

Two Approaches to Converting Historical Mining Dust Exposures into Respirable Fraction based on Microscope Sizing Measurements

Pengfei Gao, Bean T. Chen, Ziqing Zhuang, Frank J. Hearl, Diana J. Schwerha,
Michael A. McCawley, and Sidney C. Soderholm

National Institute for Occupational Safety and Health, U.S. Centers for Disease Control and
Prevention, 1095 Willowdale Road, Morgantown, WV 26505, U.S.A.

Weihong Chen and Jingqiong Chen

Department of Labor Health and Occupational Diseases, Tongji Medical University,
13 Hangkong Road, Wuhan, Hubei, People's Republic of China

ABSTRACT. In an ongoing epidemiological study to clarify the exposure-response relationship for the development of silicosis in Chinese mine and pottery industries, a large historical data source containing approximately 60,000 mining workers' exposures from 1958 to 1992 was converted into respirable silica mass concentrations. In the original Chinese database, the exposure data were expressed as total mass concentration with size distributions categorized by microscopic sizing. In this report, two options, one by direct calculation using volume contribution in each fraction and the other by using the Hatch-Choate equation, have been developed to convert count fraction into mass fraction. In general, the conversion using the Hatch-Choate equation offered a slightly lower conversion value. The direct calculations using volume contribution in each fraction may be preferable because the assumptions are less restrictive.

Key Words: respirable fraction, mining dust, conversion factor

INTRODUCTION

It has long been recognized that exposures to airborne mining dust cause adverse effects to the respiratory system.⁽¹⁾ More specifically, the development of silicosis, a disabling disease of the lung, is uniquely linked to respirable free silica.^(2,3) Currently in China millions of employees work in metal mining and factory operations where respiratory diseases have been a leading cause of death, and approximately 400,000 workers have developed silicosis.⁽⁴⁾ Common symptoms related to silica over-exposures are cough (with or without sputum), breathlessness, dyspnea, and a predisposition to colds and bronchitis. In an ongoing collaborative epidemiological study between the National Institute for Occupational Safety and Health (NIOSH) and the Tongji Medical University in China, “total dust mass concentration” data from a large historical data source were converted into respirable silica mass concentrations. The data source contains exposure records for approximately 60,000 employees who were employed from 1958 to 1992 at 29 mines and factories located in five provinces of south central China.

From 1925 through the 1960's, impinger sampling with particle counting using light-field microscopy with 100 x magnification was the standard method used in the U.S. for quantifying exposure to mineral dusts. These measurements were reported as million particles per cubic foot of air (mppcf). During the 1960's, in recognition of the relevance of *respirable mass* to the development of pneumoconiosis, efforts were made to relate existing particle-count exposure limits to measurements of respirable mass. Consequently, studies to convert impinger particle count data to respirable mass sampling techniques were conducted⁽⁵⁾. Generally, the conversion factor has varied between 0.07 to 0.13 mg/m³ respirable dust per 1 mppcf.⁽⁵⁻¹⁰⁾ These correlation studies used various instruments for the measurement of respirable dust, including horizontal elutriators and cyclones of differing dimensions. Some of the variability is undoubtedly due to the different operating characteristics of the respirable mass samplers. Studies measuring the conversion factor between impinger counts and respirable mass concentration for various industries provide a range of proposed values. In 1968, the American Conference of Governmental Industrial Hygienist (ACGIH) proposed to change the Threshold Limit Values (TLVs) based on count concentration by impinger sampling to respirable mass concentrations, and formally adopted the change in 1970.⁽¹¹⁾

The reconstruction of historical exposures are often necessary for the exposure assessment component of an epidemiological study because past sampling methods and/or data expressions were inconsistent with current technology. In China, airborne dust in mines has been collected by filter cassette at high flow rate while the tasks were in progress. The so called “total dust” levels were determined gravimetrically and particles were sized microscopically. Respirable fractions were noted for all particles having less than a 5 µm geometric diameter

regardless of the density and shape factors related to the particles' aerodynamic behaviors. However, respirable particle mass, currently defined by the ACGIH, consists of those particles that are hazardous when deposited in the gas-exchange region of the lungs with a median cut point of 4.0 μm aerodynamic diameter^(12,13). In order to estimate the respirable mass concentration by means of the ACGIH definition, and subsequently, a respirable silica concentration, it was necessary to convert the "total mass concentration" into respirable concentration based on the Chinese microscopic particle sizing data. This paper provides two approaches, one by volume and the other by using the Hatch-Choate equation, for this purpose. Some necessary assumptions have been made and are discussed. Methodology on this issue has been lacking in the literature.

MATERIALS AND METHODS

Sampling and Analysis

Sampling in this study was conducted in 20 metal mines and 9 pottery factories. A total of 134 samples were collected: 55 in tungsten mines, 23 in copper and iron mines, 7 in a tin mine, and 49 in pottery factories. As per tradition, the Chinese airborne dust sampler (Model FC-2, Wuhan Analytical Instrument Company, Wuhan, China) was used for sampling. This type of sampler has an open face 40-mm polyperchloroethylene filter (pore size 1.2 to 1.5 μm , thickness of 0.1 mm) and operates at a flow rate as high as 25 L/min. The sampling period lasted 15 minutes while the tasks were in progress.

