculite alone have been reported to date (Addison 1995), health effects such as pleural thickening, pleural calcifications, pleural effusions, asbestosis, mesothelioma, and lung cancer from occupational exposure to asbestos have been well documented. Early evidence of pulmonary fibrosis among Libby mine and mill employees was described in an X-ray survey of miners in 1959 (McDonald et al. 1986a). Additional evidence came from a report of 12 cases of pleural effusions over a 12-year period among employees of an Ohio fertilizer plant that processed vermiculite from Libby, followed by a cross-sectional study of workers in the plant that demonstrated a relationship between cumulative fiber exposure and radiographic changes and pleuritic chest pain (Lockey et al. 1984). Two separate but parallel cohort studies of workers at the vermiculite mine in Libby showed excess mortality from lung cancer, malignant mesothelioma, and nonmalignant respiratory disease (Amandus and Wheeler 1987; McDonald et al. 1986a). These same investigators also

conducted radiographic studies of then-current workers and found that the prevalence of pleural thickening and small opacities increased with increasing levels of cumulative fiber exposure (Amandus et al. 1987a; McDonald et al. 1986b). Together, these findings provide substantial evidence that exposure to the amphibole type of asbestos from the Libby vermiculite mine results in adverse respiratory health effects similar to those seen with exposure to other forms of asbestos.

Reported cases of mesothelioma among household contacts of asbestos workers led to a growing concern that asbestos exposure and the risk of later disease could spread beyond the workplace to the home and community (Anderson et al. 1976; Berry 1997; Hansen et al. 1993, 1998; Magnani et al. 2000, 2001; Newhouse and Thomson 1965; Wagner et al. 1960). Several studies have reported an increased prevalence of pleural thickening, pleural plaques, and calcifications as well as parenchymal opacities among household members of asbestos workers (Anderson et al. 1976, 1979; Kilburn et al. 1985). Libby area physicians have reported cases of asbestos-related pulmonary disease among household contacts of former mine workers and other residents of the community who were not directly associated with the mining or processing operations (Whitehouse 2000).

Although household contacts may have been exposed by workers taking home asbestos on their clothes, shoes, and hair, numerous

other sources of environmental asbestos exposure exist for Libby community members. Air sampling in downtown Libby in 1975 and at several points in the 1980s detected levels of asbestos well above the Occupational Safety and Health Administration's occupational limit of 0.1 fiber/cm^3 over 8 hr of exposure (Atkinson et al. 1982; Dixon et al. 1985; U.S. Department of Labor 1994). Residents could have also been exposed to asbestos through the use of vermiculite in gardening activities, in home insulation, as aggregate in driveways, or through other uses around the home. Additionally, Libby residents have described other activities that involved close contact with vermiculite, such as playing in piles of vermiculite at the processing facilities, expanding or "popping" vermiculite at home by heating pieces of the ore over the stove, playing at the baseball field located adjacent to the vermiculite expansion plant, and playing along Rainey Creek Road that leads from town to the vermiculite mine.

A community-based medical testing program was initiated in response to reports of illness among people exposed to asbestos-contaminated vermiculite in Libby. In this article we outline the results from radiographic testing and self-reported exposure pathways for 7,307 persons who participated in this program. The main objectives were to *a*) identify and quantify possible asbestos-related pleural and interstitial abnormalities among participants and *b*) examine associations between these outcomes and the participants' exposure histories.

Materials and Methods

Participants and data collection. People were eligible for participation in the medical testing program if they had resided, worked, attended school, or participated in other activities in the Libby, Montana, area for ≥ 6 months before 31 December 1990. We identified participants from local telephone directories and through paid newspaper, radio, and television advertisements placed locally and throughout the northwest region of the United States, and in the major newspapers in Chicago, Illinois; Boston, Massachusetts; New York, New York; and Dallas, Texas. The highest readership days of each newspaper were targeted. In addition, word of mouth and medical referrals brought participants to the testing program. A toll-free telephone line was established for interested persons to obtain information about the program and to determine eligibility for screening participants. Telephone screening to determine eligibility began in April 2000 and continued through September 2001. Eligible persons living outside of Libby had to provide their own transportation to Libby for medical evaluation. In-person interviews and medical testing were conducted in Libby in two waves:

from July through November 2000 and from July through September 2001. After informed consent was obtained, trained interviewers administered a computer-assisted questionnaire to obtain demographic characteristics, residential history, occupational history, household contact history, recreational activities and other potential pathways for vermiculite exposures, cigarette smoking status, medical history, and self-reported symptoms and illnesses. The medical screening consisted of spirometric testing and chest radiographs. In this article we report on the radiographic findings of this program. Spirometric results will be reported separately.

