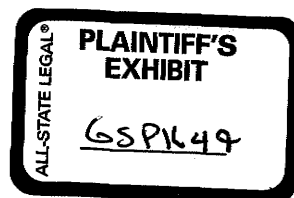


Interpretation of Airborne Asbestos Measurements



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Transmission electron microscopy (TEM) is the preferred method of measuring airborne asbestos in buildings, but TEM measurements cannot be used directly in the existing equations relating risk to exposure because the equations are based on measurements made with a different technique—phase contrast microscopy (PCM). Comparison between measurements made by different methods is not simple because the methods differ in the size of particles they can detect, and the relationship between exposure and disease is thought to depend on, among other things, asbestos fiber size. Previous suggestions for converting TEM measurements to PCM equivalents lack generality because they fail to take into account the size distribution of the asbestos particles and the expectation that fiber-size distributions in current nonoccupational environments could differ from the workplaces of the past on which the risk equations are based. A mathematical model is presented for investigating the conversion of airborne asbestos measurements made by one method to an equivalent measurement made by another method. "Equivalent" means having the same potential to cause disease. The model clarifies the issues of concern and suggests approaches for obtaining meaningful conversion factors that will allow TEM measurements to be used in PCM-based risk equations.

KEY WORDS: Asbestos; risk interpretation; transmission electron microscopy; phase contrast microscopy; fiber size distribution; relative potency.

1. INTRODUCTION

An association between exposure to airborne asbestos and cancer has been well established.⁽¹⁻³⁾ In common with most toxic substances, however, the quantitative relationship between the level of asbestos exposure and the risk of disease, especially at the low levels associated with nonoccupational exposure, is less clear. Models relating asbestos exposure to risk have been fitted to data from epidemiologic studies of occupational exposures

and extrapolated to estimate risk at low exposure levels. Although the models used for asbestos share many of the limitations common to high- to low-dose extrapolation, it is not our intention to review these limitations or suggest alternatives. Instead, we address an important measurement problem that affects the use of the risk models for asbestos—namely, the comparability of airborne asbestos measurements made by different measurement techniques. This question has become increasingly important as regulatory authorities, courts, investors, building owners, and building occupants grapple with widespread concern over exposure to asbestos.

1.1 Background

Measuring airborne asbestos exposure is complicated because the risk of disease is thought to depend on, among other factors, the physical dimensions of as-

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bestos particles. A simple determination of concentration of asbestos particles per volume of air provides only an index of exposure that may be applicable within a restricted set of circumstances, but does not fully characterize the exposure and does not allow comparison between different situations.

Occupational exposures used to derive equations relating risk of disease to exposure are expressed in terms of the concentration in air of fibers measured by phase contrast microscopy (PCM). For the purposes of PCM analysis, a fiber is defined as a particle with roughly parallel sides and a length-to-width ratio of 3 or greater. PCM counts only fibers longer than 5 μm and thicker than $\sim 0.25 \mu\text{m}$. Asbestos fibers in this size class will be referred to as "optical" fibers. PCM is not specific for asbestos. Therefore the exposure measurement may include other types of fiber, such as cellulose or glass fiber, in addition to asbestos.

Few historical measurements were actually made with PCM since the method was not readily available prior to 1965.⁽¹⁾ Total dust measurements were made with impingers and concentrations were expressed in millions of particles per cubic foot of air. Thus the risk equations already incorporate a conversion from total dust measurements to concentration of optical fibers. To simplify the discussion, this conversion will be ignored. However, many of the points made with respect to converting present-day measurements to measurements comparable with historical measurements expressed in optical fibers also apply to converting dust measurements to optical fibers.

Fibers longer than 5 μm were chosen for the convenience of optical microscopic evaluation, not because there is necessarily any sharp distinction between the risk associated with fibers longer or shorter than this length.⁽¹⁾ Fibers longer than 5 μm usually make up a small fraction of the total fibers present. Provided the relative abundances of each size class remain constant, the optical fiber count provides an appropriate index of asbestos exposure, since increases in the absolute abundance of any size class are reflected in the absolute abundance of optical fibers. When size distributions vary from situation to situation, the index is distorted and does not necessarily provide a reliable indication of the relative risk of disease.

