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Int. J. Hyg. Environ.-Health 208 (2005) 87–99
International Journal of Hygiene and Environmental Health
www.elsevier.de/ijheh

# The usefulness of computed tomography in detecting asbestos-related pleural abnormalities in people who had indeterminate chest radiographs: the Libby, MT, experience

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## Abstract

This epidemiological study was conducted to determine whether high-resolution computed tomography (HRCT) is useful to screen for pulmonary abnormalities in people exposed to vermiculite containing asbestos. During June–September 2001, we evaluated HRCT of 353 people in Libby, MT, who had been exposed to asbestiform minerals associated with vermiculite. Of these, 334 participants of the summer 2000 medical testing program underwent HRCT of the chest at St. John's Lutheran Hospital and 19 eligible people who recently had undergone an HRCT scan at the same facility and under the same testing protocol allowed the study reviewers to use that scan. All 353 study participants were former vermiculite mine/mill workers ($n = 55$), their household contacts ($n = 99$), and people exposed to vermiculite through recreational or other activities ($n = 199$). Participants' 2000 medical testing results indicated only one of the three B-reader chest radiograph reviewers had reported a pleural abnormality (indeterminate chest radiograph). Three expert computer tomography (CT) scan evaluators reviewed the HRCT scans and identified pleural abnormalities in 98 (27.8%) of the 353 participants whose previous chest radiographs were classified indeterminate. Of these 98 people, 69 (70.4%) were either former vermiculite mine/mill workers or household contacts, and 40 (40.8%) showed pleural calcification on HRCT. Thirty out of the 40 people with pleural calcification reported having no occupational exposure to either Libby vermiculite or asbestos. Our findings indicate that low-dose HRCT can be considered for screening certain former vermiculite mine/mill workers and their household contacts who have indeterminate chest radiographs and may be useful for diagnosing a suspicious finding on a chest radiograph, particularly in a high-risk person.
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***Keywords:*** Pleural abnormalities; Health effects; Asbestos; Vermiculite; Computed tomography of the chest

## Introduction

Vermiculite is a naturally occurring sheet silicate mineral usually formed by the hydrothermal alteration of mica minerals such as biotite and phlogopite (Addison, 1995; Bureau of Mines, 1960, 1980). It

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1438-4639/$ - see front matter Published by Elsevier GmbH.
doi:10.1016/j.ijheh.2005.01.019

expands as much as 12 times its original size with the application of heat between 427 °C (801 °F) and 1093°C (1999 °F) (Bureau of Mines, 1960, 1980; Lockey et al., 1984). Expanded vermiculite has been used in various industries for more than 80 years because of its fireproof nature, thermal insulation capability, and ion exchange properties. It is used in construction materials such as flooring, roof screed (lightweight insulating concrete), and acoustic finishes; agricultural products (e.g., animal feeds, bulking agents, soil additives, pesticides), horticultural materials and processes (hydroponics, potting mixes); absorbent packing; and automotive brake pads and brake shoes (Bureau of Mines, 1980).

The largest known vermiculite deposit lies near Libby, MT, a city of approximately 3000 residents.

From 1923, when commercial mining began in and near Libby until 1990, when the facility was closed, vermiculite production increased; 20,000 tons shipped in 1940; 150,000 tons in 1950; and since 1972, about 200,000 tons shipped annually (McDonald et al., 1986b). Operations at this site included strip mining the ore, transporting ore by truck to a sorting facility and processing plants in downtown Libby, expanding the ore by heating it, and shipping it by rail as a commercial product.

The Libby mine and mill are approximately 12 miles from Libby and the screening facility and loading dock are approximately 7 miles from Libby (Amandus et al., 1987a; EPA, 2002). At a transfer facility at the base of Zonolite Mountain, approximately 3 miles from Libby, vermiculite was loaded onto trains for shipping or onto trucks going into Libby. Two expansion (‘‘popping’’) facilities operated at different times within the town; these plants heated vermiculite to expand (‘‘pop’’) the crystals. Improvements in the mining and milling operations between 1961 and 1974 and cessation of expansion (popping) operations reduced fiber exposure in some Libby mine/mill facilities (Amandus et al., 1987a).

Exposure to vermiculite extended beyond the mine workers into the community. Libby residences, schools, and businesses received vermiculite free of charge from the facility for use in gardens and as fill material. Some Libby schools used vermiculite as fill in recreational areas, such as running tracks and football fields (EPA, 2002). In addition, one of the Libby expansion operations adjoined a baseball field that was readily accessible to community children.

The toxicity of vermiculite has not been thoroughly studied, but no serious health effects have been associated with exposure (Addison, 1995). However, vermiculite ore deposits always contain an assemblage of other minerals (e.g., asbestos) (Addison, 1995; Addison and Davies, 1990). The vermiculite ore taken from Zonolite Mountain contains tremolite asbestos, actinolite asbestos, and other asbestiform minerals of amphibole type. Inhalation of asbestos fibers can result in lung diseases such as asbestosis, mesothelioma, and lung cancer. Studies have documented substantial occupational exposure to these asbestiform minerals among employees of the Libby mine (Amandus et al., 1987a, b; Amandus and Wheeler, 1987; Amandus, 1987; McDonald et al., 1986a, b; Sebastien et al., 1988; Vacek and McDonald, 1991) as well as pulmonary abnormalities and disease (asbestosis and lung cancer) among employees.

