Application of the Thoracic Sampling Definition to Fiber Measurement

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As part of a consideration of the sampling method for refractory ceramic fibers, calculations were carried out at the National Institute for Occupational Safety and Health to evaluate different approaches to fiber measurement. The most common technique for estimating fibers that can reach the lungs is to use an upper diameter limit of 3 μm in the phase contrast optical microscope counting rules. Calculations were carried out to estimate the aerodynamic diameter of fibers in several lognormal size distributions likely to occur in workplaces. Using these size distributions, the use of a 3 μm fiber diameter upper limit in the counting rules was compared with results expected from a sampler designed to collect fibers according to the thoracic definition, which is based on the aerodynamic diameter of compact particles. The other limits in the optical counting procedure, i.e., counting only fibers longer than 5 μm and thicker than 0.25 μm, were included in the calculations. The calculations indicate that the 3 μm upper diameter counting rule agrees with the thoracic definition within about ±25% for a wide range of possible fiber size distributions. The advantages of using a sampler designed to collect the thoracic fiber size fraction include reducing analyst decision making (all fibers collected would be counted) and reducing the nonthoracic particles on the sample, making the sample easier to analyze. Until thoracic samplers are available for fibrous aerosols, incorporating the 3 μm upper diameter limit as part of the criteria for counting fibers may serve as a surrogate for thoracic sampling.

Keywords: fibers, measurement, thoracic fraction

It has been recognized that exposure to specific types of airborne fibers can pose a health risk to workers. Occupational exposure to asbestos fibers has been strongly associated with asbestosis, lung cancer, and mesothelioma.[1] The generally accepted etiology of these diseases indicates that those fibers capable of entering the lungs pose the greatest hazard. Reviews of fiber toxicity have concluded that different fiber sizes may be responsible for the different diseases, but that all of these fibers were in a size range capable of reaching the lungs, i.e., less than 3 μm physical diameter.[2]

Asbestos fibers are relatively small in diameter. Measurements of airborne chrysotile,[3] amosite,[4] and crocidolite[5] fibers generally indicate median diameters of much less than 1 μm. However, many synthetic minerals, such as glass, mineral, and refractory ceramic fibers can have median diameters as large as 15 μm,[6,7] indicating that a significant fraction of these fibers will be too large to enter the lungs.

The principal technique for selecting fibers capable of entering the lungs has been to apply an upper diameter limit of 3 μm to the fibers counted by phase contrast optical microscopy. Many national[8,9] and international[10,11] organizations have applied such a limit in their recommended procedures for counting fibers. Although the National Institute for Occupational Safety and Health (NIOSH) has not recommended such a limit for airborne asbestos fibers, most of which tend to have relatively small diameters, it does recommend an upper diameter limit of 3.5 μm[12] for glass fibers. The rationale for using such an upper diameter limit was based on estimates of the aerodynamic size of fibers and the observation that larger diameter fibers were not found in lung tissue.

Improved criteria for sampling aerosols in the inhalable, thoracic, and respirable size ranges have achieved international acceptance by the International Organization for Standardization[13]

and have been established in the United States by the American Conference of Governmental Industrial Hygienists (ACGIH).[14] The definition of the inhalable aerosol size fraction includes particles that can enter the nose or mouth; the thoracic size fraction (50% cutpoint relative to total aerosol = 10 μm aerodynamic diameter) includes the portion of inhalable particles that can pass the larynx; and the respirable size fraction (50% cutpoint relative to total aerosol = 4 μm aerodynamic diameter) includes the portion of thoracic particles that can reach the gas exchange region of the lungs. The equations defining these fractions are given for the inhalable fraction (SI(d)),

$$(SI(d) = 0.5\ (1+e^{-0.06d}); \qquad 0 \le d \le 100\ \mu m, \tag{1}$$

the thoracic fraction (ST(d)),

$$ST(d) = SI(d)[1-F(x)]; \qquad x = \frac{\ln\left(d/11.64\right)}{\ln(1.5)}, \tag{2}$$

and the respirable fraction (SR(d))

$$SR(d) = SI(d)[1-F(x)]; \qquad x = \frac{\ln\left(d/4.25\right)}{\ln(1.5)} \tag{3}$$

where d is the aerodynamic diameter and F(x) is the cumulative probability function of the standardized normal variable x. These sampling criteria are indicated in terms of mass sampling, but since they are defined precisely for each particle aerodynamic diameter, they can be applied equally well to particle or fiber counting.

