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therefore trapped or emitted as olivine or forsterite particles" (p. 1). An industry-related lab reported that 99.9% of the mass of original asbestos fibers was broken down into nonfibrous magnesium silicates" during brake usage (Williams & Muhlbaier, 1982, p. 70). These investigators did acknowledge that while brake usage was responsible for a minor fraction of asbestos in ambient air, there could be noticeable increases from such sources in high braking areas such as toll booths.

Jaffrey (1990) found that analysis by transmission electron microscopy of air samples collected adjacent to high-traffic areas revealed that asbestos fibers were being released from brakes and clutches from vehicular traffic. His study showed quantifiable numbers of asbestos fibers including some long fibers (>5 μm). Additionally, in contrast with the findings of Jacko et al. (1973) are findings in analysis of air samples during brake repair and samples of worn brake drums as reported by Rohl and Langer (Rohl et al., 1976). These investigators reported that unaltered chrysotile was observed. It was suggested from this study that "fiber concentrations frequently in excess of regulated limits were common" (p. 110) in brake lining maintenance, thus emphasizing the potential of exposure to after-use asbestos from such products.

Limited information exists as to exposures during either replacement of clutch components or in operations where the processes are used to refabricate the used clutches. A patient evaluated in our facility had worked in such a refabrication facility and had been diagnosed with asbestos-related disease. The tissue and sputum analysis revealed asbestos bodies. Clutches were provided that were reported as similar to those repaired in the facility. This present study examined the historical data on exposure and compared the morphological characteristics of material obtained from the clutch faces with characteristics of the asbestos fibers found in the worker's lung.

CLINICAL BACKGROUND

The patient was a 59-year-old man whose admission record indicated he had complained of both shortness of breath and persistent cough. The clinical evaluation revealed diffuse interstitial fibrosis at the lung bases as well as bilateral apical pleural scarring. The patient also was found to have coarse rales on clinical examination, and pulmonary function revealed severe restrictive lung disease and reduced diffusion capacity. The individual had smoked one to one and a half packs of cigarettes per day for 35–40 years and a history of working in a facility that reprocessed clutches. His role in the process included the use of drilling connectors as necessary for separation of the components for further processing. There was no other known occupational history of exposure to asbestos. A fiber-optic bronchoscopy was performed and the washings were found to contain appreciable numbers of ferruginous bodies. The diagnosis at this admission was determined as eosinophilic pneumonia with an underlying complication of asbestos-induced fibrosis.

The patient became more dyspneic and suffered from weight loss. In a subsequent admission, a large mass was detected in the right hilar area by computerized tomography, which also confirmed severe interstitial fibrosis (Figure 1). A computerized tomography-guided biopsy was used to determine the mass was a small-cell undifferentiated carcinoma. Formalin fixed tissue was collected at the time of autopsy and used for determination of asbestos burden by light and electron microscopy.

METHOD

Two bags containing used clutches similar to those used for refrabication were received. Eight random clutches were selected and external debris was carefully removed from their surface. The exposed face from each of the clutches was washed with a measured flow (100 µl) of distilled water. The rinse along with the suspended particles was collected and placed in a vial. The rinses were pooled and increased to a volume of 10 ml. The sample was gently swirled to resuspend the particulates and allowed to settle for one minute. One half of the volume was filtered through a 25-mm (0.2-µm pore) polycarbonate (Nuclepore) filter. The particulates were coated with evaporated carbon and the filter matrix was