Medical evaluation and classification of outcomes. Chest radiographs were offered to participants ≥ 18 years of age and included posterior–anterior (P-A), right anterior-oblique, and left anterior-oblique views. Women of child-bearing age were informed that they should postpone their chest radiograph if they were pregnant. The physician on site assessed the consistency and quality of each chest radiograph taken and provided a routine radiologic interpretation, which included recording asbestos-related changes on a summary report form. If findings on a chest radiograph suggested the need for urgent medical attention, the physician completed a referral form, and the participant was counseled and directed to an appropriate source of medical care.

After initial evaluation and interpretation by the on-site physician, the participants' chest radiographs were read and classified independently by three B-readers certified by the National Institute for Occupational Safety and Health, without knowledge of the subject's age, smoking history, or exposure category, according to guidelines developed by the International Labor Organization (ILO 1980). Although the P-A view is recommended by the ILO's guidelines for the classification of radiographs (ILO 1980), we used the lateral right and left oblique views as well as the P-A view for evaluating abnormalities. The addition of right and left oblique views increases the precision and the sensitivity and specificity of chest radiographs in finding pleural abnormalities not evident on the P-A view alone (Lawson et al. 2001; Levin et al. 2000).

A subject was classified as having a pleural abnormality if two out of three B-readers indicated *a*) any unilateral or bilateral pleural calcification on the diaphragm, chest wall, or other site or *b*) any unilateral or bilateral pleural thickening or plaque on the chest wall, diaphragm, or costophrenic angle site, consistent with asbestos-related pleural disease, using the P-A view, the oblique views, or a combination of those views. A subject was classified as having an interstitial abnormality if two out of three B-readers indicated the

presence of opacities, applying ILO guidelines, with a profusion of 1/0 or greater using the P-A view only.

Exposure characterization. To describe potential exposures to asbestos or vermiculite, participants were asked if they had ever worked for W.R. Grace or Zonolite (WRG) or as a contractor for WRG; if they had ever been exposed to dust at non-WRG jobs; if they had ever mixed, cut, or sprayed asbestos; if they had ever had other occupational exposure to asbestos; or if they had exposure to asbestos in military service. In addition, participants where asked if they had ever had a job as a pipe or steam fitter, plumber, brake repair person, insulator, dry wall finisher, carpenter, roofer, electrician, or welder. Some questions sought information about potential exposures in daily life, including having been a household contact of a WRG worker (during the time the worker was at WRG), length of residence in the Libby area (categorized by quartiles for analysis: 6 months through 14 years, 15–22 years, 23–34 years, and > 34 years), and having asbestos products in the home or using vermiculite in gardening or insulation (yes or no). There were questions about recreational activities such as playing in vermiculite piles, popping vermiculite, and playing on the baseball field near the expansion plant, or playing along the Rainey Creek Road—the road to the mine (never, sometimes, or frequently). Participants were also asked if they had any other contact with vermiculite (never, sometimes, or frequently).

Covariates. Age, sex, cigarette smoking status, a history of chest injury or chest surgery, tuberculosis, pneumonia, scleroderma, lupus, rheumatoid arthritis, congestive heart failure, cancer, or pulmonary disease were ascertained

Table 1. Distribution and characteristics of participants in the Libby medical screening program.

Variable	No. (%)
Age	
10–17	600 (8.2)
18–44	2,519 (34.5)
45–64	3,031 (41.5)
≥ 65	1,157 (15.8)
Sex	
Male	3,601 (49.3)
Female	3,706 (50.7)
Smoking history	
Never	3,711 (50.8)
Ex-smoker	2,156 (29.5)
Current	1,438 (19.7)
Years lived in Libby	
0.5–13	1,864 (25.7)
14–21	1,892 (26.1)
22–33	1,761 (24.2)
≥ 34	1,747 (24.1)
BMI	
0–18	234 (3.2)
19–24	2,185 (30.2)
25–29	2,529 (34.9)
≥ 30	2,292 (31.7)

from the examiner-administered questionnaire. Participants were also asked if they were *a)* not at all, *b)* a little, or *c)* very concerned that something in the neighborhood environment may be harmful. Body mass index (BMI) was calculated from height and weight measurements obtained during the medical examination and classified into standard categories (< 18, 19–24, 25–29, and ≥ 30) for descriptive purposes and into quartiles (< 24, 24–27, 28–31, ≥ 32) on the basis of its distribution in the participants for statistical modeling. Age was modeled as a continuous variable, and cigarette smoking status was classified as never smoked or ever having smoked (ex-smoker and current smoker).

Statistical analysis. We used unconditional logistic regression modeling to estimate, by use of the odds ratio (OR) and 95% confidence intervals (CI), the risk of respiratory abnormalities for each of the exposure pathways while controlling for all other exposure pathways and other established and suggested risk factors for respiratory illness. Models were estimated separately for the outcomes of pleural abnormalities and interstitial abnormalities.