During the summer and fall of 2000, the Agency for Toxic Substances and Disease Registry (ATSDR) and its partners conducted a medical testing program of 6149 people in Libby. People were eligible for the medical testing program if they worked for W.R. Grace Company; were household contacts of these former workers; or resided, worked, attended school, or participated in activities in the Libby area for 6 months or more before December 31, 1990. The program involved three-view (posterior–anterior and two oblique views) chest radiography reviewed by three B-readers — national experts in asbestos-related conditions. The utility of chest radiographs in screening for asbestos-related disease has been well documented (Pham, 2001) and is the standard for asbestos-related screening programs for occupationally exposed people. However, their utility in screening for asbestos-related abnormalities for non-occupationally exposed populations has not been well evaluated. Additionally, many members of the Libby community who had undergone testing expressed interest in the use of high-resolution computed tomography (HRCT) for ongoing surveillance. The goal of this study was to determine whether HRCT is useful for screening for pulmonary abnormalities in people exposed to asbestiform minerals associated with vermiculite in Libby, MT. We set two study objectives. The first objective was to determine the prevalence of asbestos-related pleural abnormalities detected by HRCT among different risk groups of asbestos-exposed people whose chest radiographs from the 2000 medical testing program were classified as indeterminate (i.e., one of the three B-readers identified a possible abnormality). The second objective was to compare the HRCT findings among different risk groups to determine whether HRCT usefulness differs significantly among them.

## Materials and methods

### Subjects

Eligibility for the HRCT study among participants in the Libby medical testing program comprised three

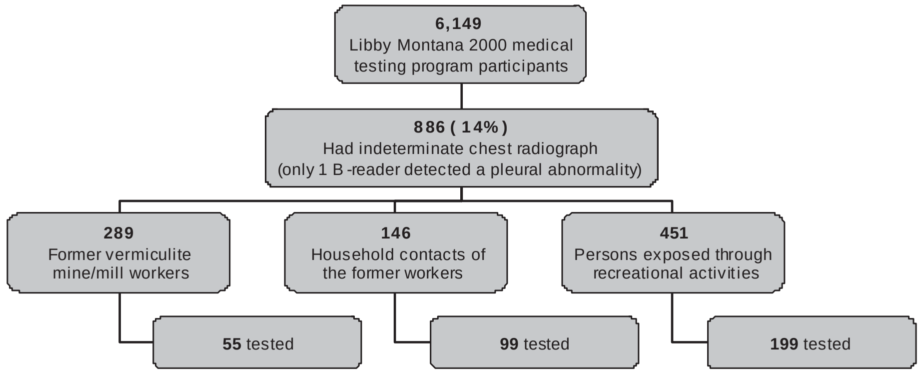


**Fig. 1.** Eligible study population.

criteria: (1) age 18 years or older; (2) previous employment as a vermiculite mine/mill worker or household contact with a former worker or exposure to vermiculite during direct recreational or other activities; and (3) indeterminate chest radiograph in the 2000 Libby medical testing program. The study excluded pregnant women because of concerns about exposure to HRCT.

Of the 6149 program participants, 886 (14.4%) met the eligibility criteria for this study (Fig. 1). Most (451, 50.9%) had been exposed through direct recreational or other activities, or were former vermiculite mine or mill workers (289, 32.6%). The smallest group comprised household contacts of former vermiculite workers (146, 16.5%). Eight hundred and eighty-two (99.6%) of the 886 people eligible for this study were whites. Four participants (two former vermiculite workers and two recreationally exposed people) could not be located. From the remaining 882 eligible cohort members, 361 were selected to achieve the study target of 330 HRCT scans. This target sample size of 330 HRCT scans was calculated using anticipated prevalence rates of pleural abnormalities within each of the study exposure groups, and included: (1) 50 former vermiculite workers; (2) 140 household contacts of former workers; and (3) 140 people exposed through recreational or other activities. The group of 361 participants selected consisted of (1) a random sample of 60 former vermiculite workers, (2) all eligible household contacts of former workers (146 people), and (3) a random sample of 155 recreationally exposed people. One household contact could not be reached during the study period, and 157 people refused to participate — a substantial number of refusals were from people who had moved out of the Libby area. For 21 scheduled appointments, people did not appear for testing. To achieve the study target, an additional 171 were randomly selected from the pool of eligible people. Three hundred and thirty-four participants of the summer 2000 medical testing program underwent HRCT of the chest at St. John's Lutheran Hospital. An additional 19 eligible people who recently had undergone an HRCT scan at the same facility and under the same testing protocol allowed the study reviewers to use that scan rather than performing another in order to avoid unnecessary radiation exposure. Ultimately, 353 people underwent chest HRCT at St. John's Lutheran Hospital in Libby during June 4–September 6, 2001.The study cohort comprised 55 former vermiculite mine/mill workers, 99 household contacts of former workers, and 199 people with exposure to vermiculite during recreational or other activities. The overall response rate was 66.4% (353 of 532 people).

## High-resolution computed tomography

We contacted eligible community members via mail and informed them about the study, and invited them to come to a local health facility for a chest HRCT scan. Two weeks later, we contacted them by phone to determine their interest in participating in the study, and to schedule an appointment for testing.