In the past, fibers causing lung diseases have been referred to as respirable fibers. Using the definition for respirable aerosol suggests that only fibers small enough to reach the gas exchange region are toxic. Since fibers depositing elsewhere in the lungs also appear to cause disease, the authors' calculations suggest that the use of the term "thoracic fibers" may be more correct when discussing potentially toxic fibers.

The thoracic size fraction is intended to provide a conservative estimate of particles capable of reaching the portion of the respiratory system below the larynx, i.e., the lungs, during mouth breathing.[15] Note that while the thoracic fraction has a 50% cutpoint of 10 μm, it includes much larger particles, e.g., 2% of particles with 25 μm aerodynamic diameter. Application of the thoracic criterion to fiber sampling would restrict the measurement of fibers to those most likely to pose a hazard. Since a large body of measurements exists with methods that restrict counting of fibers smaller than 3 μm diameter, the question arose: How well does a 3-μm upper fiber diameter limit correspond to the thoracic sampling criterion? The thoracic definition is based on compact particle aerodynamic diameter, while the 3 (or 3.5) μm upper diameter limit is based on visual selection of fibers using microscopy. Since the aerodynamic behavior of fibers is different from compact particles, the study is an attempt to quantitatively relate the two means of fiber selection.

Use of an internationally accepted health-related definition such as thoracic fraction may be preferable to using an upper diameter limit in the fiber counting rules for microscope methods. Adoption of a thoracic definition for fibers would provide consistency among sampling methods for different aerosols. An additional factor in favor of using a thoracic preclassifier is that it would produce a cleaner sample. Elimination of nonthoracic particles and fibers would help the analyst to see more fibers as well as to simplify the decision about which of the fibers to count—all visible fibers would be counted. Baron and co-workers[16–19] have noted several possible errors occurring with the currently used sampler. Further improvement in the sampling efficiency and sample uniformity might be achieved with an improved sampling inlet design.

It is assumed that an aerodynamic preclassification device can be constructed that can meet the ACGIH thoracic aerosol definition for compact particles as well as having minimal losses due to interception of fibers. There is currently no experimental data on fiber loss due to interception in the upper respiratory tract. Theoretical calculations suggest that significant losses may occur in the upper respiratory system during nose breathing, especially due to interception of fibers by nasal hairs.[20] However, the thoracic aerosol is defined only for mouth breathing as a conservative estimate of particles passing the larynx. Fiber interception in the mouth passages is expected to be minimal due to the large dimensions of the mouth relative to airborne fiber lengths.

A thoracic fraction sampler would remove the nonthoracic aerosol from the airstream and collect fibers on a filter in the same fashion as in current methods. Both techniques, i.e., the thoracic sampler and the use of the 3 μm upper diameter criterion, would use the same analytical procedure, namely phase contrast microscopy, so that both would use the same lower length and diameter limits: >5 μm long and >0.25 μm diameter (optical limit). The following calculations simulate the measured phase contrast microscope counts on filter samples by two techniques: using a physical upper diameter limit of 3 μm and using an aerodynamic preclassification device.

FIBER AERODYNAMIC DIAMETER

The aerodynamic diameter (d_{ae}) of a particle is defined as the diameter of a unit density sphere that has the same settling velocity as the particle in question.[21] The d_{ae} of compact particles determines their likelihood of depositing in various regions of the respiratory system by settling and impaction.