After sampling, the filter was placed in a small beaker and dissolved by adding 1 to 2 mL butyl acetate. The solution was stirred thoroughly, then a drop of the solution was put onto a glass microscope slide. The drop was spread out to form a thin film, which dried quickly. Additional butyl acetate was used to dilute samples from the filters with high particle concentrations in order to obtain optimum counting and sizing conditions.

Particles were sized using a light microscope, and at least 200 particles were randomly selected on each slide. Particles were categorized in four size ranges, i.e., $\leq 2 \mu\text{m}$, 2 to 5 μm , 5 to 10 μm , and $\geq 10 \mu\text{m}$. Due to the irregular shape of the dusts, slides were always moved vertically and sizes were measured in the horizontal direction.

Dust densities from each mine and factory were measured by using a pycnometer in the College of Engineering and Mineral Resources of the West Virginia University. Two to three replicates were taken. The dust density ranged from 2.39 to 2.68 g/cm^3 .

Data Processing

Log-probability plots were drawn to obtain the count median diameter (CMD) and

geometric standard deviation (GSD) for each sample so that size distribution curves could be generated based on the two-parameter lognormal density function.⁽¹⁴⁾ The straight lines by “eye” on most of the lognormal probability plots indicated the lognormal distribution as the correct model. As shown in Figure 1, the integration of the lognormal curves produced percentages of dust by count less than 5 μm in good agreement with the original sizing data. This also gives an impression that the lognormal distribution could be a reasonable assumption in general. Strictly, a goodness-of-fit test, such as the W test⁽¹⁴⁾ or Chi-square test⁽¹⁵⁾, should be used as a powerful general-purpose test for the lognormality if needed.

Two Approaches for the Conversions

By direct calculation using volume contribution in each fraction. The basic assumption for this conversion method was that particles have “similar shapes” by the mathematical definition. For instance, if the dusts were cuboid, each of the three corresponding aspects among them were identical. The conversion was based on the following steps:

(1). Calculation of volume fractions based on the count fractions in each size range. First, a count median size (CMS) in each range was calculated. For example, for the range 2 - 5 μm , CMS was calculated as a geometric mean $(2 \mu\text{m} \times 5 \mu\text{m})^{0.5} = 3.16 \mu\text{m}$, because a logarithmic size scale would be more reasonable for the size distribution due to a process that breaks the original powder down.^(15, 16) The smallest size in the “ $\leq 2 \mu\text{m}$ ” range was estimated by the limit of detection of the microscope used, which was roughly of the order of 0.5 μm . The largest size in the “ $\geq 10 \mu\text{m}$ ” range was estimated by the concept that area under the curve in a plot of (number fraction/ μm) against particle size equals to the number fraction in each size range. In this estimate, the “ $\leq 2 \mu\text{m}$ ” and “ $\geq 10 \mu\text{m}$ ” ranges are better approximated by right triangles,⁽¹⁷⁾ whereas the other two ranges are approximately as rectangular. After CMS was calculated, percentage of volume (or mass assuming the densities are the same) was computed by using the count percentage data and CMS approximately as the size of average volume. Assuming the total number of particles on a filter was N, the total volume of particles in each size range equaled the product of the particle number (N times the count percentage) and the average volume of the particles in the range. The volume percentage was then the ratio of the total volume in each size range to the total volume of the N particles. N was an arbitrary number and independent of the calculations since the N in the numerator and denominator were canceled out.

(2). Calculation of mass median aerodynamic diameter (MMAD). Taking into account the particle density (ρ) and dynamic shape factor (χ), CMS was converted into mass median aerodynamic diameter (MMAD). For example, for a particle with a CMS of 3.16 μm , the aerodynamic diameter is 4.75 μm , where ρ_0 is unit density. A shape factor (χ) of 1.36 for quartz was used.^(18,19) A typical reconstructed mass fraction plot by this option is shown in Figure 2.

(3). Calculation of the respirable fraction. First, the respirable fraction in each size range was calculated as the product of the volume percentage and the respirable fraction at MMAD based on the ACGIH definition^(12,13). The sum of the respirable fractions in each size range

yielded the respirable fraction for the sample.

By using Hatch-Choate Equation. The use of this option necessitated that two assumptions be made: 1) the size distribution is lognormal, and 2) particles are spherical. The conversion was calculated as follows:

(1). Using the count median diameters (CMD) and the geometric standard deviations (GSD) from the log-probability plots, the mass median diameter (MMD) was calculated according to the Hatch-Choate equation⁽¹⁹⁾.

$$MMD = CMD \times \exp(3 \ln^2(GSD)) \quad (1)$$

(2). Calculation of mass median aerodynamic diameter (MMAD) was based on the density (ρ) and dynamic shape factor (χ). Again, ρ_0 is unit density, and a shape factor of 1.36 for quartz was used as in the volume option.

$$MMAD = MMD \sqrt{\frac{\rho}{\rho_0 \chi}} \quad (2)$$

(3). Size distributions were reconstructed based on the two-parameters of lognormal distributions, MMAD and GSD. A typical plot is shown in Figure 2, which has a MMAD 10.86 and GSD 1.8, respectively. The respirable fraction was then calculated by taking the products of the integration of the lognormal distribution and the ACGIH respirable curve. Details of the calculation are given in the Appendix.