All eligible study participants underwent an HRCT of the chest during which they were scanned in both prone and supine positions. Participants were scanned without intravascular infusion of contrast material using a Picker PQS spiral HRCT scanner at full inspiration. The onsite radiologist evaluated all 353 scans for quality, provided a routine radiologic interpretation, and recorded asbestos-related abnormalities. Two national expert readers proficient in evaluating HRCT then independently reviewed the scans for both pleural and interstitial abnormalities. Both readers were blinded to the patients' exposure status as well as to their medical and demographic information. Agreement between the two expert readers regarding the presence of a pleural[1] abnormality was considered a final decision. If the two expert readers could not agree, the scans were sent to a third blinded expert reader, and

[1]Interstitial abnormalities identified by the reviewers were reported to the study participants and their designated health care providers as a service to the participants, but were not analyzed as part of the study.

agreement by two of the three readers was considered final. The third HRCT reader also was asked to evaluate scans where no agreement was reached for pleural calcification or for other notable findings (i.e., interstitial abnormalities and non-calcified nodules). We requested the onsite radiologist and the three HRCT readers to immediately refer participants, as appropriate, for urgent medical needs.

## Exposure assessment

We extracted exposure information for study participants from data collected during interviews for the medical testing program in Libby during June–November 2000. In addition to obtaining detailed information about asbestos exposure, the medical testing questionnaire also collected information about respiratory symptoms, demographics, and smoking status for each participant. The Libby medical testing program identified several potential asbestos exposure pathways for participants. Overall, this study participants reported 16 pathways of exposure to either asbestos or vermiculite. These included, but were not limited to working for W.R. Grace/Zonolite, exposure to dust or asbestos in the military or any other non-W.R. Grace/Zonolite job; history of residence in the same household as a W.R. Grace worker, asbestos insulation or other asbestos products in the home, use of vermiculite for gardening, or popped vermiculite; history of play in vermiculite piles or at a ball field near an expansion plant, or other direct recreational activities. We categorized these exposures into the following three groups (in the order of their expected harmful effects): (1) employment at any time with W.R. Grace/Zonolite or at a non-W.R. Grace/Zonolite job that involved exposure to vermiculite; (2) household contact with a former W.R. Grace/Zonolite worker; and (3) exposure to vermiculite due to past recreational or other activities. For this study, every participant in the medical testing program of 2000 was classified into the exposure category of the highest significance he or she reported.

## Statistical analysis

We merged the original data set with the demographic and chest radiograph data extracted from the Libby 2000 medical testing data by unique identifiers. We analyzed the data using the Statistical Analysis System (SAS) for Windows, version 8.2 (SAS Institute Inc., 2001) and SPSS for Windows, release 10.1.3. (SPSS Inc., 1999).

The analysis goal was to compare the effectiveness of chest radiography with that of HRCT. We evaluated the screening adequacy of chest radiography by calculating the percentage of test-negative cases that was reversed because HRCT resulted in a test-positive classification. This is equivalent to calculating the complement of the negative predictive value, $P(D+|T-)$, where $P$ is the probability of having a disease $(D+)$ for a person who had a negative test $(T-)$. It should be noted that this differs from calculating the percentage of positive diagnoses missed. Moreover, this approach does not allow for assessing the validity or reliability of chest radiographs. A test-negative screening result was defined as an indeterminate chest radiograph; and a test-positive screening result, as a positive chest radiograph. The results of the analysis determined the number of test-negative results reversed by the HRCT scan, which is considered the gold standard. Logistic regression compared the odds of reversal among the three exposure groups. The results could be applied to the 886 participants who met the eligibility requirements for the study.

# Results

HRCT detected pleural abnormalities in 98 (27.8%) of all people whose chest radiographs were classified indeterminate (Table 1). The highest prevalence (47.5%) of pleural abnormalities was in household contacts of former vermiculite workers. The former vermiculite workers group comprised W.R. Grace/Zonolite mine or mill workers, secondary contractors, and persons exposed to vermiculite at non-W.R. Grace/Zonolite work. The household contacts group was limited — for consistency of exposure — to those who lived with former W.R. Grace/Zonolite workers.

Table 2 presents demographic and other characteristics of those with and without pleural abnormalities on HRCT scans. The groups were comparable in terms of the sex distribution. Compared with the group having negative scans, the group with pleural abnormalities was older, thinner, had resided in Libby for longer periods, and reported more pathways of exposure to vermiculite. A larger proportion of people with pleural abnormalities on HRCT than with negative scans reported ever smoking. A larger proportion of people among those with pleural abnormalities were current smokers at the time of the study. The proportion of participants who were former smokers was similar in both groups. Asbestos-related abnormalities found by HRCT differed among the three exposure groups (Table 3). The risks of finding a pleural abnormality of any type on an HRCT scan were higher among former vermiculite workers and their household contacts than among participants exposed to vermiculite through recreational or other activities (adjusted odds ratio (OR) = 3.96, 95% confidence interval (CI): 1.86, 8.41; and OR = 6.32; 95% CI: 3.47, 11.54, respectively). The risks of detecting pleural calcification among former vermiculite workers

**Table 1.** Crude prevalence of pleural abnormalities on HRCT, by exposure category and sex — Libby, MT, 2001

| Exposure groups | *N* | Pleural abnormality identified | | No pleural abnormality identified | |
|---|---|---|---|---|---|
| | | *n* | % | *n* | % |
| Former workers | 55 | 22 | 40.0 | 33 | 60.0 |
| Male | 47 | 21 | 44.7 | 26 | 55.3 |
| Female | 8 | 1 | 12.5 | 7 | 87.5 |
| Household contacts | 99 | 47 | 47.5 | 52 | 52.5 |
| Male | 23 | 9 | 39.1 | 14 | 60.9 |
| Female | 76 | 38 | 50.0 | 38 | 50.0 |
| People recreationally exposed | 199 | 29 | 14.6 | 170 | 85.4 |
| Male | 74 | 9 | 12.2 | 65 | 87.8 |
| Female | 125 | 20 | 16.0 | 105 | 84.0 |
| Total | 353 | 98 | 27.8 | 255 | 72.2 |