Although PCM has proven useful in the occupational environment, it is less satisfactory in settings where a large proportion of fibers may be nonasbestos, and where most of asbestos structures may be smaller than the size range detectable by PCM. In these situations, transmission electron microscopy (TEM) is the preferred measurement method. TEM can detect the smallest as-

bestos fibrils and can distinguish asbestos from nonasbestos structures.

1.2. Objective

TEM is the preferred method of measuring airborne asbestos in buildings, but TEM measurements cannot be used directly in the equations relating risk to exposure because the equations are based on PCM. Various suggestions for converting TEM measurements to PCM equivalents have been made. Most lack generality because they fail to take into account the size distribution of the asbestos particles and the expectation that fiber-size distributions in current nonoccupational environments could differ from the workplaces of the past on which the unit risk factors are based. A difference in fiber-size distributions between these settings potentially provides a bias in estimating exposures, particularly if the likelihood of disease varies with fiber size and the measurement methods of the past have not been able to detect all of the relevant fiber sizes.

In this paper we present a mathematical model for investigating the conversion of airborne asbestos measurements made by one method to an equivalent measurement made by another method. "Equivalent" means having the same potential to cause disease. The model clarifies the issues of concern and suggests approaches for obtaining meaningful conversion factors that will allow TEM measurements to be used in PCM-based risk equations.

2. MODEL FOR DERIVING CONVERSION FACTORS

2.1. Description

We express the problem generally by considering the conversion of an airborne asbestos measurement made in environment 2 with measurement method 2 (e.g., a building environment measured by TEM) to a value equivalent to a measurement made in environment 1 with measurement method 1 (e.g., occupational environment measured with PCM). From our model we will derive a conversion factor, c , that allows measurements to be placed on a common exposure scale. Once measurements have been placed on a common scale, their relative magnitudes are meaningful (i.e., a measurement that is, say, three times larger than another measurement represents three times the exposure and, for a linear dose-response curve, three times the risk).

The model has three ingredients:

1. The distribution of structure sizes in each environment (f_1 and f_2).
2. The relative potency of each structure size (r).
3. The ability of each measurement method to detect each structure size (d_1 and d_2).

We will regard f , r , and d as functions of structure size (length and width). However, they may be defined as functions of any quantity of interest. They do not need to be continuous functions. In fact, even when considering essentially continuous quantities, such as length and width, information will often be based on discrete size categories. Within this context, there is no difficulty in adding additional categories to the model to cater to nonasbestos structures or complex asbestos structures, such as bundles, clusters, or matrices.

The function f is a probability density function. That is, the proportion of structures less than or equal to x in length and less than or equal to y in width is given by

$$\int_0^x \int_0^y f(x,y) dx dy$$

Relative potency, r , refers to the ability of a structure to cause disease and represents the cumulative effect of many individual factors (inhalation, clearance from the lung, etc.). The maximum value of r is set arbitrarily at 1, so that for any structure of length x and width y , $r(x,y)$ represents the potency of that structure relative to the structure size with maximum potency. For example, $r(x,y) = 0.1$ indicates that the potential for a structure of this size to cause disease is one tenth that of the most potent size class. Since relative potency of a given structure size may depend on the disease being considered,⁽⁴⁾ there may be a different relative potency function for each disease. Similarly, different types of asbestos (chrysotile, amphiboles, etc.) could be treated separately if necessary.

For a given measurement method, $d(x,y)$ represents the probability that a structure in this size class will be detected when it is present in the air. Like r , d represents the cumulative effect of several individual factors. These may include sampling (e.g., sample collection techniques that deliberately exclude certain structures), method performance (ability of method to detect certain structures), and analytical protocol (counting rules that exclude certain structures).

We assume that the total effect of any particular exposure is given by the sum of the effects of each of its component structures (i.e., the sum of the abundance of each structure size weighted by its relative potency). This assumption (which is implicit in most, if not all, work to date) implies that there is no interaction between

the effects of individual structures. Under these conditions, the conversion factor, c , is given by

$$c = \left(\int r df_2 / \int r df_1 \right) \left(\int d_1 df_1 / \int d_2 df_2 \right)$$

(see Appendix A) where r , d , and f are all functions of structure length and width. Measurements made in environment 2 with method 2 are converted to the same scale as those made in environment 1 with method 1 by multiplying by c .

When there is a finite number, k , of discrete categories, the integrals can be written as sums. For example $\int r df_2$ could be written as $\sum r_i f_{2i}$ for $i = 1$ to k , where r_i is the relative potency of structures in category i and f_{2i} is the relative frequency of structures in category i in environment 2. We will use the integral notation because it is more general and easier to write. Most calculations, however, will be simple weighted sums.