RESULTS AND DISCUSSION

For mining and pottery industries, factors to convert “total dust” of the Chinese system to respirable dust were calculated by the two different approaches described above. As shown in Table I, respirable dust percentages averaged by job titles fluctuated from 0.9 to 11.3% by using the Hatch-Choate equation, while respirable percentages ranged from 1.1 to 12.3% by direct calculation using volume contribution in each fraction. Variations within each job title are generally high as indicated by the standard deviations in the parentheses. Variations among the values may really reflect different task-specific size distributions. In the tin mines, for instance, it seems reasonable that the pumper was exposed to less respirable dust than was the unloader because the vacuum device that the pumper operated removed a greater number of smaller particles than larger ones. Some discrepancies are not easily interpreted, however, and they may result from sampling and analysis errors, especially for the count fraction in the larger size range.

The use of the Hatch-Choate equation required several more restrictive assumptions than did the volume method. First, with the Hatch-Choate equation the particles must be assumed to be spherical, rather than just being similar as with the other method. Second, the overall particle size distribution should be lognormal, and this option applies only for single-mode size distributions. However, the size distributions of mining dust often appear as bimode or multimodes⁽²¹⁾. Willeke and Baron⁽¹⁷⁾ pointed out that it is frequently tempting to draw a straight line on a log-probability plot through the data without knowing the distribution is bimodal. For instance, an aerosol with mode 1 (CMD=1.5 μm and GSD=2) and mode 2 (CMD=10 μm and GSD=2) would be mis-calculated as a single mode (CMD=3.4 μm and GSD=3.4). Assuming a density of 2.5 mg/cm^3 and a shape factor of 1.36, the calculated respirable percentages using the Hatch-Choate equation for mode 1 and mode 2 would be 23.9 and 0.1%, respectively. If each of the two modes possesses same particle number, the respirable percentage calculated by volume-weighted average would be 0.18%. However, the mis-calculated single mode would result in a respirable percentage of 0.03%, only one-sixth the real value. Most likely, this could be a reason why the Hatch-Choate equation yields lower conversion factors than those obtained by the other method in general. Third, the mass median diameter calculated by using the Hatch-Choate equation greatly depends on an accurate estimation of GSD from the log-probability plots. With the same density and dynamic shape factor stated above, the respirable percentage by the Hatch-Choate equation for the distribution shown in Figure 2 (with a CMD 2.84 μm , a MMAD 10.86 μm , and a GSD 1.8) is 9.4%. However, if the true GSD was 1.62, only 10% smaller, MMAD would decrease to 7.74 μm , and the respirable percentage would increase to 17.1%; while if the true GSD was 1.98, 10% larger, MMAD would increase to 15.61 μm , and the respirable percentage would decrease to 5.1%, nearly a doubling in the difference would occur in both cases based on the calculations by using the Hatch-Choate equation. In contrast, the volume option is less susceptible to such variation.

On the other hand, results by the option that directly calculated volume contribution in each size fraction are largely dependent upon the accurate sizing of the larger particles. Even though the respirable fraction for an 1 μm particle is 97 times as high in probability as that for a 10 μm particle, the volume contribution from the former is only one thousandth the latter. For example, if a total of 200 particles were counted on each of two filters and each has 50 particles less than 2 μm and 110 particles between 2 and 5 μm . Assuming one filter has 34 particles between 5 and 10 μm , and 6 particles greater than 10 μm , the respirable percentage would be 7.4%. However, if 2 particles larger than 10 μm had been mis-sized into the smaller size range, the real respirable percentage would be reduced to 6.6%.

The Chinese sampling system was expected to collect greater quantities of bigger particles, say $\geq 10 \mu\text{m}$, because of the higher sampling flow rate and the short-term sampling duration. In addition, the particle size distribution of the dust samples was supposed to be mainly governed by the operations, which suspended larger particles in air for shorter periods than were the smaller ones because of gravitational settling. A field study by Wu and et al.⁽²²⁾ showed that

the Chinese sampling system did collect 38% more “total dust” than the 37-mm cassettes operating at 2 L/min. Based on these data, respirable concentrations should be estimated at an equivalent level where we have a calculated a conversion factor to be 38% lower.

As mentioned earlier, in China, “respirable dust” was noted for the dust that was less than 5 µm geometric diameter. Total dust and the free silica content were mainly regarded as the exposure indices for the development of silicosis; while the count “respirable fraction” are considered as a qualitative rather than a quantitative index to estimate the health effect. However, it is clear that the development of human silicosis is uniquely linked to the respirable free silica rather than the total dust. Thus, the ability to convert the historical dust exposures based on microscopic sizing data into respirable fraction is an important objective in the epidemiology research. The two approaches established in this study provide useful methodologies for the clarification of the exposure-response relationship.