and their household contacts also were much greater than that among people exposed to vermiculite through recreational or other activities (adjusted OR = 4.98; 95% CI: 1.69, 14.67; OR = 8.15; 95% CI: 3.30, 20.10, respectively). Former vermiculite workers were approximately twice as likely as the non-workers to have pleural abnormalities on HRCT (adjusted OR = 2.09; 95% CI: 1.05, 4.18) (Table 4). Risk of detecting a pleural abnormality on HRCT was also higher among household contacts than that among exposed persons who were not household contacts (adjusted OR = 4.67; 95% CI: 2.68, 8.14). Overall, the risk for pleural abnormalities was higher among former W.R. Grace workers, their household contacts, secondary contractors; people who reported ever smoking cigarettes, having frequently popped vermiculite, having vermiculite insulation in the home, being 65 years of age or older, and residing in Libby for 35 or more years.

During the 2000 medical testing, all 353 study participants were asked about their respiratory health. Some participants reported more than one respiratory symptom. Of the 98 people whose HRCT scan showed pleural abnormalities, 46 (47.0%) reported shortness of breath, 26 (27.0%) reported coughing on most days, and 10 (10%) reported chest pain related to breathing. Overall, 192 (54.4%) of the 353 study participants reported having at least one such respiratory symptom, including 55 (56.1%) of the 98 who had pleural abnormalities on HRCT.

Among the household contacts, 30.3% were daughters and 30.3% were spouses of former mine/mill workers. These two household contact groups demonstrated the highest risks for pleural abnormality on HRCT. The HRCT readers detected pleural abnormalities in 56.7% of daughters and 50.0% of spouses of the former vermiculite workers. In addition, 33.3% of the former vermiculite workers' sons demonstrated pleural abnormalities (data not shown).

Table 5 shows exposure pathways for the 199 study participants exposed to vermiculite through recreational or other activities. Twenty-one percent of people who handled vermiculite insulation and 18.5% of those who reported the presence of vermiculite insulation in their Lincoln County homes had pleural abnormalities. Pleural abnormalities were detected in 17.1% of people who reported using vermiculite for gardening. Play in vermiculite piles and at the ball field near an expansion plant was associated with pleural abnormalities in 15.9% and 14.9% of people, respectively.

HRCT detected extrapleural or subcostal fat in 15 (4.25%) participants. Only one of these 15 persons also demonstrated a pleural abnormality on HRCT scan while 14 persons did not (data not shown). Of the 14 persons who demonstrated an extrapleural/subcostal fat but no pleural abnormality, four (28.6%) were former vermiculite workers, two (14.3%) were household contacts, and eight (57.1%) were recreationally exposed to asbestos. Five (35.7%) of the 14 persons never smoked, nine (64.3%) were ex-smokers; there were no current smokers among these 14 persons. All 14 people were either overweight or obese (mean BMI 32.0 + 2.6, ranging from 28.5 to 38.5), placing them into either third or fourth BMI quartiles. The BMIs of the 14 people were much higher than those of the people who had both pleural abnormalities and extrapleural/subcostal fat on HRCT scan (BMI of 23.5) and higher than the BMIs of the remaining 337 study participants who demonstrated no extrapleural/subcostal fat on HRCT scan (mean 30.1 + 6.7) (data not shown).

## Discussion

HRCT of the lungs is widely available to and frequently requested by US pulmonologists in a variety

**Table 2.** Demographic and other characteristics of the study participants — Libby, MT, 2001

| Characteristics | *N* | Pleural abnormality identified | | | No pleural abnormality identified | | |
|---|---|---|---|---|---|---|---|
| | | *n* | %[a] | Mean (SD) | *n* | %[b] | Mean (SD) |
| Sex (%) | | | | | | | |
| Male | 144 | 39 | 39.8 | | 105 | 41.2 | |
| Female | 209 | 59 | 60.2 | | 150 | 58.8 | |
| Age (years) | 353 | 98 | | 58.0 (12.43) | 255 | | 51.7 (13.42) |
| Age categories | | | | | | | |
| 18–44 | 104 | 20 | 20.4 | | 84 | 32.9 | |
| 45–64 | 183 | 48 | 49.0 | | 135 | 52.0 | |
| ⩾65 | 66 | 30 | 30.6 | | 36 | 14.2 | |
| Cigarette smoking | | | | | | | |
| Never | 160 | 35 | 35.7 | | 125 | 49.0 | |
| Former | 120 | 35 | 35.7 | | 85 | 33.3 | |
| Current | 73 | 28 | 28.6 | | 45 | 17.7 | |
| BMI[c] ($n = 352$) | | | | | | | |
| Male | 144 | 39 | | 27.8 (5.39) | 105 | | 29.5 (4.91) |
| Female | 208 | 59 | | 28.0 (5.30) | 149 | | 32.1 (7.81) |
| BMI[c] — by age group, national comparison ($n = 352$) (%) | | | | | | | |
| 19–24 | 82 | 35 | 35.7 | | 47 | 18.5 | |
| 25–29 | 113 | 38 | 38.8 | | 75 | 29.5 | |
| ⩾30 | 157 | 25 | 25.5 | | 132 | 52.0 | |
| BMI[c] — by quartiles | | | | | | | |
| Low 1st quartile | 61 | 26 | 26.5 | | 35 | 13.8 | |
| 2nd quartile | 63 | 19 | 19.4 | | 44 | 17.3 | |
| 3rd quartile | 98 | 34 | 34.7 | | 64 | 25.2 | |
| High 4th quartile | 130 | 19 | 19.4 | | 111 | 43.7 | |
| Residence in Libby (years) | 353 | 98 | | 35.2 (17.21) | 255 | | 28.5 (13.73) |
| Residence in Libby | | | | | | | |
| 0–14 | 51 | 10 | 10.2 | | 41 | 16.1 | |
| 15–22 | 61 | 12 | 12.3 | | 49 | 19.2 | |
| 23–34 | 106 | 26 | 26.5 | | 80 | 31.4 | |
| ⩾35 | 135 | 50 | 51.0 | | 85 | 33.3 | |
| Number of exposure pathways | | | | | | | |
| 1–3 | 78 | 8 | 8.2 | | 70 | 27.4 | |
| 4–5 | 93 | 28 | 28.6 | | 65 | 25.5 | |
| ⩾6 | 182 | 62 | 63.2 | | 120 | 47.1 | |