The conversion factor, c , is the product of two quantities. The first depends on the structure-size distributions in the two environments, f_1 and f_2 , and relative potency, r . This quantity does not depend on either measurement process. The second quantity depends on the structure-size distributions in the two environments and the sensitivity of the two measurement processes, d_1 and d_2 . This quantity does not depend on relative potency.

2.2. Implications

Several important observations can be made.

1. The conversion factor, c , always depends on the fiber-size distributions f_1 and f_2 , even when $f_1 = f_2$. Therefore, c is expected to vary from situation to situation. There is no single conversion factor that can be applied universally.

2. If the two environments under consideration have the same structure-size distribution ($f_1 = f_2$), then c depends only on f and d . Information on relative potency is not needed to calculate the conversion factor when measurements are made in similar environments.

3. Setting $c = (\int d_1 df_1 / \int d_2 df_2)$, will be conservative in the sense of overestimating c and hence the estimate of exposure, provided $\int r df_2 < \int r df_1$. This will be true when the more potent structure sizes are more common in environment 1 (e.g., where the epidemiologic studies were conducted) relative to environment 2 (where current, nonoccupational exposures are taking place).

Using a value of c that is larger than its true value is conservative in the sense that it will inflate measurements of exposure and hence risk. We will use the expression "overestimate of exposure" as a convenient

way of expressing this relationship. It should be recognized, however, that there are many sources of uncertainty contributing to an exposure estimate and making a conservative assumption in one part of the process does not imply that the final estimate will necessarily be an overestimate.

The amount by which c is overestimated will depend on the value of $(\int r df_2 / \int r df_1)$ and, therefore, can vary from environment to environment. If relative potency does not depend on fiber size [i.e., $r(x,y)$ is constant], then c equals $(\int d_1 df_1 / \int d_2 df_2)$ and no overestimation is involved.

4. If we assume that method 2 detects all structures (or essentially all) and that $\int r df_2 < \int r df_1$ as in 3 above, an overestimate of c is given by $\int d_1 df_1$, the proportion of structures detected by method 1 in environment 1. This implies that the proportion of PCM-detectable structures present in the historical occupational environment, rather than the present environment, is the critical quantity for placing an upperbound on the conversion of TEM measurements to the same scale as the PCM-based risk equations. Of course, the structure-size distributions in both environments are needed to estimate c .

5. If the same measurement technique is used in both environments (i.e., $d_1 = d_2$), $c = (\int r df_2 / \int r df_1)$ which is not necessarily equal to 1. Merely using the same measurement technique in two different environments does not necessarily provide comparable measurements of exposure. For example, a PCM measurement in environment 1, which is twice a PCM measurement in environment 2, does not necessarily imply that exposure in environment 1 is twice that in environment 2. Environment 2 may have a larger proportion of structures with high relative potency.

6. The effect on c , and hence estimates of risk, of ignoring a particular size class (e.g., deciding to ignore asbestos structures shorter than a particular length) is determined by the relative potency of that size class *weighted by its relative abundance in both environments* (Appendix B). The model can be used to design more efficient measurement protocols by identifying size classes that can be ignored and size classes that should receive particular emphasis.

3. DATA SOURCES AND LIMITATIONS

The conversion factor, c , can be calculated precisely when f , r , and d are known. Although complete information will rarely be available, our model provides a basis for making approximations, determining whether c will be under- or overestimated by a particular ap-

proach, and identifying information needed to improve the estimate. Even when information is available, c will be calculated using estimates rather than actual values of f , r , and d . The sensitivity of c to the uncertainty associated with the estimates is a topic for future research. This section provides a brief overview of our current knowledge of size distributions (f), relative potency (r), and method performance (d).

3.1. Size Distributions

Since our focus is on the conversion of present-day measurements made with TEM, we will assume that the size distribution of the current exposure (f_2) is well characterized, and that the important unknown is the size distribution associated with past exposures on which the risk equations are based (f_1). This assumption conveniently ignores factors such as the effect of different TEM preparation methods on size distributions,⁽⁵⁾ which can be handled by the model but are beyond the scope of this paper. The remainder of this section concentrates on size distributions associated with past exposures.