The fiber d_{ae} can vary as a function of its orientation relative to gravity. Fibers can be aligned by a number of mechanisms[22] including shear flow, accelerated flow, electrostatic effects, and magnetic effects. Fibers can achieve a random orientation by Brownian diffusion and by turbulence. The fiber orientation in the respiratory system is likely to vary depending on flow conditions as well as initial orientation on entering the respiratory system. Thus, d_{ae} of fibers is not as well-defined as it is for compact particles. However, the variation of fiber d_{ae} with orientation is limited. Chen and Baron[16] calculated that for fibers of interest (longer than 5 μm and aspect ratio >3) the maximum difference in d_{ae} from d_{ae}(mean) was no more than about 10%. The fiber aerodynamic diameter was calculated using equations from Oseen[23] for elongated spheroidal particles as modified by Griffiths and Vaughan[24] for the volume of straight cylindrical particles. Griffiths and Vaughan showed that settling velocities calculated with the modified Oseen equations matched experimental fiber settling velocities quite well.

The mean aerodynamic diameter ($\bar{d}_{ae}$) was calculated assuming totally random orientation:

$$\bar{d}_{ae} = \frac{2d_{ae,\perp}}{3} + \frac{d_{ae,\parallel}}{3} \tag{4}$$

Table I gives the calculated mean d_{ae} for several fiber sizes as well as values for fiber orientation perpendicular and vertical to the direction of settling.

TABLE I. Aerodynamic Diameters for Several Fiber Sizes, Assuming a Fiber Density of 2.5 g/cm³

Diameter (μm)	Length (μm)	d_{ae} (μm)	$d_{ae,\parallel}$ (μm)	Ratio[A]
0.5	1.5	1.19	1.32	1.11
0.5	50	1.89	2.43	1.29
1	3	2.39	2.65	1.11
1	50	3.54	4.49	1.27
2	6	4.77	5.29	1.11
2	50	6.59	8.20	1.24
5	15	11.93	13.23	1.11
5	100	16.04	19.82	1.24
10	30	23.85	26.45	1.11
10	100	29.32	35.18	1.20

[A] The ratio indicates the maximum error that could occur by assuming the fibers are always in one orientation when they are actually in the other.

COMPARISON OF THORACIC AND MICROSCOPICALLY SIZE-SELECTED DIAMETER FIBERS

Thoracic samplers have been proposed using at least two size selective devices: impactors[25] and porous foam.[26] There are currently no commercially available samplers suitable for thoracic sampling of fibers. In the present study the penetration through a hypothetical thoracic sampler using the ACGIH thoracic definition was calculated. The calculation was carried out for several size distributions of fibers. Fiber size distributions have been shown to be generally lognormal in both length and diameter. The size distribution of a lognormal fibrous aerosol is represented by several parameters: count median diameter, diameter geometric standard deviation $\sigma_{g,d}$, median length, length geometric standard deviation $\sigma_{g,l}$, and τ, the correlation between length and diameter.[27,28] The value of τ is generally small but positive, i.e., longer fibers tend to have a larger diameters.

The size distributions of a range of fiber lengths and diameters were calculated using a spreadsheet.[29] The frequency distribution was calculated in 64 length and 64 diameter intervals. The size intervals were selected for each distribution to ensure that at least 99% of the total distribution was included. In the results presented below, the parameters of $\sigma_{g,l}$ and $\sigma_{g,d}$ were 2 and τ was 0.2. The density of fibers was assumed to be 2.5. The aerodynamic diameter can be calculated for fibers settling in an orientation parallel ($d_{ae,\parallel}$) to the direction of motion and perpendicular ($d_{ae,\perp}$) to the direction of motion. The aerodynamic diameters of fibers in each size bin were calculated based on the median length and diameter for that bin. Based on the $\bar{d}_{ae}$, the fiber penetration through a thoracic sampler was calculated according to the thoracic definition. The total number of fibers longer than 5 μm, thicker than 0.25 μm, and passing through the thoracic classifier was calculated for each distribution. For comparison, the total number of fibers in each distribution longer than 5 μm, thicker than 0.25 μm, and thinner than 3 μm was also calculated. Since the integral of the size distribution is normalized to 1, the final calculated number represents the fraction selected (either by thoracic sampler or by upper diameter limit) out of the original distribution. These calculations were carried out for a range of fiber size distributions, and the results are presented in Figures 1 and 2. The ratios of fibers counted by the upper diameter method to the thoracic selection method for the range of size distributions is presented in Figure 3.