[a]Calculated of 98 people.
[b]Calculated of 255 people.
[c]BMI is the body mass index (body weight in kg/height$^2$ in m).

of practice settings (Scatarige et al., 2002). HRCT was chosen for this study over conventional computer tomography (CT) because HRCT detects asbestos-related pleural abnormalities more frequently than does conventional CT (Aberle et al., 1988). This study utilized HRCT in both supine and prone positions because scanning both positions greatly enhances ability to evaluate lung parenchyma (Gamsu et al., 1989). The HRCT protocol also called for a bone reconstruction algorithm to improve spatial resolution (Mayo et al., 1987).

This study detected pleural abnormalities in 98 (27.8%) of the 353 people tested in the 2000 medical testing program whose chest radiographs were classified indeterminate (only one of the three B-reader chest radiograph reviewers had reported a pleural abnormality). Benign pleural abnormalities are the most common manifestation of asbestos exposure (Rosenstock and Hudson, 1987; Ameille and Letourneux, 1998, 1999; Karjalainen et al., 1994). Pleural plaques, the most frequent observed lesions, rarely develop until 20 years after asbestos exposure (Lordi and Reichman, 1993).

**Table 3.** Crude and adjusted ORs, by exposure group, of pleural abnormalities detected on HRCT — Libby, MT, 2001

| HRCT findings | *n* (%) | Crude OR | 95% CI | Adjusted OR[a] | 95% CI |
|---|---|---|---|---|---|
| Pleural abnormalities consistent with exposure to asbestos, any type | | | | | |
| People recreationally exposed (reference group, $n = 199$) | 29 (14.6) | 1 | | 1 | |
| Former workers ($n = 55$) | 22 (40.0) | 3.91 | 2.00–7.62 | 3.96 | 1.86–8.41 |
| Household contacts ($n = 99$) | 47 (47.5) | 5.30 | 3.03–9.25 | 6.32 | 3.47–11.54 |
| Overall ($n = 353$) | 98 (27.8) | | | | |
| Rounded atelectasis | | | | | |
| People recreationally exposed (reference group, $n = 199$) | 1 (0.5) | | | | |
| Former workers ($n = 55$) | 0 | | | | |
| Household contacts ($n = 99$) | 2 (2.0) | | | | |
| Overall ($n = 353$) | 3 (0.9) | | | | |
| Pleural calcification | | | | | |
| People recreationally exposed (reference group, $n = 199$) | 8 (4.1) | 1 | | 1 | |
| Former workers ($n = 55$) | 10 (18.2) | 5.31 | 1.98–14.20 | 4.98 | 1.69–14.67 |
| Household contacts ($n = 99$) | 22 (22.2) | 6.82 | 2.91–15.98 | 8.15 | 3.30–20.10 |
| Overall ($n = 353$) | 40 (11.3) | | | | |

[a]Adjusted by age (>65 vs. <65), sex, duration of residence in Libby (>35 years vs. <35 years), and smoking status (ever vs. never).

This study and the 2000 Libby medical testing program used the same criteria to reach decisions about the chest radiographs and HRCT: agreement between at least two of the three evaluators. Each medical testing participant whose chest radiograph was classified indeterminate was notified if one of the three B-readers detected a pleural abnormality. However, overall chest radiograph results for these participants were deemed negative because two B-readers classified the radiographs as normal. Therefore, the HRCT scan reversed the negative chest radiograph results for 98 of the 353 people tested in 2000.

Previous screenings of former construction, shipyard, and asbestos workers (Aberle et al., 1988; Gamsu et al., 1989; Gamsu, 1991; Koskinen et al., 1996, 1998) and studies that found asbestos-related pleural changes in household contacts of shipyard workers (Kilburn et al., 1985) support the results of this study. Also, several previous studies show that conventional CT is superior to chest radiography in detecting both asbestos-related pleural abnormalities (Tiitola et al., 2002; Oksa et al., 1994; Kim et al., 2001) and interstitial abnormalities (Kido et al., 1986; Topcu et al., 2000; Leipner et al., 1984; Zhang et al., 1995). The density resolution of conventional CT permits visualization of abnormalities not found with chest radiography (Weinberger and Drazen, 1999; Zerhouni et al., 1985; Stein et al., 1987; Gonzalez et al., 1997). HRCT is even more sensitive than conventional CT in detecting asbestos-related pleural abnormalities, although images were obtained only at preselected sites and covered a small fraction of the total pleura and lung (Gamsu et al., 1989; Gamsu, 1991). The Gamsu studies involved a large group of workers who had been occupationally exposed to asbestos. Results were similar in a study that used HRCT on 70 asymptomatic shipyard workers whose chest radiographs had been judged "normal" by outside readers (Neri et al., 1994). Among the 70 workers, 34 (49%) were found on HRCT to have pleural plaques, six (9%) had parenchymal abnormalities, and 13 (19.6%) had both parenchymal abnormalities and pleural plaques; no pathologic findings were shown in the remaining 17 (24%) workers. Neri et al. (1994) also found that HRCT can detect pulmonary or pleural changes caused by exposure to asbestos before the onset of clinical symptoms. Parenchymal abnormalities consistent with asbestosis were found in 33% of asbestos-exposed people studied by CT, whereas conventional chest radiographs were abnormal in only 16% (Katz and Kreel, 1979). Two other studies indicated similar results (Sperber and Mohan, 1984; Yoshimura et al., 1986). However, a previous occupational study found that conventional CT did not detect asbestosis in 10 (19%) of the 53 people whose chest radiographs were abnormal (Begin et al., 1984). The Begin et al. (1984) study compared the ability of posteroanterior, four-view radiographs with conventional CT of the chest to detect asbestos-related pleural and parenchymal fibrosis in 127 workers occupationally exposed to asbestos. The study probably used an early generation CT scanner and protocols.