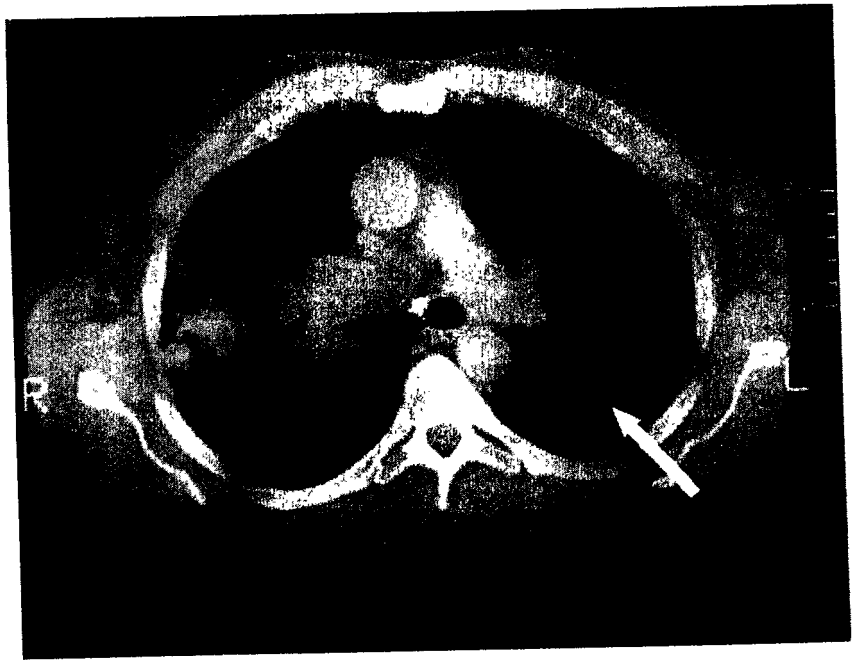

FIGURE 1. Computerized tomography (CT) scan of the chest. This slice shows a large right hilar mass enveloping the right mainstem bronchus (black arrow). Dense consolidation is noted just lateral to the right hilar mass compatible with obstructive pneumonitis. Severe interstitial changes are seen bilaterally consistent with the diagnosis of asbestosis (white arrow).

removed with chloroform. The carbon replicas mounted on 100-mesh grids were examined at magnifications of up to 50,000× in a JEOL 1200EX analytical transmission electron microscope, which was equipped with an EDAX DX Prime x-ray energy-dispersive analysis system.

Tissue Preparation

Formalin-fixed lung tissue was submitted for analysis to determine the presence of asbestos. There were 18 sites sampled and a digest pool was made that contained 0.3814 g dry weight. The pool was carried through a modified bleach digestion procedure (Williams et al., 1982), and aliquots were collected on filters. For light microscopy analysis, one-fourth of a mixed cellulose ester filter (0.22-μm pores) that contained 0.0346 g dry weight was mounted on a glass slide and cleared by exposure to an acetone vapor. The transparent wedge of the filter was then scanned for the presence of ferruginous bodies by light microscopy (AO Microstar light microscope) at 200/400×. A ferruginous body, which consisted of an elongated structure with rust-colored, often beaded surface features and a clear fibrous core, was considered to be an asbestos body.

The preparation for electron microscopy analysis representing 0.0069 g dry weight was collected on a 25-mm polycarbonate (0.2-μm pores) filter. Strips of the carbon-coated filter were cut and the filter matrix was removed by exposure to chloroform, which produced a carbon extraction replica containing the entrapped particulates. All fibers with an aspect ratio $\geq$5:1 and equal to or longer than 0.5 μm were evaluated at 20,000× in the analytical electron microscope, and a scan was carried out at low magnification (1200×) for the presence of ferruginous bodies.

RESULTS

The clutches showed considerable physical wear (Figure 2). There were abundant fibers and some bundles found in the collected sample of the clutch washings. These particulates could be classified as bundles, fibrils, or clusters of chrysotile asbestos (Figure 3). Confirmation of the abundance of chrysotile structures, which were readily freed via a gentle rinse, is that there were up to 1000 fibers per grid opening (Figure 4). There were 2% of the fibrous particulates in one sampling, which had a diameter greater than 0.25 μm. Five percent of the fibers were between 0.24 and 0.11 μm in diameter, while 93% were less than 0.1 μm in diameter. Most of these were typically single chrysotile fibrils with diameters ranging from 0.04 to 0.08 μm. Regarding length, 90% of the structures were less than 8 μm in length while 75% were less than 5 μm. Less than 1% of the asbestos fibers were larger than 20 μm. The shortest fibril was 2 μm, while the longest was 60 μm and had a diameter of only 0.06 μm. The serpentine asbestos components of the

FIGURE 2. Illustration of the conditions of typical clutches that were scheduled for relabrication. The surface of the material shows conspicuous wear.