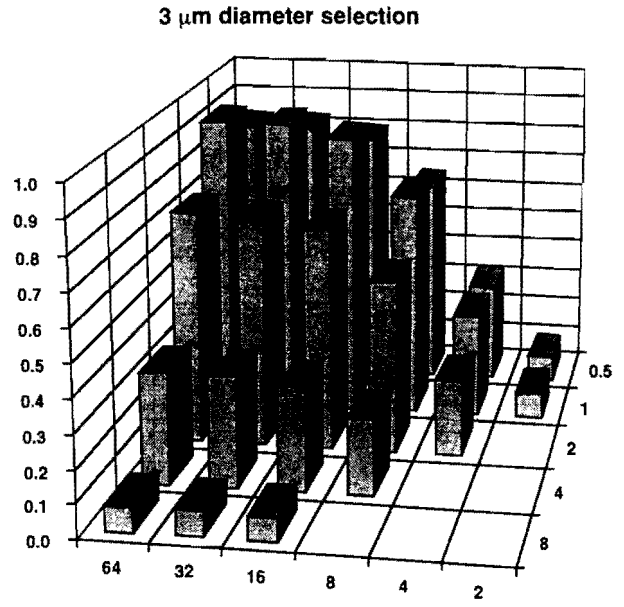

FIGURE 1. Calculated fraction of fibers counted by phase contrast microscopy using an upper diameter limit of 3 μm for a range of size distributions. Note that calculations for size distributions with median lengths only twice their median diameters are presented here to indicate trends and are not used in the discussion.

The values for size distributions with the median length twice the median diameter have been plotted to indicate the trends, but are not included further in the discussion, since most fiber distributions have a greater median aspect ratio. Fibers larger than 8 μm median diameter were not included in the calculation because such distributions are likely to produce very low concentrations of thoracic fibers.

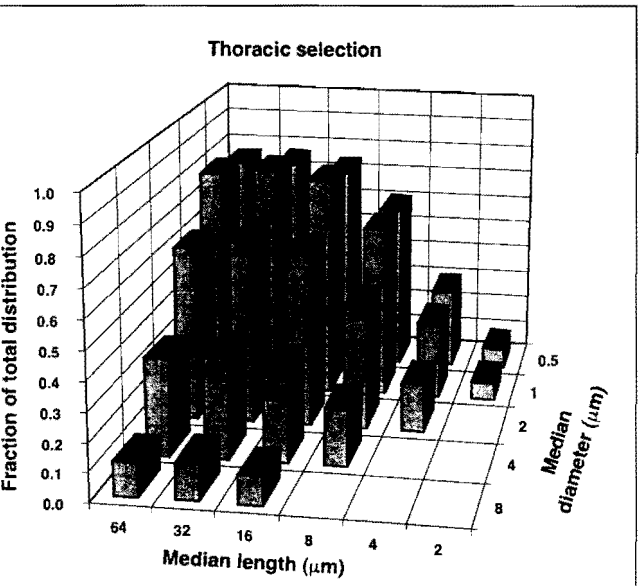

FIGURE 2. Calculated fraction of fibers counted by phase contrast microscopy using a sampler with a preclassifier designed to give a thoracic cut for a range of size distributions. Note that calculations for size distributions with median lengths only twice their median diameters are presented here to indicate trends and are not used in the discussion.

Some calculations of other conditions were also made, i.e., measured concentration with upper diameter limit below and above 3 μm; varying $\sigma_{g,l}$ and $\sigma_{g,d}$, the effect of density, and the effect of fiber orientation on the aerodynamic sizing. The trends observed in the results of these calculations are discussed below.