In summary, two approaches have been used to convert the historical mining exposures to respirable fraction based on the microscopic sizing data. Although the results are not significantly different between the two methods, the direct calculations using volume contribution in each fraction are preferable because the assumptions are less restrictive and the applications are broader, as shown in Table II.

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DISCLAIMER

Mention of product or company name does not constitute endorsement by the Centers of Disease Control and Prevention.

APPENDIX

After converting count median diameters into mass median diameters by the Hatch-Choate equation, respirable fraction was calculated using Mathcad (MathSoft Inc. Cambridge, Mass.). For example, respirable percent was calculated as 8.3% for the distribution shown in Figure 2 that has a MMAD of 10.86 μm and a GSD of 1.8 as the following using Mathcad format. Note that a colon ":" is required as a definition symbol, and "TOL" is the numerical tolerance for the approximation algorithms. The term "norm(z(x))" in the following integration is the cumulative probability function of a standardized normal random variable. A convenient algorithm for this function has been given by Soderholm⁽¹²⁾.

$$\text{MMAD} = 10.86$$

$$\text{GSD} = 1.8$$

$$z(x) = \frac{\log(x) - \log(4.25)}{\log(1.5)}$$

$$\text{TOL} = 0.000001$$

$$d = 100$$

$$\int_0^d \left[\left[(2 \cdot \pi)^{0.5} \cdot x \cdot (\ln(\text{GSD})) \right]^{-1} \cdot e^{-\left[\frac{(\ln(x) - \ln(\text{MMAD}))^2}{2 \cdot (\ln(\text{GSD}))^2} \right]} \right] \cdot 0.5 \cdot (1 + e^{-0.06 \cdot x}) \cdot (1 - \text{cnorm}(z(x))) \, dx = 0.08$$

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Table I. Percentage of Respirable Dust Categorized by Job Titles ^a

Mine/Industry	Job Title	Number of Samples	Option 1 ^b	Option 2 ^c
Tungsten	Crusher	4	4.4 (3.5)	3.6 (3.0)
	Driller	20	5.8 (2.5)	4.1 (2.8)
	Loader	3	4.3 (1.4)	2.3 (1.6)
	Mining	6	10.2 (4.8)	7.5 (5.6)
	Transport way	9	7.0 (3.1)	5.1 (1.1)
	Unloader	12	6.9 (2.4)	5.9 (2.4)
	Working Lane	1	4.5	0.8
Copper/Iron	Driller	9	7.8 (3.6)	6.2 (4.1)
	Excavator	2	3.7	0.8
	Face Worker	1	5.4	0.8
	Loader	3	6.0 (1.9)	4.2 (2.2)
	Transport	5	8.7 (4.0)	5.0 (5.0)
	Tunnel	2	4.0	1.4
	Unloader	1	6.7	5.8
Tin	Driller	2	8.1	5.1
	Excavator	3	7.0 (0.9)	4.7 (1.1)
	Pumper	1	3.1	0.4
	Unloader	1	11.5	4.5

Table I. Percentage of Respirable Dust Categorized by Job Titles ^a (Continued)

Mine/Industry	Job Title	Number of Samples	Option 1 ^b	Option 2 ^c
Pottery	Crusher	1	5.6	2.9
	Dragger	1	7.4	4.4
	Driller	1	1.9	0.3
	Forming	6	6.8 (3.5)	4.1 (3.4)
	Furnace	3	7.4 (1.6)	5.7 (3.1)
	Glazer	3	4.2 (2.9)	1.2 (0.2)
	Loader	3	5.7 (2.2)	3.9 (2.4)
	Milling	2	6.6	3.1
	Mixer	5	6.3 (2.0)	2.9 (1.8)
	Molder	1	12.8	9.7
	Ore Loading	2	3.6	1.4
	Polishing	6	7.0 (5.1)	5.2 (5.4)
	Preparation Worker	5	8.0 (1.7)	4.0 (1.5)
	Raw Material Worker	6	5.6 (1.1)	2.8 (1.4)
	Transport	2	3.6	1.3
Tunnel	2	7.2	5.5	

^a Values are in percent (%) of the respirable dust with respect to the total dust mass concentrations as measured by the Chinese method based on the ACGIH definition of respirable dust⁽¹³⁾. Values in parentheses are the standard deviations.

^b Values calculated using volume contribution in each size fraction.

^c Values calculated using the Hatch-Choate equation.