Fiber-size distributions are essentially unknown for the cohorts of workers that have been the subjects of epidemiologic studies. The lack of data is not surprising because many of the workers experienced their exposures to asbestos as long ago as the 1930s or 1940s, when monitoring programs were rare and the importance of fiber-distribution analyses was not perceived. For some cohorts it has been possible to construct dose-response relationships through estimates of fiber-exposure levels taken from the available monitoring data or by using contemporary monitoring data as an index of exposures that occurred in the past.

Using scanning electron microscopy (SEM) or TEM, several investigators have analyzed the size distributions of fibers taken from asbestos operations.⁽⁶⁻¹⁰⁾ In some instances, the fibers have been characterized using TEM, and proportional distributions by diameter and length have been ascertained. The principal limitation of these data is not knowing the extent to which the data are representative of the distributions to which workers were exposed long ago. There is good reason to believe that the distributions have changed over time just as exposure levels have undoubtedly been affected by new equipment and exposure-control devices. It is known that dust-control strategies have been imposed in many production operations^(11,12) and that ventilation systems, as one strategy, can change particle-size distributions, because particle collectors are generally more efficient at capturing the larger particles.⁽¹³⁾ The extent to which recently

collected fiber samples are influenced by ventilation systems is unknown, but it is reasonable to assume that the fiber-size distributions in samples taken from operations in the 1970s may not necessarily be representative of the exposures encountered by workers decades earlier, when dust-reduction strategies were different or nonexistent.

Since PCM does not distinguish asbestos from other fibers within the optical size range, the PCM measurement may also include nonasbestos fibers. Therefore, a complete characterization of the occupational exposures requires knowing the contribution from nonasbestos fibers. Investigation of size distributions has concentrated on asbestos fibers, and information on the proportion of nonasbestos optical fibers in each exposure setting is not available. It is reasonable to assume that, in many of the occupational settings, the majority of fibers were asbestos, but this is by no means certain. Complex asbestos structures (bundles, clusters, and matrices) have also tended to be ignored by researchers.

Another limitation of the available fiber-size distribution data is the limited number of samples that have been taken in the industry. The cohorts that have been studied consisted of workers employed in numerous operations and activities, whereas only a few operations have been considered in the recent studies of fiber distributions. Some of the samples have come from operations which have been the subject of an epidemiologic study. For example, Dement and Harris⁽⁷⁾ took chrysotile samples from textile, friction, and cement pipe operations and amosite from a pipe-finishing plant. Some of the textile samples came from the same textile plant examined in a cohort investigation by Dement *et al.*⁽¹⁴⁾

In Table I we attempt to match the epidemiologic studies listed in Table 3-31 of the 1986 EPA Airborne Asbestos Health Assessment Update⁽¹⁾ with data on asbestos fiber-size distributions. These studies were used to assess dose-response relationships for lung cancer. In some instances, the matching is not as ideal as one would prefer, particularly where more than one type of asbestos may have been involved. The fiber-size distributions selected correspond to the asbestos type thought to be predominant in a given exposure. Three size categories are used in Table I to summarize each distribution. The summary is for convenient display only. Where applicable, subsequent calculations were based on the complete size distribution provided. When size categories reported in the literature did not correspond to those used here, estimates were obtained by linear interpolation.

Given the uncertainties in the appropriateness of these data for exposures occurring in the past, the selection of one data set over another to link to epidemiologic studies is somewhat arbitrary. For example, the cohort

studies by McDonald *et al.*⁽¹⁵⁾ consisted of workers primarily involved in the production of textiles, and therefore the size distribution data for textile processes might be considered appropriate; however, friction products were also produced at this plant and therefore the actual exposure may be a combination of the two distributions. There is also uncertainty in the extent to which size-distribution data collected in one country, such as the data collected in U.S. by Dement and Harris⁽⁷⁾ for textile and friction-product operations, would be applicable to the plants studied in other countries, such as the United Kingdom or Italy.