Table 2. Number (percent) of participants reporting each exposure pathway.[a]

Exposure pathway	No. (%)
Ever work for WRG	370 (5.1)
Secondary contractor work	465 (6.4)
Dust exposure at non-WRG jobs	2,396 (32.8)
Vermiculite exposure at non-WRG jobs	1,103 (15.2)
Worked non-WRG job	
As a pipe fitter or steam fitter	164 (2.2)
As a plumber	168 (2.3)
As a brake repair person	249 (3.4)
As an insulator	240 (3.3)
As a dry wall finisher	221 (3.0)
As a carpenter	568 (7.8)
As a roofer	362 (5.0)
As an electrician	187 (2.6)
As a welder	467 (6.4)
Mixing, cutting, or spraying asbestos	144 (2.0)
In a shipyard or performed ship construction or repair	129 (1.8)
Exposed to asbestos	851 (11.8)
Worked around anyone performing non-WRG jobs (listed above)	804 (11.0)
Asbestos exposure in the military	182 (2.7)
Lived with WRG workers	1,418 (19.5)
Vermiculite insulation in Lincoln County homes	3,017 (45.8)
Asbestos products in Lincoln County homes	1,155 (17.4)
Used vermiculite for gardening	3,702 (51.9)
Used vermiculite around the home	638 (8.8)
Handled vermiculite insulation	3,635 (50.5)
Recreational activities along Rainey Creek Road	4,898 (67.4)
Played at ball field near expansion plant	4,772 (65.5)
Played in vermiculite piles	2,442 (33.7)
Popped vermiculite	2,797 (38.4)
Other contact with vermiculite	2,232 (31.0)

[a]Participants may have answered "yes" to more than one category.

We first tabulated the frequencies of demographic and other participant characteristics to obtain a descriptive profile of the participants. We then tabulated prevalence of pleural abnormalities and interstitial abnormalities for each of the occupational, recreational, and household exposure pathways and for each of the covariates, as well as for the increasing number of exposure pathways. Crude ORs and 95% CIs for pleural abnormalities and interstitial abnormalities were calculated for each of these pathways and covariates. We began an unconditional logistic regression multivariate model with all potential exposure pathways and covariates. The presence of effect modification was evaluated in this model by use of interaction terms between the exposure variables and demographic characteristics. We modeled age as a continuous variable and, when appropriate, included linear and nonlinear terms in the model. Criteria for inclusion in the final model included statistical significance of the explanatory variables ($p < 0.10$), stability of the estimate, effect on other variables in the model (confounding), biologic plausibility of the interaction, and fit of the model. We used a logistic regression model to describe an exposure–response relationship with the number of exposure pathways while controlling for covariates. A chi-square test and pairwise contrasts between pathway levels were used to assess the statistical significance of this trend. We used Procedures in SAS, release 8.01 (SAS Institute 2001) to perform all statistical analyses.

Results

Description of the participants. Of 12,829 persons screened by telephone, 3,527 did not meet the criteria for eligibility and 66 had unknown eligibility status. Of those eligible, 1,689 either did not schedule an appointment or did not report for medical testing, 231 refused medical testing, 4 had died before they were tested, and 5 were physically unable to come in for testing. The remaining 7,307 current and former residents of Libby and the surrounding area participated in the medical testing program (6,149 in the first wave and 1,158 in the second wave, resulting in a 78.6% participation rate). Among those who participated, 81% stated that they currently lived in Montana, and of those, 80% currently resided in the Libby, Troy, or Eureka areas. Most of the participants outside of Montana came from Idaho, Oregon, and Washington. Because participants in the first and second years of medical testing were similar in demographic characteristics, exposure pathways, concern about neighborhood contamination, and prevalence of outcomes, the data from both years were combined.

Of the 7,307 participants, 6,668 (91.2%) were ≥ 18 years of age and therefore were eligible for and received chest radiographs. During

the two waves of medical testing, the physician on site determined that 525 radiographs could not be read because of poor quality, and these were later repeated.

Characteristics of the participants are presented in Table 1. The participants were almost evenly divided by sex with 49% male and 51% female. The majority of participants were 18–64 years of age (76.0%). Almost half of the participants were former or current smokers. Roughly 74% of participants had lived in the Libby area for ≥ 14 years. Many of the participants were overweight. A BMI of 25–29.9 is considered overweight, and a BMI of ≥ 30 is considered obese; 67% of participants had a BMI of ≥ 25, with almost 32% of all participants in the obese category.

The 29 exposure pathways used in the analyses and the number of participants reporting each pathway are presented in Table 2. These include occupational, recreational, household, and other potential exposures. Participants may have reported one, several, or none of these exposures. The most common pathways were recreational activities along Rainey Creek Road (4,898, or 67.4%), playing in the baseball fields near the expansion plant (4,772 participants, or 65.5%) and playing in the vermiculite piles (2,442, or 33.7%). The most common occupational exposure was dust exposure at non-WRG jobs (2,396, or 32.8%), and the least common occupational exposure was working in a shipyard or ship construction or repair (129, or 1.8%).