Comparisons between the current study and these previous studies are problematic because the study designs differed considerably. The previous studies varied by the numbers of reviewers used for CT scan evaluations, degree of participants' exposures, and amount of demographic and medical information released to the readers. Finally, none of these early

**Table 4.** Crude and adjusted ORs for pleural abnormalities on HRCT — Libby, MT, 2001

| Characteristic | *N* | Pleural abnormality identified *n* (%) | No pleural abnormality *n* (%) | Crude OR (95% CI) | Adjusted OR (95% CI) |
|---|---|---|---|---|---|
| Former workers | | | | | |
| No | 298 | 76 (25.5) | 222 (74.5) | 1 | 1 |
| Yes | 55 | 22 (40.0) | 33 (60.0) | 1.95 (1.07–3.55) | 2.09 (1.05–4.18)[a] |
| W.R. Grace workers | | | | | |
| No | 242 | 90 (37.2) | 152 (62.8) | 1 | 1 |
| Yes | 11 | 8 (72.7) | 3 (27.3) | 7.44 (1.93–28.64) | 13.5 (3.22–56.64)[a] |
| Secondary contractors | | | | | |
| No | 337 | 88 (26.1) | 249 (73.9) | 1 | 1 |
| Yes | 16 | 10 (62.5) | 6 (37.5) | 4.72 (1.67–13.35) | 4.20 (1.41–12.51) [a] |
| Household contacts | | | | | |
| No | 254 | 51 (20.1) | 203 (79.9) | 1 | 1 |
| Yes | 99 | 47 (47.5) | 52 (52.5) | 3.60 (2.18–5.93) | 4.67 (2.68–8.14) [a] |
| Cigarette smoking | | | | | |
| Never | 160 | 35 (21.9) | 125 (78.1) | 1 | 1 |
| Ever | 193 | 63 (32.6) | 130 (67.4) | 1.73 (1.07–2.80) | 1.55 (0.94–2.55)[b] |
| Former | 120 | 35 (29.2) | 85 (70.8) | 1.47 (0.85–2.53) | 1.18 (0.67–2.10)[b] |
| Current | 73 | 28 (38.4) | 45 (61.6) | 2.22 (1.22–4.06) | 2.29 (1.23–4.28) [b] |
| Popped vermiculite | | | | | |
| Never | 173 | 43 (24.9) | 130 (75.1) | 1 | 1 |
| Sometimes | 158 | 42 (26.6) | 116 (73.4) | 1.10 (0.67–1.79) | 1.22 (0.73–2.05)[a] |
| Frequently | 20 | 13 (65.0) | 7 (35.0) | 5.61 (2.10–14.98) | 6.88 (2.49–19.02) [a] |
| Vermiculite insulation in home | | | | | |
| No | 149 | 39 (26.2) | 110 (73.8) | 1 | 1 |
| Yes | 174 | 59 (33.9) | 115 (66.1) | 2.04 (1.22–3.39) | 2.09 (1.23–3.55)[a] |
| Age ⩾ 65 years | | | | | |
| No | 287 | 68 (23.7) | 219 (76.3) | 1 | 1 |
| Yes | 66 | 30 (45.5) | 36 (54.5) | 2.69 (1.54–4.68) | 2.30 (1.30–4.08)[c] |
| Residence in Libby ⩾ 35 years | | | | | |
| No | 218 | 48 (22.0) | 170 (78.0) | 1 | 1 |
| Yes | 135 | 50 (37.0) | 85 (63.0) | 2.08 (1.30–3.35) | 1.98 (1.22–3.20)[d] |

[a]Adjusted for age, sex, duration of residence in Libby, and smoking status.
[b]Adjusted for age, sex, work with asbestos, and duration of residence in Libby.
[c]Adjusted for sex, duration of residence in Libby, and smoking status.
[d]Adjusted for sex and smoking status.

investigations studied people with indeterminate chest radiograph.

Among people with indeterminate chest radiographs, former vermiculite mine/mill workers and their household contacts may be at highest risk of having asbestos-related pleural abnormalities detected on HRCT. Particularly, daughters and spouses of the former vermiculite workers in our study had the highest prevalence of pleural abnormalities on HRCT: 56.7% and 50.0%, respectively.