FIGURE 3. Material collected from the surface of the used clutches contained various types of chrysotile structures. Magnification 12,000×

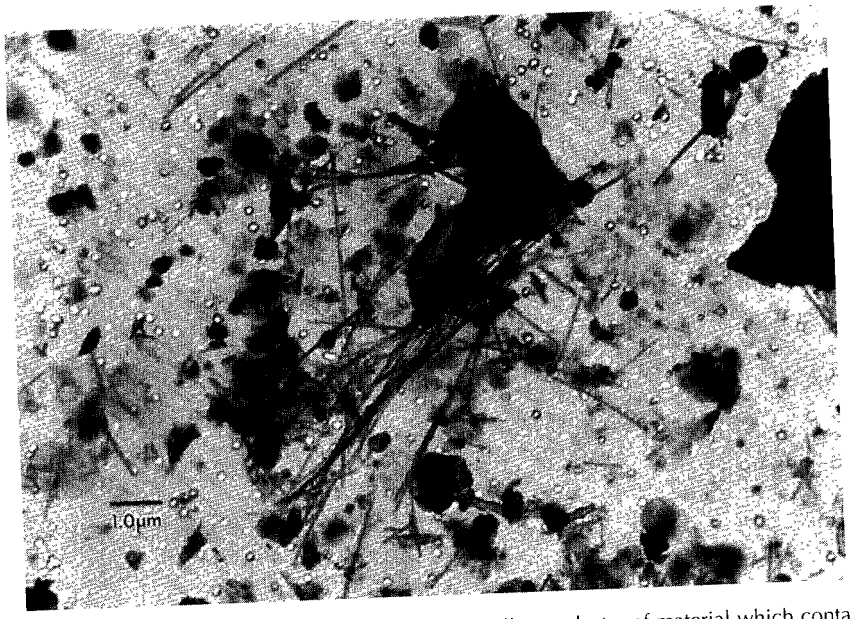

FIGURE 4. This figure shows both individuals fibrils as well as a cluster of material which contains the individuals fibrils as well as multiple fibrils. Magnification 10,000×.

particulates were readily classifiable as chrysotile by the typical scroll appearance at higher magnification (Figure 5) and as further confirmed by the elemental composition by x-ray energy dispersive analysis (Figure 6) as well as crystalline composition confirmed by selected-area diffraction. There were no indications of fiber degradation or conversion that could be detected.

Tissue analysis confirmed the presence of appreciable numbers of asbestos bodies (3810 per gram of dry tissue). These entities represented a portion of the longer population (>8 μm) of asbestos fibers that had been inhaled and eventually coated through interactions with pulmonary macrophages. Several of the bodies were obviously formed on bundles, not an unusual finding characterizing such core material (Dodson et al., 1982, 1983). The analysis of the cores by analytical transmission electron microscopy confirmed the cores, whether of several fibrils or of more complex composition, to be chrysotile asbestos (Figure 7). There were occasional bundles of chrysotile fibrils; however, the most commonly encountered finding was chrysotile in the form of an individual fibril. An example of the compositional features was demonstrated in a continuous 33-fiber count by transmission electron microscopy, where 30 of the fibers were chrysotile with an average length of 12.95 μm and an average diameter of 0.063 μm. There was one anthophyllite fiber, one magnesium aluminum ferrosilicate, and one titanium fiber also found in the count area. The uncoated chrysotile fiber burden in the tissue was determined to be greater than 2 million chrysotile structures (fibrils combined with bundles) per gram of dry tissue.

FIGURE 5. This higher magnification view of the chrysotile components clearly shows the tubular configuration consistent with the morphology of chrysotile. Magnification 100,000×

DISCUSSION

The sample of the loose surface material from the used clutch faces contained a large number of bundles, fibers, and fibrils. These structures were identified by ultrastructural morphology, x-ray energy-dispersive analysis, and selected-area diffraction, as chrysotile asbestos. There were no discernable changes in the fibers or any indication of transitional forms to another mineralogical form. There were abundant individual fibrils as well as bundles of fibers that were in the respirable range (Timbrell, 1965). These included both short (<5 μm) and longer fibers. The majority of the freed fibers were less than 8 μm, which is consistent with data from air samples in many occupational exposure settings. The process for removal of the loose material utilized a gentle rinse with water. Given the potential

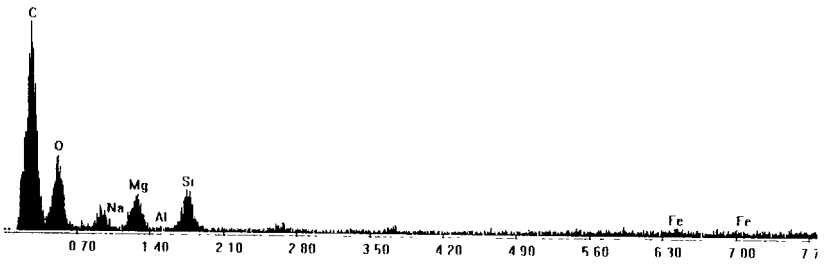

FIGURE 6. X-ray energy-dispersive pattern from the retrieved material indicated elemental composition and peak ratios consistent with chrysotile asbestos.