Males were much more likely than females to have reported occupational exposures. Among those who reported having worked at WRG, 341 (92.2%) were male and 29 (7.8%) were female. Males also were more likely than females to have been exposed to asbestos or vermiculite during nonoccupational activities, although differences were less pronounced when compared with the occupational exposures. For instance, among the exposure pathways, males were more likely than females to report dust exposures at work (76.8% vs. 23.2%), working at any job with exposure to asbestos (71.2% vs. 28.8%), vermiculite exposure at other jobs (77.2% vs. 22.8%), frequently playing in vermiculite piles (61.1% vs. 38.9%), or frequently popping vermiculite (54.4% vs. 45.6%). The only notable exception was that females were more likely than males to have been a household contact of a WRG worker (60.0% of household contacts were female).

Pleural and interstitial abnormalities. Table 3 presents the crude prevalence rates of pleural and interstitial abnormalities by exposure pathways for 6,668 participants, ≥ 18 years of age, who underwent chest radiography. The pathways presented here are not mutually exclusive; for example, a participant who reported having been a WRG worker, playing

on the baseball field, and using vermiculite for gardening would be represented in all three categories. The overall prevalence of pleural abnormalities was considerably greater than the prevalence of interstitial abnormalities. Almost 18% of participants who underwent chest radiography had a pleural abnormality, compared with only 1% of participants having an interstitial abnormality. The exposure pathway with the highest unadjusted rate for pleural abnormalities was being a former WRG worker, with 186 (51.0%) having pleural abnormalities. WRG workers also had the highest rate of interstitial abnormalities (3.8%). Other pathways associated with high rates of pleural abnormalities included history of asbestos exposure in the military (42.9%), working in a shipyard or performing shipyard construction or repair (34.9%), and being a secondary contract worker for WRG (34.8%). The lowest prevalence of pleural abnormalities (14.4%) was seen for the "sometimes" exposure category of playing at the baseball field near the expansion plant.

The rate of pleural abnormalities increased from 5.1% in younger adults 18–44 years of age, to 20.0% for participants 44–65 years of age, to 39.7% for participants ≥ 65 years of age. Males had a significantly higher rate of pleural abnormalities (26.6%) compared with female participants (9.1%). The crude OR for pleural abnormalities among males compared with females was 3.61 (95% CI, 3.14–4.15). Current and former smokers (ever smokers) were twice as likely to have findings of pleural abnormalities than those who never smoked (crude OR, 2.18; 95% CI, 1.91–2.49). Participants with a high BMI were more likely to have a finding of pleural abnormalities than were those with a lower BMI. This risk increased with increasing quartiles of BMI. Compared with the first quartile, the crude ORs for pleural abnormalities were 1.80 (95% CI, 1.44–2.24) for the second quartile, 2.80 (95% CI, 2.253–3.49) for the third quartile, and 3.71 (95% CI, 2.99–4.60) for the highest quartile. Increasing length of residence in the Libby area was also associated with increasing risk of pleural findings. Compared with participants residing in the Libby area for < 14 years, crude ORs ranged from 0.91 (95% CI, 0.73–1.13) for a residential duration of 14–21 years to 3.62 (95% CI, 3.00–4.36) for residential duration of > 34 years.

Table 4 presents the final unconditional logistic regression model in which all exposure pathways, as well as other risk factors and interaction terms, were assessed for their contribution to the risk of pleural abnormalities. The model shows that the following factors were associated with pleural abnormalities: having been a WRG worker, having been a household contact of a WRG worker, having

been exposed to asbestos in the military, having played in vermiculite piles, being male, being older, having lived in the Libby area for a longer period of time, having smoked cigarettes, and having a high BMI.

We found significant interaction terms between age and being a former WRG worker and between sex and being a household contact of a WRG worker. Although the odds of finding a pleural abnormality is higher for former WRG workers than for nonworkers, the magnitude of the OR decreases with increasing age. Table 5 shows that estimated odds of finding a pleural abnormality ranges from 4.18 for a 30-year-old former WRG worker compared with a nonworker, to 1.14 for a 90-year-old former worker compared with a non-WRG worker, after adjusting for all other variables in the model. The model also shows that the estimated odds of finding a pleural abnormality is almost five times greater for males than for females (among nonhousehold contacts) after adjusting for other variables in the model (OR,

4.84; 95% CI, 3.83–6.11). The estimated odds of finding a pleural abnormality is 3.62 (95% CI, 2.70–4.83) times greater for females who were household contacts of former WRG workers when compared with females who were not. The corresponding increased odds of pleural abnormalities among male household contacts is 1.71 (95% CI, 1.32–2.22).