3.2. Relative Potency

A number of researchers^(4,16,17) have suggested that long and thin fibers are more potent than short and thick fibers, particularly with respect to lung cancer, but there have been few advances made in quantifying the risks of various fiber-size categories. The evidence in favor of differences in relative potency is for the most part indirect and comes from at least four categories of sources. These include animal studies in which exposures were by the inhalation route⁽¹⁸⁻²⁰⁾ or by implantation/inoculation^(16,20-22), fiber-deposition studies of autopsied lung tissues from workers,⁽²³⁻²⁵⁾ comparative analyses of animal and epidemiologic studies that attempt to reconcile study findings according to fiber-dimension characteristics^(4,26) and other biological evidence.^(17,27) None of these studies alone, however, provides a good data set by which one can estimate relative potency for specific size categories of fibers. For example, although considerable attention has been given to the fiber-desposition patterns found in lung tissues of workers, it has not been established that the fiber-size distributions found at death are necessarily the same as those that initiated the disease years earlier.

Several investigators have proposed fiber dimensions, particularly for fiber length, which distinguish fiber sizes of considerable carcinogenic potency from those with little or no potency. The Stanton hypothesis, which is one of the best known, suggests that the most potent fibers are those with a length greater than 8 μm and a width of 0.25 μm or less.⁽¹⁶⁾ Another hypothesis by Bertrand and Pezerat⁽²⁸⁾ propose that the relative potency of fibers is a continuous function of aspect ratio (length divided by width), regardless of the fiber length or diameter. One of the tenets of their hypothesis, which was based on a reanalysis of the work by Stanton *et al.*⁽²¹⁾ is that short fibers may be just as carcinogenic as long fibers if the aspect ratio is a certain critical value. (Note that our model can readily cater

Table I. Epidemiologic Studies Used in EPA's Asbestos Health Assessment Update⁽¹⁾ and Possible Asbestos Fiber-Size Distributions

Epidemiologic study	Size distribution source	Size distribution (proportion ^a)		
		Short ^b	Long, thin ^c	Optical ^c
Dement <i>et al.</i> ⁽¹⁴⁾	Dement and Harris, ⁽⁷⁾ C1–C3	0.79	0.09	0.13
McDonald <i>et al.</i> ⁽¹⁵⁾	Dement and Harris, ⁽⁷⁾ C1–C3	0.79	0.09	0.13
Peto ⁽³¹⁾	Dement and Harris, ⁽⁷⁾ C1–C3	0.79	0.09	0.13
McDonald <i>et al.</i> ⁽²²⁾	Dement and Harris, ⁽⁷⁾ C1–C3	0.79	0.09	0.13
Berry and Newhouse ⁽³³⁾	Dement and Harris, ⁽⁷⁾ C4–C6	0.86	0.07	0.07
McDonald <i>et al.</i> ⁽³⁴⁾	Dement and Harris, ⁽⁷⁾ C4–C6	0.86	0.07	0.07
McDonald <i>et al.</i> ⁽³⁵⁾	Gibbs and Hwang, ⁽¹⁰⁾ Table 2	0.97	0.01	0.01
Nicholson <i>et al.</i> ⁽³⁶⁾	Gibbs and Hwang, ⁽¹⁰⁾ Table 2	0.97	0.01	0.01
Rubino <i>et al.</i> ⁽³⁷⁾	Gibbs and Hwang, ⁽¹⁰⁾ Table 2	0.97	0.01	0.01
Seidman <i>et al.</i> ^(38,39)	Dement and Harris, ⁽⁷⁾ C10–12	0.57	0.06	0.36
Selikoff <i>et al.</i> ^{(40)*}	See note			
Henderson and Enterline ^{(41)*}	See note			
Weill <i>et al.</i> ⁽⁴²⁾ Hughes and Weill ^{(43)*}	See note			
Finkelstein ^{(44)*}	See note			

^aProportions may not sum to 1 due to rounding.^bLength $\leq 5 \mu\text{m}$.^cLength $> 5 \mu\text{m}$, diameter $\leq 0.25 \mu\text{m}$.^cLength $> 5 \mu\text{m}$, diameter $> 0.25 \mu\text{m}$.^cMixed exposures—size distribution difficult to characterize.

to this hypothesis since relative potency, r , can be any function of length and width).