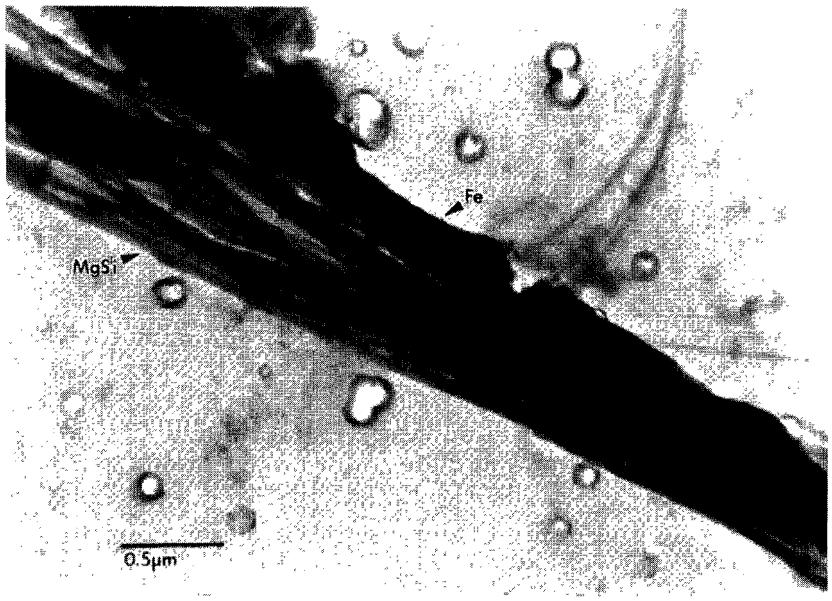

FIGURE 7. This higher magnification view of the core material of a ferruginous body shows both the multiple components of chrysotile that make up the core material and the tubular array consistent with chrysotile. Magnification 40,000×.

for chrysotile to separate under trauma, it is reasonable that a physical disturbance of the surfaces of the clutches would create even larger numbers of respirable size fibers as the aggregates break into smaller units. These findings are in contrast with those suggesting that asbestos and friction products are "pulverized and trapped in the housing" or converted to a nonasbestos mineral during use (Jacko et al., 1973; Williams et al., 1982).

The lung tissue from the worker contained both short fibers of chrysotile and longer fibers (including the cores of the ferruginous body population). There is considerable contrast between the ferruginous body burden in this individual's lung (3810 per gram of dry tissue) and that constituting the burden of the general population of nonoccupationally exposed individuals living in East Texas. Our studies indicate that in this group, the ferruginous body burden ranges from 0 to 200 ferruginous bodies per gram of dry lung tissue (Dodson et al., 1983, 1999).

The finding of 2 million chrysotile structures per gram of dry tissue also contrasts with our findings regarding asbestos burden in nonoccupationally exposed individuals from the East Texas region. In a study of 33 such individuals, only 14 were found to be positive for chrysotile fibers in the lung (Dodson et al., 1999). In a numerical comparison, the average of uncoated chrysotile fibers for the 14 positive individuals consisted of 68,000 fibers per gram dry lung whereas the average for all 33 individuals was 29,000 fibers per gram of dry weight of lung tissue (Dodson et al., 1999).

The numbers of uncoated chrysotile fibers are of even greater relevance given the impact that clearance can take place from time of first exposure to that of death. It is recognized that chrysotile, being a curved fiber, is less respirable when compared to a comparable-length amphibole fiber. Furthermore, it has been reported that chrysotile (more readily inhaled in a short form) clears more rapidly from the lung than amphiboles (Hammar & Dodson, 1994). An expected difference in this case report, was in the limited numbers of bundles found within the tissue samples as compared with the clutch washings. While this could be explained by the limitations of respirability (as based on "theoretical diameter"), there were adequate numbers of such bundles in the workplace that some bypassed entrapment in the upper airways and were found in the parenchyma.

The study shows a striking similarity between chrysotile structures obtained from the faces of clutches that were similar to those being repaired by the worker and the chrysotile population found in the lung tissue. These data suggest that work with such friction materials in the after-use phase may result in appreciable exposure to asbestos dust, sufficient to cause clinical disease of the type seen in this case, including interstitial fibrosis and lung cancer.

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