As age increases, the odds of finding a pleural abnormality increase, although the rate of that increase slows. For example, among non-WRG workers, the estimated odds of finding a pleural abnormality for a 40-year-old was three times greater than for a 30-year-old (OR, 3.04; 95% CI, 2.69–3.43). However, the odds reduce to 2.02 (95% CI, 1.87–2.18) when comparing a 60-year-old with a 50-year-old. This effect is slightly attenuated for age contrasts involving former WRG workers (OR = 2.45 for a 40-year-old vs. a 30-year-old; OR = 1.63 for a 60-year-old vs. a 50-year-old). Among the recreational exposure pathways, those who played in the

Table 3. Number (percent) of pleural and interstitial abnormalities by exposure pathways.

Exposure pathway	Pleural, all views	Interstitial, P-A view
All participants ≥ 18 years of age (n = 6,668)	1,186 (17.8)	54 (0.8)
Ever worked for WRG (n = 365)	186 (51.0)	14 (3.8)
Secondary contractor work (n = 463)	161 (34.8)	8 (1.7)
Dust exposure at non-WRG jobs (n = 2,390)	527 (22.1)	21 (0.9)
Vermiculite exposure at non-WRG jobs (n = 1,100)	254 (23.1)	8 (0.7)
Worked non-WRG job		
As a pipe or steam fitter (n = 164)	54 (32.9)	2 (1.2)
As a plumber (n = 168)	50 (29.8)	3 (1.8)
As a brake repair person (n = 247)	68 (27.5)	2 (0.8)
As an insulator (n = 240)	44 (18.3)	1 (0.4)
As a dry wall finisher (n = 221)	41 (18.6)	0 (0.0)
As a carpenter (n = 566)	129 (22.8)	2 (0.4)
As a roofer (n = 361)	79 (21.9)	2 (0.6)
As an electrician (n = 187)	48 (25.7)	3 (1.6)
As a welder (n = 465)	122 (26.2)	5 (1.1)
Mixing, cutting, or spraying asbestos (n = 143)	47 (32.9)	2 (1.4)
In a shipyard or performed ship construction or repair (n = 129)	45 (34.9)	4 (3.1)
Exposed to asbestos (n = 849)	208 (24.5)	7 (0.8)
Worked around anyone performing previous 12 jobs (n = 801)	184 (23.0)	6 (0.8)
Asbestos exposure in the military (n = 182)	78 (42.9)	2 (1.1)
Lived with WRG workers (n = 1,376)	358 (26.0)	17 (1.2)
Vermiculite insulation in homes (n = 2,819)	600 (21.3)	27 (1.0)
Asbestos products in homes (n = 1,071)	222 (20.7)	9 (0.8)
Used vermiculite for gardening (n = 3,469)	702 (20.2)	29 (0.8)
Used vermiculite around the home (n = 586)	120 (20.5)	1 (0.2)
Handled vermiculite insulation		
Sometimes (n = 2,739)	572 (20.9)	25 (0.9)
Frequently (n = 732)	191(26.1)	9 (1.2)
Recreational activities along Rainey Creek		
Sometimes (n = 3,134)	546 (17.4)	21 (0.7)
Frequently (n = 1,433)	307 (21.4)	15 (1.1)
Played at ball field near expansion plant		
Sometimes (n = 2,034)	293 (14.4)	10 (0.5)
Frequently (n = 2,290)	432 (18.9)	16 (0.7)
Played in vermiculite piles		
Sometimes (n = 1,430)	269 (18.8)	8 (0.6)
Frequently (n = 875)	220 (25.1)	5 (0.6)
Popped vermiculite		
Sometimes (n = 2,140)	460 (21.5)	13 (0.6)
Frequently (n = 538)	138 (25.7)	9 (1.7)
Other contact with vermiculite		
Sometimes (n = 1,759)	340 (19.3)	14 (0.8)
Frequently (n = 323)	73 (22.6)	5 (1.6)

vermiculite piles frequently had twice the risk of pleural abnormalities compared with those who never played in the piles (OR, 2.02; 95% CI, 1.59–2.57).

The rate of interstitial abnormalities increased from 0.04% in younger adults 18–44 years of age, to 0.5% for participants 44–65 years of age, to 3.2% for participants ≥ 65 years of age. Males had a higher rate of interstitial abnormalities (1.2%) compared with female participants (0.4%). The crude OR for interstitial abnormalities among males compared with females was 2.68 (95% CI, 1.47–4.86). Current and former smokers (ever smokers) were twice as likely to have findings of interstitial abnormalities than were those who never smoked (crude OR, 2.18; 95% CI, 1.91–2.49). BMI was not associated with interstitial abnormalities. Participants residing in the Libby area for > 34 years had a 4-fold increased risk of interstitial abnormalities (crude OR, 4.38; 95% CI, 1.82–10.54).