To the best of our knowledge only Pott⁽¹⁷⁾ provides quantitative estimates of relative potency. Pott's hypothesized estimates of relative potency are based on observations by several investigators. His model takes into account fiber length and diameter. For example, Pott suggests that the carcinogenic potency of a fiber is greatest at a length of approximately $20 \mu\text{m}$ and that $8 \mu\text{m}$ fibers are one half as potent as $20 \mu\text{m}$ fibers. With regard to fiber diameters, fibers that are approximately $0.1 \mu\text{m}$ are the most potent, and fibers $0.5 \mu\text{m}$ in diameter are one half as potent as the $0.1 \mu\text{m}$ fibers. No distinction is made between fibers causing lung cancer and those causing mesothelioma. Lippmann⁽⁴⁾ argues that the critical fiber dimensions for these two diseases may be different. To apply the model presented in this paper, we assume only that the relative potency of long fibers is not less than the relative potency of short fibers. In many cases this assumption is sufficient to obtain overestimates of exposure. As additional information on relative potency becomes available, it can be incorporated in the model to refine the estimate of the conversion factor c .

3.3. Performance of the Microscopy Method

The model allows for precise definition of the performance of the microscopy method used to analyze the

sample. For the examples that follow we will assume that TEM detects asbestos structures of every size with probability equal to 1 (i.e., $d_2 \equiv 1$). Although Steel and Small⁽²⁹⁾ have shown that the probability of detecting small structures is less than 1, and possible effects of different preparation methods are ignored,⁽⁵⁾ the assumption is adequate for the purposes of illustration.

We assume that PCM detects all structures longer than $5 \mu\text{m}$ and with diameter greater than 0.25 and that structures outside this range are not detected (i.e., $d_1(x, y) = 1$ for $x > 5$ and $y > 0.25$, and 0 elsewhere). This is the typical operating range of PCM.⁽³⁰⁾

4. EXAMPLE

Table II lists $f d_1 d_2$ for the epidemiologic studies in the EPA Health Update,⁽¹⁾ assuming the fiber-size distributions suggested in Section 3.1. The values in the table are simply an estimate of the proportion of optical structures in the historical environment. We are ignoring any contribution to the PCM measurement from nonasbestos fibers. Appendix C shows that the effect on nonasbestos fibers in the optical size range is to increase the value of $f d_1 d_2$ by q/p , where q is the proportion of nonasbestos fibers in the optical size range and p is the proportion of asbestos fibers ($p + q = 1$). Provided q is less than 0.1 , the effect of nonasbestos fibers on the estimate of c will be small relative to other sources of uncertainty.

Table II. Values of $\int d_1 df_1$ (Proportion of Optical Fibers) for Studies Listed in Table I

Epidemiologic study ^a (ref.)	Type of exposure	K_L^b	$\int d_1 df_1$	$1000 K_L \int d_1 df_1$
38,39	Amosite insulation manufacture	0.04300	0.36	15.48
14	Textile production	0.02800	0.13	3.64
15	Textile production	0.02500	0.13	3.25
32	Textile production	0.01400	0.13	1.82
31	Textile production	0.01100	0.13	1.45
33	Friction products	0.00058	0.07	0.04
36	Mining and milling	0.00170	0.01	0.02
37	Mining and milling	0.00081	0.01	0.01
34	Friction products	0.00010	0.07	0.01
35	Mining and milling	0.00060	0.01	0.01

^aOrdered according to $K_L \int d_1 df_1$, a measure of relative potency of the exposure with respect to lung cancer. See text for assumptions.

^bUnit risks for lung cancer calculated in EPA's Asbestos Health Assessment Update (Ref. 1).

In addition to listing information needed to estimate c , Table II also provides insight into relative potency. The conversion factor, c , can be expressed as $c_1 c_2$, where $c_1 = \int d_1 df_1 / \int r df_1$ and $c_2 = \int r df_2 / \int d_2 df_2$. c_1 is determined by environment 1, whereas c_2 is determined by environment 2. Instead of multiplying the measurement made in environment 2 by c and inserting the result in the risk equation, one may equivalently multiply the parameter of the risk equation, K , by c_1 and multiply the measurement made in environment 2 by c_2 . If the effects of different size distributions are the only differences among the epidemiologic studies, then $c_1 K$ should be constant across all studies. That is, c_1 is an adjustment factor that corrects for size distribution. Setting the constant arbitrarily equal to 1 gives $\int r df_1 = K \int d_1 df_1$. The overall relative potency of the fiber-size distribution associated with each study, $\int r df_1$, is given by the parameter K of the risk equation multiplied by the proportion of structures detectable by PCM. Thus $K \int d_1 df_1$, rather than K , should be used to rank studies in terms of relative potency of their fiber-size distributions. K is inappropriate for ranking because it depends on both potency and the proportion of structures in the PCM size range.