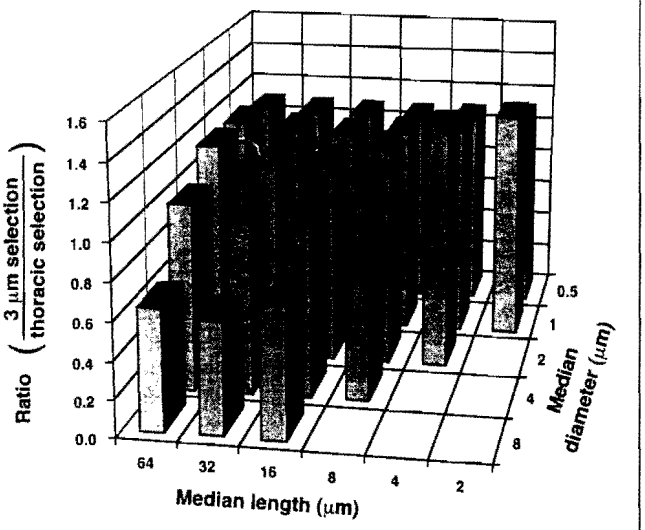

FIGURE 3. Ratio of 3 μm upper diameter selection to thoracic sampler selection for a range of size distributions. Note that calculations for size distributions with median lengths only twice their median diameters are presented here to indicate trends and are not used in the discussion.

DISCUSSION

The current practice in most analytical methods using optical microscopy is to limit the count to fibers less than 3 μm in diameter. For asbestos this may not be critical. Asbestos fibers are often present in distributions that have median diameters <1 μm. As seen in Figures 1 and 2, a large fraction of fibers with a median diameter of 1 μm and median lengths >8 μm are counted by either method (about 0.90 or 90%). As the median diameter decreases, fewer fibers are counted because more of the fibers are below the visibility limit of the optical microscope. However, in this case the ratio of the two methods is close to 1, since there are relatively few fibers with large physical or aerodynamic diameter.

The toxicity of asbestos fibers has brought into focus the potential toxicity of other fibers. Refractory ceramic fiber use is increasing in the United States. Some chronic inhalation studies with these fibers have produced lung carcinomas in animals.[30,31] A survey of the aerosol in three production plants found a geometric median diameter of 0.7 μm and geometric median length of 13 μm.[7] In another survey of 13 glass fiber, rock wool, and slag wool production plants, the median diameter of airborne fibers was typically 3 to 8 times smaller than the manufacturer-indicated nominal diameter of the fibers.[6] For example, production glass wool that was nominally 8 μm in diameter resulted in an airborne fiber distribution with a median diameter of about 1.8 μm. Also, fiber concentrations were found to vary inversely with nominal fiber diameters.

Comparing these fibers' dimensions with the calculation results in Figure 3, it is apparent that for most likely fiber size distributions, the physical 3 μm diameter selection criterion agrees well with the thoracic definition. The best agreement occurs for small median fiber diameters (≤1 μm) where the 3 μm criterion gives 8–17% higher values for distributions with mean aspect ratios greater than 3. The 3 μm criterion gives significantly lower counts (~40%) relative to the thoracic definition for large median fiber diameter (8 μm). However, the concentrations of such fibers will tend to be low as noted above, so a discrepancy in this size range may not be so important.

The effect of varying some of the distribution parameters was observed. Changing the geometric standard deviation over the range of 1.5 to 3 did not change the ratio between the two methods by more than a few percent either way. The same lack of sensitivity was noted in the correlation (τ) between length and diameter. This suggests that the ratios calculated in Figure 3 are reasonably robust with respect to the other size distribution parameters. Changing the upper diameter selection criterion from 3 μm to other values, such as 3.5 μm, was also tested. With a criterion of 3.5 μm the ratios for the fiber diameters ≤1 μm increased up to 3%, while for 8 μm diameter fibers the ratio improved from 0.60–0.65 to 0.83–0.91. Use of a smaller diameter selection criterion (2.5 μm) gives the reverse trends, i.e., slightly better agreement for small diameter fibers and worse agreement for large diameter fibers.