**Table 5.** Comparison of exposure pathways between people exposed to vermiculite through recreational or other activities with and without pleural abnormalities on HRCT — Libby, MT, 2001

| Exposure pathway | N | Pleural abnormality identified | | No pleural abnormality identified | |
|---|---|---|---|---|---|
| | | N | % | n | % |
| Handled vermiculite insulation[a] | | | | | |
| Never | 79 | 4 | 5.1 | 75 | 94.9 |
| Sometimes | 95 | 20 | 21.1 | 75 | 78.9 |
| Frequently | 20 | 4 | 20.0 | 16 | 80.0 |
| Used vermiculite for gardening | 111 | 19 | 17.1 | 92 | 82.9 |
| Had vermiculite insulation in Lincoln County home | 92 | 17 | 18.5 | 75 | 81.5 |
| Participated in recreational activities along Rainey Creek | | | | | |
| Never | 59 | 9 | 15.3 | 50 | 84.7 |
| Sometimes | 102 | 14 | 13.7 | 88 | 86.3 |
| Frequently | 38 | 6 | 15.8 | 32 | 84.2 |
| Played at ball field near expansion plant | | | | | |
| Never | 58 | 8 | 13.8 | 50 | 86.2 |
| Sometimes | 73 | 11 | 15.1 | 62 | 84.9 |
| Frequently | 68 | 10 | 14.7 | 58 | 85.3 |
| Popped vermiculite | | | | | |
| Never | 111 | 18 | 16.2 | 93 | 83.8 |
| Sometimes | 83 | 9 | 10.8 | 74 | 89.2 |
| Frequently | 5 | 2 | 40.0 | 3 | 60.0 |
| Played in vermiculite piles[b] | | | | | |
| Never | 135 | 19 | 14.1 | 116 | 85.9 |
| Sometimes | 44 | 7 | 15.9 | 37 | 84.1 |
| Frequently | 19 | 3 | 15.8 | 16 | 84.2 |
| Had contact with vermiculite during other activities[a] | | | | | |
| Never | 119 | 18 | 15.1 | 101 | 84.9 |
| Sometimes | 69 | 9 | 13.0 | 60 | 87.0 |
| Frequently | 10 | 1 | 10.0 | 9 | 90.0 |
| Was exposed to dust at non-W.R. Grace/Zonolite jobs | 65 | 9 | 13.9 | 56 | 86.1 |
| Had asbestos products in Lincoln County home | 49 | 8 | 16.3 | 41 | 83.7 |
| Used vermiculite around the home | 17 | 2 | 11.8 | 15 | 88.2 |
| Was exposed to asbestos in military | 5 | 1 | 20.0 | 4 | 80.0 |

[a]Some people did not provide answers in these categories.
[b]People may be included in more than one category.

Fifty-five of the 98 study participants whose HRCT demonstrated pleural abnormality reported at least one of the symptoms considered to be the most specific for exposure to asbestos; cough, shortness of breath, or pleuritic chest pain. However, 43 people (43.9%) did not report any of these symptoms. This suggests that HRCT may have detected pleural abnormalities in these people before onset of clinical symptoms. Previous studies that showed HRCT effectively detected pleural abnormalities in asymptomatic workers (Koskinen et al., 1998; Neri et al., 1994, 1996; Falaschi et al., 1993) support these findings. In addition, 40 out of the 98 participants (40.8%) who had positive HRCT scans in the current study demonstrated pleural calcification on HRCT. Thirty out of these 40 participants (75.0%) reported no occupational exposure to either vermiculite or asbestos. Pleural calcification has been shown to be associated with heavy exposure to asbestos (Neri et al., 1994) that usually lasted for at least 20 years (Lodi and Reichman, 1993).

HRCT of three (0.9%) current study participants demonstrated rounded atelectases; 49 (13.9%) people showed parenchymal bands caused by pleuroparenchymal scars longer than 2 cm and thicker than 1 mm; and seven (2.0%) people demonstrated subpleural curvilinear lines on scans (data not shown). Earlier studies indicating that these abnormal features of asbestosis can be detected by HRCT (Ameille and Letourneux, 1998; Gamsu et al., 1989; Kishimoto et al., 2000) support these findings.

Fifteen people in the current study demonstrated extrapleural/subcostal fat on HRCT; just one of these people also had a pleural abnormality on HRCT. Therefore, HRCT clarified the indeterminate chest radiographs for 14 people as having extrapleural/subcostal fat rather than a pleural abnormality. These findings are supported by previous studies indicating that extrapleural fat can mimic pleural thickening on chest radiographs in people exposed to asbestos and that conventional CT and HRCT can distinguish between the two (Sargent et al., 1984; Friedman et al., 1988). In another study, chest HRCT of 23 people who had been exposed to low levels of asbestos and whose right anterior oblique (RAO) view chest radiographs showed pleural thickening, revealed pleural abnormalities in only six people (26%) (Ameille et al., 1993). Considering HRCT as the gold standard, the positive predictive value of RAO was therefore only 13–26%; most of the 17 false-positive diagnoses resulted from significant pleural fat.

Of 353 study participants in the current study, 73 people (20.7%) were current smokers at the time of testing, including 10 (18.2%) former vermiculite workers. Although these proportions are similar to those found in another cohort of asbestos workers (16.4%) (Osinubi et al., 2002), they represent a substantial number of vermiculite workers who are being exposed to both asbestos and smoking. Smoking increases the risk for lung cancer from asbestos. Asbestos workers have 2–3 times greater chance of developing lung cancer than people in the general population (Lordi and Reichman, 1993). However, asbestos workers who are heavy cigarette smokers may have an 80–90-fold increased risk for lung cancer (Lordi and Reichman, 1993; Selikoff et al., 1968). A previous mortality study that involved large groups of heavily exposed asbestos insulators and blue-collar cigarette smokers not exposed to asbestos found that the standardized mortality ratio was 5.17 for non-smoking asbestos workers, 10.85 for smokers not exposed to asbestos, and 53.24 for asbestos-exposed smokers (Hammond et al., 1979).