We assessed the independent contributions of the exposure pathways and covariates to the risk of interstitial abnormalities using multivariate logistic regression. The strongest predictors of interstitial abnormalities were having been a former WRG worker (OR, 2.71; 95% CI, 1.26–5.87) and being male (OR, 2.48; 95% CI, 1.08–5.68). Increasing age, having worked on a ship or done ship repair, and having a history of pneumonia were also significantly associated with interstitial abnormalities.

The models above demonstrate the relative importance of various exposure pathways and covariates in predicting pleural and interstitial abnormalities. However, the majority of participants reported multiple pathways rather than a single exposure pathway. Only 2% of the participants reported "no" to all exposure pathways, whereas 48.1% of the participants

reported six or more exposure pathways. The prevalence rates for pleural and interstitial abnormalities among participants with multiple exposures compared with those with no apparent exposures is displayed in Figure 1. An exposure–response relationship is apparent between the number of exposure pathways and the prevalence of pleural abnormalities. Among those who reported "no" to all exposure pathways, 6.7% had pleural abnormalities, compared with an almost 35% prevalence among those reporting ≥ 12 pathways. An exposure–response relationship is not seen for interstitial abnormalities, which had a prevalence of about 1% regardless of the number of pathways reported. This trend in increasing pleural abnormalities with increasing number of pathways could not be solely attributed to former WRG workers. This relationship was apparent, although slightly attenuated, even after we removed the workers from the analysis (30.1% prevalence of pleural abnormalities among those reporting ≥ 12 pathways). Table 6 presents the results from an unconditional logistic regression model of this relationship controlling for age, sex, BMI, smoking, and residential duration. There was a statistically significant trend of increased pleural abnormalities with increasing number of pathways, with ORs ranging from 1.40 for one pathway to 3.75 for ≥ 12 pathways.

Discussion

In this analysis we sought to identify radiographic abnormalities and significant exposure pathways among participants in a community-based medical testing program in Libby, Montana. Almost 18% of the participants undergoing radiography had pleural abnormalities identified by at least two of three certified B-readers. Interstitial abnormalities

were identified in 1% of participants. These findings are consistent with clinical reports by Libby area physicians that patients more commonly have pleural abnormalities and that interstitial disease is generally diagnosed at a later stage (Whitehouse 2000). Pathologic effects of asbestos and of asbestos-contaminated vermiculite have been established for both the pleura and parenchyma (Amandus et al. 1987a; Becklake 1976; Lockey et al. 1984; McDonald et al. 1986b), and the severity of these effects has been associated with latency, duration, and intensity of exposures among workers. Our findings of predominantly pleural effects suggests less prolonged or intense exposures and/or shorter latency periods. Alternatively, the cross-sectional study design may have removed a disproportionate number of people suffering or dying from more severe disease. Furthermore, differential respiratory health effects observed in a number of asbestos-exposed populations also may be due to differences in the physical and chemical properties of the mineral fiber exposures (ATSDR 2001).

Our analyses further demonstrated a statistically significant increase in the prevalence of pleural abnormalities with an increasing number of exposure pathways. Participants reporting more pathways might be expected to have more cumulative exposure than would those reporting fewer pathways. Those who reported ≥ 12 exposure pathways had a prevalence rate of almost 35% for pleural abnormalities, compared with a prevalence of 6.7% for those who reported no exposure pathways. No directly comparable Montana or U.S. population studies are available to estimate the rate of pleural abnormalities among those in Libby with no work-related exposures. Studies of differing groups within the United States believed to have no substantive work-related asbestos exposures have found prevalence of pleural abnormalities ranging from 0.2% among blue-collar workers in North Carolina (Castellan et al. 1985), to 2.3% among patients at Veterans Administration hospitals in New Jersey (Miller and Zurlo 1996), to 4.6% among urban New Jersey residents (Anderson et al. 1979). Subjects in our category of "no apparent exposure" had a greater rate of pleural abnormalities (6.7%) than did those in the

Table 4. Risk of pleural abnormalities by exposure pathways and covariates.[a]

Variable	Level	Beta	Adjusted OR (95% CI)
Intercept		−19.46	
Workwr	Yes	2.08	—[b]
HHWR	Yes	1.29	—
Vermplay	Sometimes	0.60	1.82 (1.48–2.25)
	Frequently	0.70	2.02 (1.59–2.57)
Sex	Male	1.58	—
Resdur (years)	14–21	0.25	1.29 (0.97–1.71)
	22–33	0.22	1.25 (0.96–1.62)
	≥ 34	0.75	2.12 (1.66–2.70)
ln(Age)		3.86	—
BMI	2nd quartile (24–27)	0.18	1.20 (0.91–1.60)
	3rd quartile (28–31)	0.56	1.75 (1.32–2.32)
	4th quartile (≥ 32)	1.14	3.12 (2.37–4.12)
Smoke	Ever	0.30	1.35 (1.14–1.59)
Age × Workwr	Yes	−0.02	—
HHWR × sex	Yes × male	−0.75	—
Milexp	Yes	0.47	1.61 (1.10–2.35)
Age × ln(Age)		−0.05	—