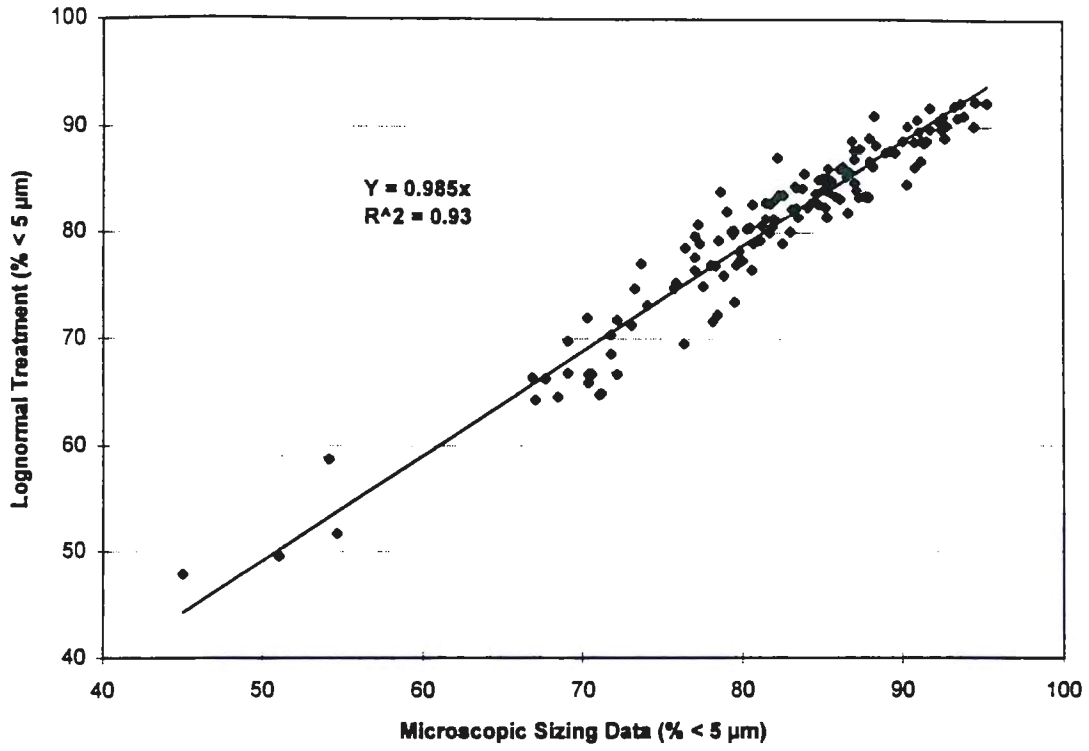
Table II. Comparisons of the Two Approaches

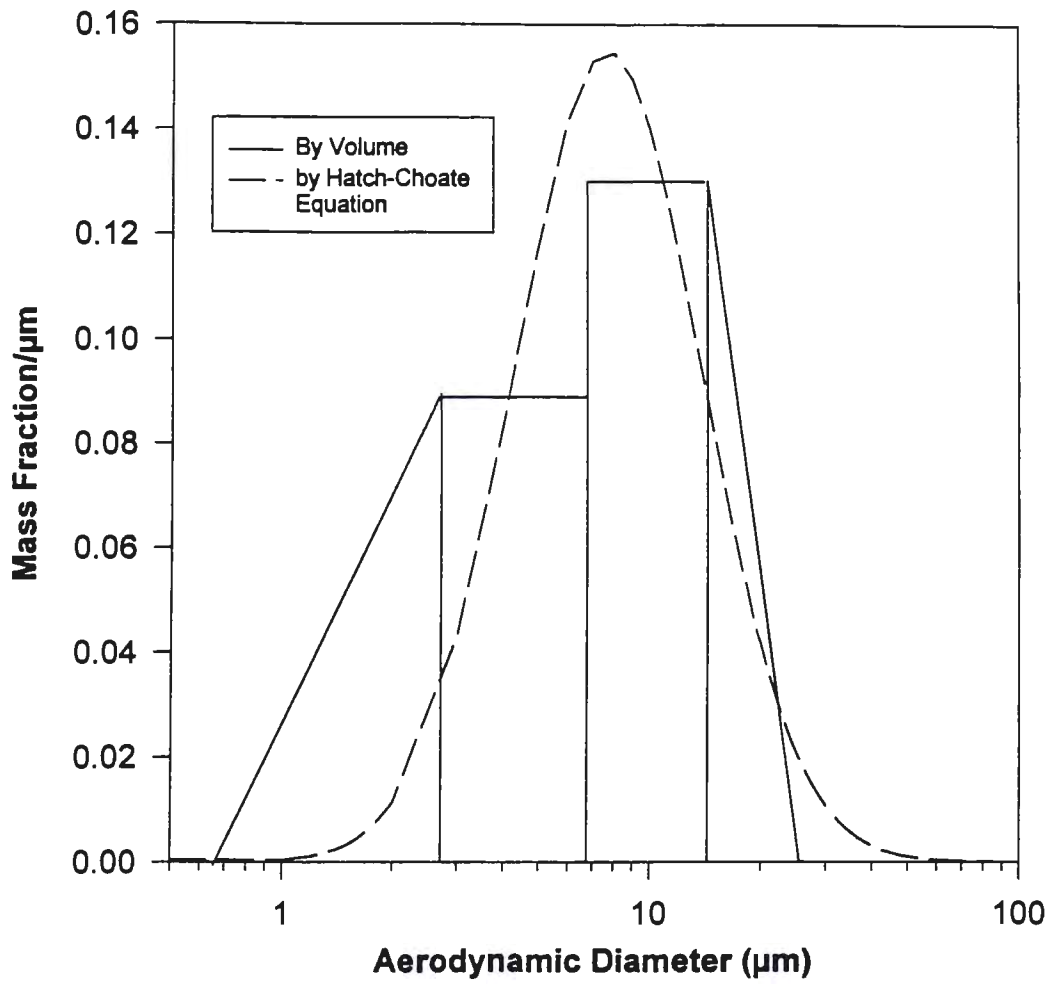
Option	Hatch-Choate	Direct calculations using volume
Assumption	(1). lognormal distribution overall; (2). spherical particle	(1). doesn't matter what kind of distribution overall; (2). similar geometry
Applicable	single mode	more than 1 mode