The entries in Table II are ranked according to the estimated value of $K_L \int d_1 df_1$, where K_L is the proportionality constant for lung cancer reported in Table 3-31 of the EPA Health Update.⁽¹⁾ Keeping in mind the uncertainties discussed in Section 3, the rankings suggest that the highest relative potency is associated with amosite insulation manufacturing, followed by asbestos textile production, and mining and friction products. The rankings are not dissimilar from those of K_L , but adjustment by c_1 indicates relative magnitudes. The relative potencies associated with

mining are 3 to 4 orders of magnitude less than the potency associated with amosite-insulation manufacturing. These differences in overall potency could reflect the effect of different fiber-size distributions as well as the effect of fiber type or other factors specific to the exposure.

Consider a hypothetical, nonoccupational exposure of 0.02 asbestos structures per cubic centimeter (s/cm^3) measured by TEM in which 96% of the asbestos structures are shorter than 5 μm , and of the remaining 4%, half (2%) have diameters greater than 0.25 μm . The current information on relative potency suggests that this size distribution is unlikely to represent a greater relative potency than the majority of occupational studies in Table I (i.e., $\int r df_2 < \int r df_1$). Therefore taking $c = (\int d_1 df_1 / \int d_2 df_2)$ is expected to overestimate exposure. Since the exposure was measured by TEM, we put $\int d_2 df_2 = 1$ and obtain $c = \int d_1 df_1$.

To convert the original TEM measurement of 0.02 s/cm^3 for insertion in the EPA Health Update risk equations, we need to multiply by $\int d_1 df_1$. The EPA Health Update risk equation for lung cancer was derived excluding the mining and milling studies. Therefore, we multiply 0.02 s/cm^3 by 0.15, the average value of $\int d_1 df_1$ for the remaining studies in Table II, to give 0.003 f/cm^3 , an overestimate of exposure. Estimates of risk can then be read from Table 6-3 of the Health Update. (Table 6-3 is based on U.S. general population death rates and does not consider smoking habits. Details are given in Ref. 1.) For a lifetime exposure beginning at birth, the lifetime risk of death from lung cancer per 100,000 persons is 16 for females and 51 for males.

We have used the EPA Health Update merely as an

example. The approach can be applied to other risk equations and to mesothelioma as well as lung cancer.

Recall that the extent to which c is overestimated depends on $(\int r df_2 / \int r df_1)$. While the overestimation approach may be very valuable in obtaining a conservative estimate of risk, it does not provide a good basis for comparing two different risk estimates because the degree of overestimation will vary from environment to environment. When comparisons are desired, additional information on r , beyond merely assuming $\int r df_2 < \int r df_1$, should be inserted in the model.

5. CONCLUSIONS AND RECOMMENDATIONS

We have developed a flexible model that allows TEM measurements to be used in risk equations based on occupational exposures measured with PCM. The model provides a basis for proceeding when data are limited as well as a framework for incorporating new information as it becomes available. Information, such as relative potency of different size classes (including complex structures), differences between asbestos types, or more precise descriptions of method performance, can be incorporated in the model and used to refine estimates of exposure. The model may be used to answer questions such as, "Will it make a difference if the potency of a particular size class is 5, 10, or 100 times another?" and to design measurement methods by quantifying the effect of reducing the emphasis on, or ignoring, certain size classes.

In the absence of quantitative information on relative potency, we recommend checking the TEM fiber-size distribution to determine that it qualitatively represents a lower potency than that associated with the occupational exposures used to derive the risk equation. When this is true, multiplying the TEM measurement by the proportion of optical structures in the occupational environment will provide an overestimate of exposure.

APPENDIX A

Model for Converting Asbestos Exposure Measurements Between Environments and Analytical Protocols

Notation

Let s = the number of structures per unit volume of air;

$f(x,y)$ = the frequency distribution of structure size, such that the proportion of structures shorter than x and narrower than y is $\int_0^x \int_0^y f(x,y) dx dy$; (Note that although x and y are used here to represent structure length and width, respectively, the argument below applies to any exhaustive and mutually exclusive classification system. For example, a nonasbestos category can be added when considering PCM.)

$r(x,y)$ = the relative potency of structures of size x,y ; and

$d(x,y)$ = the probability of the measurement process detecting a structure of size x,y given that the structure is present.