Abbreviations: HHWR, household contact with WRG worker; Milexp, asbestos exposure in the military; Resdur, duration of residence in Libby area; Vermplay, played in vermiculite piles; Workwr, ever worked for WRG.
[a]Twenty-nine exposure pathways and all covariates were assessed for their contribution to the risk of pleural abnormalities; final model fit: Hosmer-Lemeshow goodness-of-fit test, $\chi^2 = 2.47$, degrees of freedom = 8, $p = 0.96$. [b]A single value cannot be presented for adjusted ORs involving interaction terms.

Table 5. Risk of pleural abnormalities for former WRG workers compared with non-WRG workers at different ages.

Age (years)	OR (95% CI)
30	4.18 (2.20–7.94)
40	3.37 (2.14–5.29)
50	2.71 (2.00–3.67)
60	2.18 (1.66–2.86)
70	1.76 (1.19–2.58)
80	1.41 (0.80–2.48)
90	1.14 (0.53–2.44)

control groups or general populations found in other studies. Given the ubiquitous nature of vermiculite contamination in Libby, along with historical evidence of elevated asbestos concentrations in the air, it would be difficult to find participants who could be characterized as unexposed. Our unexposed category was based on negative responses to specific pathway questions and is likely to have missed some potential exposure pathways.

Not unexpectedly, being a former WRG worker was a significant risk factor for each of the outcomes examined in these analyses. With respect to pleural abnormalities, we found a significant interaction between age and being a former WRG worker, in which the magnitude of the OR among former WRG workers compared with nonworkers decreases with increasing age. This may be due to nonworkers having had the opportunity for accumulating multiple, nonoccupational exposures with increasing age, thus making them more similar to former WRG workers. This result may also be attributed to a survivor effect. If workers are at a higher risk of fatal respiratory disease than nonworkers, and that risk of dying increases with age, a cross-sectional design might show older surviving workers to be more similar to older nonworkers in terms of pleural outcome. A study that linked death certificate data with employment information from a Libby mining and milling facility found that, between 1979 and 1998, 11 of 12 asbestosis decedents, 21 of 124 lung cancer decedents, and 2 of 3 mesothelioma decedents were former workers (ATSDR 2002). Given the relatively small proportion of former WRG workers in this study, differential mortality of workers may explain this interaction.

In addition to being a former WRG worker, results from our multivariate logistic regression models indicate the other factors most strongly related to having pleural abnormalities were being older, being a household contact of a WRG worker, and being male. Women household contacts of former WRG workers compared with noncontacts were at a greater risk of pleural abnormalities than were male contacts versus noncontacts. This may be due to gender differences in responsibilities for laundry and cleaning that may lead to greater

exposure to "take-home" dust. Additionally, women workers, who traditionally are more likely to be found in administrative or office occupations within industries, may have been exposed to less vermiculite on the job site than were male workers and thus brought less vermiculite home. Men had almost five times the risk of pleural abnormalities compared with women. Although men and women may have engaged in similar occupational and recreational activities, gender differences in intensity or duration of activities may explain this excess risk among men. Other pathways of exposure associated with pleural abnormalities included playing in vermiculite piles and having been exposed to asbestos in the military.

BMI was also associated with pleural abnormalities in these analyses. Although there is no known biologic or pathologic relationship between body mass and the development of pleural abnormalities, a heavier BMI can make it more difficult to distinguish between pleural abnormalities and subpleural or extrapleural fat (Proto 1992; Sargent et al. 1984). Nevertheless, even after controlling for BMI, we were able to demonstrate a significant trend in increasing pleural abnormalities with increasing number of exposure pathways. Current and former smokers were also more likely to have findings of pleural abnormalities than were those who never smoked. Smoking was not associated with pleural changes in previous studies of Libby vermiculite workers, although the authors suggest that the small number of nonsmokers may have limited its assessment (Amandus et al. 1987a; McDonald et al. 1986b). Our finding of a smoking effect on the prevalence of pleural abnormalities may indicate an independent effect, or it may have resulted from an association between cigarette smoking and one or more exposure risk factors or with unmeasured exposures. Although we found that current and former smokers were twice as likely to have interstitial abnormalities (crude OR, 2.2; 95% CI, 1.9–2.5), this association was no longer statistically significant in the full model. The exposures and covariates most strongly associated with interstitial abnormalities were increasing age, having been a former WRG worker, having worked a job in a shipyard, and having a history of pneumonia.

The association with shipyard work would not be unexpected given the probable higher levels of exposure.