FIGURE CAPTIONS

FIGURE 1. Percentage of dust by count less than 5 μm : after lognormal treatment vs. the original microscopic sizing data

FIGURE 2. A typical reconstructed mass fraction/ μm plot





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总粉尘浓度转换为呼吸性粉尘浓度的两种方法学研究

P. Gao BT. Chen 陈卫红 Z. Zhuang FJ. Hearl D. Schwerha
MA. McCawley SC. Soderholm 陈镜球

【摘要】 目的 探讨流行病学研究中历史性总粉尘浓度转换成呼吸性粉尘浓度的理论方法。方法 采用两种方法:一种通过体积直接计算;另一种用 Hatch-Choate 方程计算,推导出计数百分比和计量百分比的转换关系。结果 得到总粉尘浓度与呼吸性粉尘浓度的理论转换系数,其中,用 Hatch-Choate 方程计算结果偏低。结论 体积直接计算法更适用。

【关键词】 呼吸性百分数 粉尘 转换系数

Two approaches to convert historical mining dust exposures into respirable fraction (based on microscope sizing measurements) Gao Pengfei*, Chen BT, Chen Weihong, et al.* National Institute for Occupational Safety and Health, Morgantown, USA

【Abstract】 Objective A large historical total dust exposure was converted into respirable mass concentrations for an epidemiological study. Methods Two options, one by direct calculation using volume contribution in each fraction and the other by using the Hatch-Choate equation, have been developed to convert count fraction into mass fraction. Results In general, the conversion using Hatch-Choate equation offered a slightly lower conversion value. Conclusion The direct calculations using volume contribution in each fraction are preferable.

【Key words】 Respirable fraction Dust Conversion factor

我国以往对接尘厂矿空气中粉尘危害程度监测主要依据总粉尘浓度、分散度和游离 SiO₂ 百分比含量,这种表达方式与国内外现用标准不完全一致。美国国家职业安全卫生研究所(NIOSH)和同济医科大学近 10 年在中国 29 个厂矿收集了 7 万多个研究成员的历史性(1950~1994 年)接总粉尘浓度的监测资料。为了更好地使用这部分历史性接尘资料,以利于流行病学分析,我们对总粉尘浓度转换成呼吸性粉尘浓度的方法进行了研究。

材料与与方法

一、样品和分析

样品取自 4 类矿山和瓷厂,总计 134 个:钨矿 55 例、铜铁矿 23 例、锡矿 7 例、瓷厂 49 例。按中国标准规

作者单位:美国国家职业安全卫生研究所(NIOSH)(P. Gao, BT. Chen, Z. Zhuang, FJ. Hearl, D. Schwerha, MA. McCawley, SC. Soderholm);中国同济医科大学劳动卫生学教研室(陈卫红、陈镜球)

定用过氯乙烯滤膜采样,滤膜暴露面积(毛面)40 mm²。滤膜溶解后,制成载玻片,在显微镜下随机测量至少 200 个尘粒。粒径按大小分为 4 级:< 2 μm、~ 5 μm、~ 10 μm 和 > 10 μm(由于粉尘形状不规则,载片总是反复顺垂直方向后移,因此按水平方向测量)。用西弗及尼亚大学工程矿物学院的比重计测定粉尘比重,每个样品重复 2~3 次,粉尘密度介于 2.39~2.68 g/cm³。

资料处理:用对数概率图对每个样品的显微镜数据作图并计算其中位直径(count median diameter, CMD)和几何标准差(s_g),依据两参数对数正态密度函数得到分散度曲线^[1]。绝大多数的对数正态概率图呈直线。对对数正态曲线中 < 5 μm 的粉尘积分,与原始数据中 < 5 μm 粉尘所占的百分比很接近。所以,总体上看对数正态分布是合理的假设。

二、两种转换方法

(一)体积直接计算法

假定尘粒按数理定义具有类似的形态。具体计算步骤如下:

1. 计算尘粒各段在总体中所占体积百分比:取体积中位值(count median size, CMS)。如:2~5 μm 尘粒

段 CMS 为 $\sqrt{2 \mu\text{m} \times 5 \mu\text{m}} = 3.16 \mu\text{m}$, “最小”的粒径估算为显微镜检出限值, 而“最大”粒径则根据每 μm 的粉尘数对粒径的图形求出, 即每一尘粒段曲线下的面积等于尘粒数目的百分比。用三角形近似表示最小和最大两个尘粒段; 用矩形近似表示另两个尘粒段。假定 4 个粒段(粒径由小到大)的尘粒数目分别为 60、86、38 和 16(共数 200 个尘粒), 则尘粒的构成比分别为 30%、43%、19% 和 8%, 如图 1 所示。则各段的体积:

三角形 A 的高度 = $2 \times 30\% \div (2 - 0.5) = 0.40$
 矩形 B 的高度 = $43\% \div (5 - 2) = 0.143$
 矩形 C 的高度 = $19\% \div (10 - 5) = 0.038$
 \therefore “最大”粒径 = $2 \times 8\% / 0.038 + 10 = 14.2 (\mu\text{m})$
 然后计算各尘粒段的体积百分比。

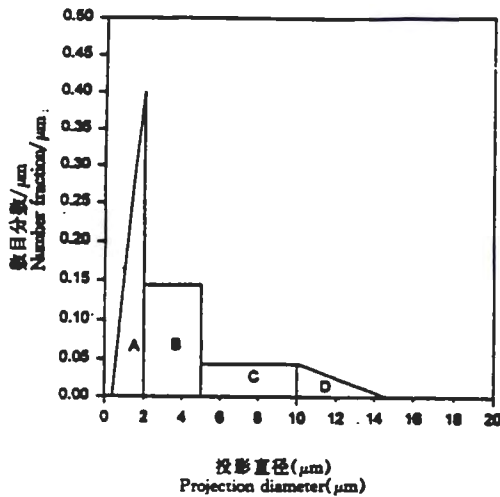


图 1 体积直接计算法估算“最大”投影粒径示意图
 Fig 1 Estimate “Largest” particle size projection by volume

2. 空气动力学中位值 (mass median aerodynamic size, MMAS) 的计算: 根据密度 (ρ_0) 和动力学形态参数 (χ), CMS 可转换成 MMAS, 即:

$$3.16 \mu\text{m} \times \sqrt{(\rho) / (\rho_0 \times \chi)} = 4.32 \mu\text{m}$$

此处采用的是石英的形态参数 (χ) 1.36^[1,2] 和尘粒的平均密度 2.54 g/m^3 。

3. 呼吸性粉尘所占百分比的计算: 按美国政府工业卫生学会 (ACGIH) 的规定, 各尘粒段呼吸性粉尘所占百分比等于各尘粒段的体积百分数乘以 MMAS 的呼吸性部分, 即粒径等于 MMAS 的粉尘进入肺气体交换部位的概率。总计各尘粒段的百分数, 即样品的呼吸性百分数。

(二) Hatch-Choate 方程法

使用该法须满足样品分散度呈对数正态分布、尘粒呈球形。计算步骤如下:

1. 取对数概率图的 CMD 和 s_c , 按 Hatch-Choate 方程^[2] 计算重量中位直径 (mass median diameter, MMD): $MMD = CMD \times \exp(3 \ln^2(s_c))$ 。

2. 按 ρ 和 χ 计算空气动力学中位直径 (mass median aerodynamic diameter, MMAD) (石英的 $\chi = 1.36$):

$$MMAD = MMD \sqrt{\frac{\rho}{\chi}}$$

3. 按 MMAD 和 s_c 的结果重建分散度分布: MMAD = $10.86 \mu\text{m}$, $s_c = 1.8$ 时的典型分布图见图 2。可根据对数正态分布积分和 ACGIH 呼吸性曲线的乘积计算呼吸性粉尘所占百分比。详细计算方法为: 采用 Hatch-Choate 方程将 CMD 转换成 MMD 后, 用 Mathcad (计算机计算软件) 计算呼吸性粉尘所占百分数。如图 2: MMAD = $10.86 \mu\text{m}$, $s_c = 1.8$, 计算出呼吸性粉尘所占百分比为 8.3%。下式积分的 “cnorm [$z(x)$]” 是标准正态随机变量的累积概率函数^[3]。

$$MMAD = 10.86$$

$$s_c = 1.8$$

$$z(x) = \frac{\log x - \log 4.25}{\log 1.5}$$

$$TOL = 0.000001$$

$$d = 100$$

$$\int_0^d [((2 \cdot \pi)^{0.5} \cdot x \cdot (\ln s_c))^{-1} \cdot e^{-\frac{(\ln x - \ln MMAD)^2}{2 \cdot (\ln s_c)^2}}] \cdot 0.5(1 + e^{-0.06x}) \cdot (1 - \text{cnorm}(z(x))) dx = 0.094$$