Despite their higher sensitivity, the use of CT — either conventional or high resolution — in screenings for asbestos-related chest abnormalities is under debate. Computed tomography results in greater radiation exposure to the patient than does chest radiography (Evans et al., 1989; Murphy and Heaton, 1985; Rueter et al., 1990). The radiation dose from HRCT to the chest in this study was about 2–5 rads. This dose was approximately 15 times greater than that of a posteroanterior chest radiograph at the skin surface of the breast, and approximately three times greater than the dose of a mammogram to the breast. CT also can result in false-positive findings that would require follow-up CT or HRCT procedures and, therefore, additional irradiation.

No standard system exists for classifying CT or HRCT scans for asbestos-related abnormalities (International Labour Office (ILO), 1980; Kraus et al., 1996). The International Expert Meeting on Asbestos, Asbestosis, and Cancer, Helsinki, 1997 (Tossavainen et al., 1997) indicated a need for (1) development of a standardized system for the reporting of HRCT for asbestos-related disorders similar to the ILO system and (2) studies on the specificity of lesions of the pleura visualized by HRCT as markers of asbestos exposure. Meeting participants concluded that "HRCT can confirm radiological findings of asbestosis and show early changes not seen on chest X-ray, but should be performed only in selected cases".

On February 22 and 23, 2000, EPA (Region VIII) and ATSDR convened a panel of experts on asbestos-related exposure and health effects. One important topic related to the current (February 2000) recommendations for screening for asbestos-related health effects in an exposed population. Most of participants agreed that HRCT scans were not suitable for screening because of the cost and radiation doses associated with the procedure. However, these experts also noted that HRCT is more sensitive and specific for detecting pleural changes than the standard posterior–anterior chest radiograph (pers. Comm.). Despite the expense and additional radiation exposure, HRCT technology might be useful for additional testing of high-risk people with normal chest radiographs who have respiratory symptoms consistent with asbestosis.

## Limitations and sources of bias

The results of this study are subject to several limitations. First, 7–11 months elapsed between the chest radiographs taken during the 2000 medical testing program and the HRCT. However, the chest radiographs were completed in 2000, 10 years after the W.R. Grace/Zonolite mine/mill facilities closed. Also, the duration of occupational exposure was as long as 17 years for former W.R. Grace/Zonolite employees and up to 33 years for secondary contractors. Additionally, 88 (90%) of the 98 people who had pleural abnormalities on HRCT lived in Libby for at least 15 years and as long as 83 years (mean duration, 35.2 years). Nevertheless, it is possible that at least some of the pleural abnormalities detected on HRCT developed during those 7–11 months.

Second, there were a number of people who refused to participate in the study. The targeted sample size for the current study was 330 scans; 353 ultimately were obtained. Although this goal was achieved, 157 eligible people refused to participate in the study. A substantial number of them, 60 people (38.2%), were former vermiculite workers and their household contacts — the two exposure categories with the highest prevalence of pleural abnormalities on HRCT scan. To achieve the study target, we tested more people whose exposures were likely to be lowest among the three exposure categories — people who were exposed to vermiculite during direct recreational or other activities. If we had tested more former workers and their household contacts, the prevalence of asbestos-related abnormalities on HRCT might have been greater. Third, no HRCT of people with totally negative or totally positive chest radiographs were completed. Therefore, we were not able to calculate the following statistical measures for chest radiograph screening: sensitivity $P(T+|D+)$; probability of false-negative $P(T-|D+)$; specificity $P(T-|D-)$; probability of false-positive $P(T+|D-)$; positive predictive value $P(D+|T+)$; or complement of positive predictive value $P(D-|T+)$, where for example, $P(T-|D-)$ is the probability ($P$) of observing a negative test ($T-$) for a person without disease ($D-$).

Finally, no widely accepted standardized system exists for diagnosing and categorizing asbestos-related disorders by HRCT scan that is similar to the ILO system of classifying chest radiographs for pneumoconiosis. Therefore, the identification and reporting of asbestos-related abnormalities can be observer-related and make interstudy and intrastudy comparison difficult.

## Conclusions

This study suggests that HRCT might be a useful screening tool for former vermiculite workers and their household contacts who have indeterminate chest radiographs. An HRCT also may be helpful in confirming a suspicious finding on chest radiograph, particularly in a high-risk person (e.g., persons exposed to vermiculite through direct recreational activities). This study also demonstrates that HRCT may detect asbestos-related pleural abnormalities in people exposed to asbestos through either occupational or non-occupational pathways before the onset of clinical symptoms. The International Expert Meeting on New Advances in the Radiology and Screening of Asbestos-Related Diseases of February 9–11, 2000, concluded that the primary prevention of disease through elimination of hazardous exposure should replace screening (Tossavainen, 2000). Unfortunately, for former asbestos workers, their household contacts, and people exposed to asbestos through recreational activities in Libby, primary prevention is no longer possible. Secondary prevention through effective screening and smoking cessation are among the only preventive methods remaining. However, the lack of participation in screening may demonstrate a lack of knowledge about adverse asbestos-related health outcomes in the Libby community and emphasizes the importance of public health education and outreach campaigns in such communities prior to screening efforts.

## Acknowledgement

The authors thank Lori Hutwagner, MS, at the Centers for Disease Control and Prevention, Atlanta, GA, USA, for her help with data set and initial analysis for the study this manuscript describes.

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