Then m , the number of structures detected by the measurement process is given by

$$m = s \iint f(x,y) d(x,y) dx dy$$

and a , the effective exposure in terms of potential for developing disease, is given by

$$a = s \iint f(x,y) r(x,y) dx dy$$

The expression for a assumes that the total effect of any particular exposure is given by the sum of the effects of each of its component structures (i.e., there is no interaction between structures).

Derivation of Conversion Factor

Consider two environments, $s_1, f_1(x,y)$ and $s_2, f_2(x,y)$, and two measurement processes, d_1 and d_2 . Suppose measurement process 2 measures m_2 in environment 2. The objective is to find m_1 for measurement process 1 in environment 1, such that m_1 represents the same effective exposure, in terms of potential for developing disease, as m_2 .

Since $s_2 = m_2 / \iint f_2(x,y) d_2(x,y) dx dy$, we have

$$a_2 = m_2 (\iint f_2(x,y) r(x,y) dx dy) / (\iint f_2(x,y) d_2(x,y) dx dy)$$

Similarly

$$a_1 = m_1 (\iint f_1(x,y) r(x,y) dx dy) / (\iint f_1(x,y) d_1(x,y) dx dy)$$

Putting $a_1 = a_2$ gives

$$m_1 = m_2 (\iint f_2(x,y) r(x,y) dx dy) / (\iint f_1(x,y) r(x,y) dx dy)$$

$$\times (\iint f_1(x,y) d_1(x,y) dx dy) / (\iint f_2(x,y) d_2(x,y) dx dy)$$

which can be written more concisely as

$$m_1 = cm_2,$$

where

$$c = (\int r df_2 / \int r df_1) (\int d_1 df_1 / \int d_2 df_2)$$

APPENDIX B

When Can a Size Class Be Ignored?

Let XY represent a subset of possible size classes. Let c^* be the conversion factor that would be obtained if size class XY were ignored.

Let $p_i = \int_{xy} df_i$. Then f_i^* , the size distribution in environment i ignoring size class XY , is given by

$$f_i^* = \begin{cases} f_i / (1 - p_i) & \text{for } (x,y) \in XY \\ 0 & \text{for } (x,y) \notin XY \end{cases}$$

and c^* is given by

$$((\int r df_2 - \int_{xy} r df_2) / (\int r df_1 - \int_{xy} r df_1)) ((\int d_1 df_1) / (\int d_2 df_2))$$

If c is the "correct" conversion factor, then the ratio of c^* to c is given by

$$c^*/c = (1 - \int_{xy} r df_2 / \int r df_2) / (1 - \int_{xy} r df_1 / \int r df_1)$$

The ratio depends on the relative weighted potency of size class XY in each environment.

If $r(x,y) = 0$ for $(x,y) \in XY$, then the ratio is one and ignoring the size class has no effect. Similarly, if $f_1 \equiv f_2$, the ratio is also 1. Note that the equality must be true for all (x,y) . It is not sufficient that $f_1 = f_2$ for $(x,y) \in XY$.

Depending on the precision with which it is desired to estimate c , there may be a range of other situations for which ignoring a particular size class is acceptable. For example, if the relative weighted potencies in environments 1 and 2 are both less than 0.5, then c^* differs from c by no more than a factor of 2. This may be an acceptable variation relative to other sources of uncertainty. Note that relative potency alone is not sufficient to determine the effect of ignoring a size class. The relative potency must be weighted by relative abundance.

APPENDIX C

Effect of Nonasbestos Fibers on Calculation of c

Define $f^*(A)$ as the proportion of particles in class A , such that

$p \cdot f(x,y)$ for asbestos particles
of length x and diameter y

$$f^*(A) =$$

q for nonasbestos particles in
the optical size range

where $p + q = 1$ and f is the size distribution of asbestos particles as defined previously.

Let q_1 be the proportion of nonasbestos particles in environment 1 and q_2 be the proportion of nonasbestos particles in environment 2. Then

$$c = (\int r df_2^* / \int r df_1^*) (\int d_1 df_1^* / \int d_2 df_2^*)$$

We will assume $r=0$ for nonasbestos particles. Then, assuming measurement method 2 does not count non-asbestos particles,

$$\begin{aligned} c &= (p_2 \int r df_2 / p_1 \int r df_1) (p_1 \int d_1 df_1 + q_1 / p_1) \\ &= (\int r df_2 / \int r df_1) (\int d_1 df_1 + q_1 / p_1) \end{aligned}$$

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