The principal limitations of these analyses are the cross-sectional design of the testing program and self-selection of participants, rather than random selection. Studies involving volunteers are subject to selection bias that can occur in a number of ways. It is possible that those who volunteered for the program were more likely to have been previously diagnosed with an illness or were more likely to have experienced symptoms compared with a randomly selected population. Also more likely to participate may have been the "worried well" or very concerned healthy persons. Alternatively, persons who believed they had little or no exposure may have chosen not to participate, or those already diagnosed with disease may have felt they had little to gain from participation. The requirement for travel to Libby also may have contributed to selection bias. In addition, cross-sectional studies are limited in assessing in- or out-migration that may have important effects on the population. Nevertheless, the medical testing program screened 7,307 people in Libby and the surrounding area. Of those, 5,846 were from the Libby area. This represents a substantial proportion (61%) of the 9,521 persons in central Lincoln County—a population that has been relatively stable for the past 30 years (U.S. Bureau of the Census 2002). Before the start of the medical testing program, there had been national-level press coverage of the asbestos-contaminated vermiculite in Libby that may have resulted in a high level of community awareness. This, along with an intensive community outreach campaign, resulted in high participation rates.

Another potential limitation in this analysis was that the B-readers knew that the radiographs were from the Libby medical screening program and control films were not included among the Libby series of radiographs. Readers were, however, blinded to the exposure pathways and other characteristics reported by these participants. Additionally, observer bias was limited by following established standards for interpretation of chest radiographs that require
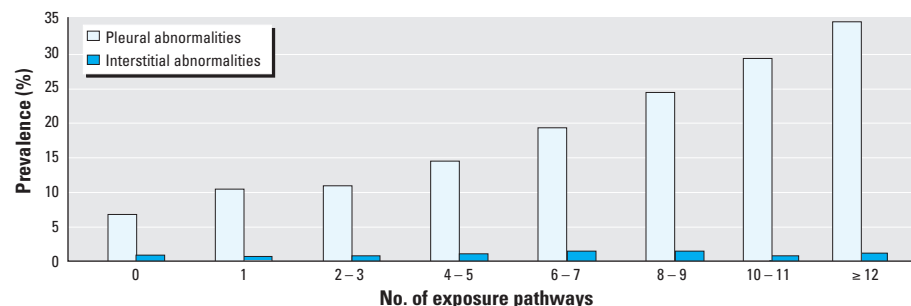

Figure 1. Prevalence of abnormalities by number of exposure pathways.

Table 6. Risk of pleural abnormalities by number of exposure pathways (baseline: no apparent exposure) controlling for age, sex, BMI, residential duration, and smoking.

No. of exposure pathways	OR (95% CI)
1	1.40 (0.60–3.26)
2–3	1.36 (0.62–2.97)
4–5	1.80 (0.83–3.90)
6–7	2.41 (1.11–5.23)
8–9	3.12 (1.43–6.83)
10–11	3.48 (1.56–7.77)
≥ 12	3.75 (1.65–8.50)

Final model fit: Hosmer-Lemeshow goodness-of-fit test, $\chi^2 = 5.45$, degrees of freedom = 8, $p = 0.71$.

the use of B-readers trained in detection of occupational disease, and agreement in two of three B-readers. Nevertheless, differences in interpretation of radiographs remains a source of variation (Bourbeau and Ernst 1988). All films were taken in one location, and those judged to be of poor quality or unreadable were repeated, thereby limiting variability in radiographic technique and quality.

The Libby community medical testing program was designed primarily to identify illnesses experienced by participants exposed to asbestos to better inform local health care providers and to characterize pathways of exposure. However, these results may have broader implications because vermiculite from the Libby mine was shipped to and processed at facilities throughout the country. For example, a recent case report describes a 65-year-old accountant who presented with extensive pleural plaques and end-stage pulmonary fibrosis (Wright et al. 2002). This patient progressed rapidly to respiratory failure and death. His only exposure to asbestos was during a summer job in a vermiculite expansion plant 50 years before his death. The asbestiform fibers found in his lungs were very similar to those contaminating the vermiculite mined near Libby, Montana. In addition to occupational exposures at the many vermiculite expansion plants, asbestos-contaminated vermiculite was placed in millions of homes and businesses across the country as insulation. The U.S. Environmental Protection Agency recently decided to warn consumers that disturbing this insulation can release asbestos fibers, resulting in hazardous respiratory exposures (Schneider 2003).

The magnitude of the public health problem nationally is not yet clear, but this analysis provided important information on the prevalence and degree of asbestos-related abnormalities among current and former Libby residents. As such, it forms a foundation for further analyses of exposure pathways in Libby and other sites where vermiculite was shipped, handled, and processed. The results of this analysis will inform those planning intervention services and those future health investigators of the natural history of respiratory illnesses among people exposed to asbestos-contaminated vermiculite.

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