While chrysotile and glass fibers tend to have densities of approximately 2.5 g/cm^3, amosite and crocidolite fibers have densities closer to 3.4 g/cm^3. A calculation of the effect of increasing the density to 3.4 g/cm^3 increased the ratio between the two methods for all calculated size distributions. The largest increase was for 8 μm median diameter fibers, where the ratio was 0.84–0.92, while for 2 μm median diameter fibers the ratio increased to 1.15–1.22. Organic fibers may have densities closer to 1.5 g/cm^3. A calculation for this density gave ratios of 0.4–0.5 for 8 μm median diameter fibers and ratios of 0.95–1.25 for 2 μm median diameter fibers. Overall, the effect of density does not appear to change the overall picture significantly. The largest effect appears for large diameter fibers, for which the lower the density, the poorer the estimate of thoracic fraction by the PCM method.

The calculations were carried out with the assumption that the optical microscope limits the visibility of short and thin fibers. Other analytical techniques, such as scanning electron microscopy and transmission electron microscopy, allow observation of more of these smaller fibers. Either method would add an equal number of fibers (δ) to the fiber count relative to the optical count.

$$\frac{3\ \mu\text{m limit (optical)} + \delta}{\text{thoracic classification (optical)} + \delta} \qquad (5)$$

The larger the value of δ, the closer the ratio approaches one. Therefore, using an electron microscope-based method for counting the smaller fibers would produce better agreement between the thoracic classification limit and 3 μm diameter count limit.

The use of a fixed diameter selection criterion appears to give good agreement with a hypothetical thoracic sampler. Without samplers developed according to the thoracic criterion, it is difficult to provide experimental confirmation of this agreement. Thoracic samplers have been constructed,[25,26,32] but no extensive evaluation or field measurements with these samplers have been reported in the literature to date. The PM10 sampler developed by the Environmental Protection Agency has the same 50% cut point of 10 μm as a thoracic sampler, but has a slightly sharper cut. A commercial PM10 sampler exists (MSP Corporation, Minneapolis, Minn.), but is not suitable for fiber sampling because of the analytical requirement for uniform filter deposit of the collected particulate. Further work needs to confirm the relationship between impactor cutpoint and aerodynamic diameter of fibers. Burke and Esmen[33] found that cutpoints for fibers were slightly different than for compact

particles, with collection increasing with aspect ratio due to interception, and developed formulas for these relationships.

In addition to the issue of size classification, the fiber counting method is predicated on the particles being uniformly distributed on the filter surface. Inertial samplers such as impactors and cyclones tend to produce aerosol streams that are highly stratified. Filter deposits produced with this type of preclassifier may be nonuniform and result in inaccurate fiber counts. Careful design may remove the filter deposit nonuniformity in these types of samplers. Although open-pore foam preclassifiers appear to allow accurate size classification and are likely to give uniform filter deposits, they have not been tested for fibers. Thus, there is a need to develop a thoracic sampler with the following criteria: thoracic preclassification according to aerodynamic diameter of fibers; a preclassifier with minimal loss for long fibers (similar to upper respiratory losses in mouth breathing); and uniform particle deposition on the filter surface. Such a sampler should agree reasonably well with the current practice of counting only fibers with diameters less than 3 μm.

RECOMMENDATIONS AND CONCLUSIONS

In principle the sampling method for fibers should reflect potential health effects by collecting only fibers that can reach the lungs. ACGIH has defined the thoracic fraction as the fraction of particles available for deposition anywhere in the lung airways and in the gas exchange region.[14] The current technique for approximating the thoracic definition for fibers is to use an upper diameter limit of 3 or 3.5 μm. Most national and international methods use the 3 μm diameter limit for fiber counting. The calculations presented here indicate that the 3 μm counting rule agrees with the thoracic definition within about ±25% for a wide range of possible size distributions. An exception occurs for low density, large diameter fibers, where the 3 μm counting rule underestimates the thoracic fraction by as much as 60%. The advantages of using a thoracic sampler would be to reduce analyst decision making (all visible fibers would be counted) and to reduce the nonthoracic aerosol on the sample, making the sample easier to count and less prone to interference by large particles. Until thoracic samplers are available for fibrous aerosols, incorporating the 3 μm upper diameter limit in the fiber counting rules may serve as a surrogate for thoracic sampling.

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