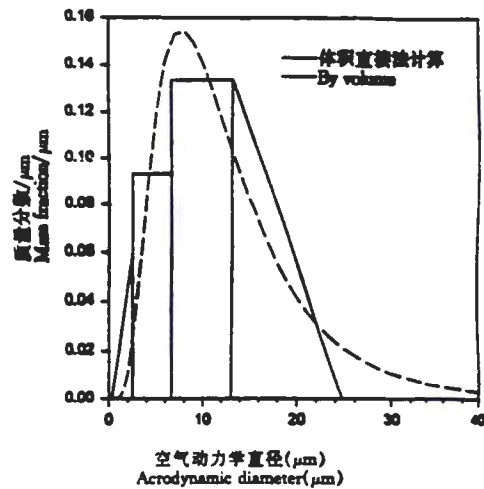


图 2 重建分散度图
 Fig 2 A typical mass frequency plot reconstructed by the Two-parameter

结 果

表 1 所示为两种不同方法转换总粉尘浓度为呼吸性粉尘浓度的转换系数的算术平均值。

用 Hatch-Choate 法,呼吸性粉尘的百分数波动在 0.3%~7.5% 之间;用体积直接计算法,呼吸性粉尘百分数则在 1.1%~12.3% 之间。

表 1 按工种分类的呼吸性粉尘百分比(%)
Table 1 Percentage of respirable dust(%) categorized by job titles

厂(矿)工种 Job title in mine(industry)	样品数 n	方法 1 [◆] Option 1 G(s _c)	方法 2 [▲] Option 2 G(s _c)
钨矿 Tungsten			
破碎工 Crusher	4	4.4(3.5)	3.6(3.0)
风钻工 Driller	20	5.8(2.5)	4.1(2.8)
装矿工 Loader	3	4.3(1.4)	2.3(1.6)
地质采样工 Mining	6	10.2(4.8)	7.5(5.6)
运输工 Transporter	9	7.0(3.1)	5.1(1.1)
卸矿工 Unloader	12	6.9(2.4)	5.9(2.4)
管道工 Working lane	1	4.5	0.8
铜铁矿 Copper/Iron			
风钻工 Driller	9	7.8(3.6)	6.2(4.1)
铲矿操作工 Excavator	2	3.7	0.8
地面工 Face worker	1	5.4	0.8
装矿工 Loader	3	6.0(1.9)	4.2(2.2)
运输工 Transporter	5	8.7(4.0)	5.0(5.0)
巷道工 Tunnel	2	4.0	1.4
卸矿工 Unloader	1	6.7	5.8
锡矿 Tin			
风钻工 Driller	2	8.1	5.1
铲矿操作工 Excavator	3	7.0(0.9)	4.7(1.1)
水泵工 Pumper	1	3.1	0.4
卸矿工 Unloader	1	11.5	4.5
瓷厂 Pottery			
破碎工 Crusher	1	5.6	2.9
勤杂工 Dragger	1	7.4	4.4
风钻工 Driller	1	1.9	0.3
成型工 Forming	6	6.8(3.5)	4.1(3.4)
焙烧工 Furnace	3	7.4(1.6)	5.7(3.1)
釉坯工 Glazer	3	4.2(2.9)	1.2(0.2)
装坯工 Loader	3	5.7(2.2)	3.9(2.4)
球磨机工 Milling	2	6.6	3.1
混合工 Mixer	5	6.3(2.0)	2.9(1.8)
模型工 Molder	1	12.8	9.7
上矿工 Ore loading	2	3.6	1.4
抛光工 Polishing	6	7.0(5.1)	5.2(5.4)
准备工 Preparation worker	5	8.0(1.7)	4.0(1.5)
原料准备工 Raw material worker	6	5.6(1.1)	2.8(1.4)
运输工 Transporter	2	3.6	1.3
巷道工 Tunnel	2	7.2	5.5

◆ 体积法计算的结果; ▲ Hatch-Choate 方程法计算的结果

◆ The results by using volume contribution; ▲ The results by using Hatch-Choate equation

讨 论

美国 60 年代就要求将冲击式采样结果(以尘粒计数表示)转换为重量单位,而且研究表明:计数结果与呼吸性粉尘重量法结果存在一个衡定的转换系数,大约各矿尘比值是 1 mpcf,相当于 0.09(0.07~0.13) mg/m³ 呼吸性粉尘^[4-7]。

我国按总粉尘中粉尘分散度大小确定:尘粒中几何学直径小于 5 μm 归入呼吸性粉尘。此法没有涉及尘粒空气动力学有关的形态及其密度因素。而 ACGIH 定义的呼吸性粉尘包括所有可进入肺内气体交换部位的尘粒^[3,8]。因此,仅根据分散度资料将总粉尘转换为呼吸性粉尘和呼吸性游离二氧化硅粉尘是否合适尚需研究。我们提供了上述两种方法, Hatch-Choate 方程法比体积计算法要求严格:首先, Hatch-Choate 法要求尘粒呈球型,而体积法只要求是相似体;其次, Hatch-Choate 法要求粉尘分散度呈对数正态分布,而且仅限于单一的模式分布^[1],但实际上矿尘往往是双模式或多模式分布;第三, Hatch-Choate 法计算 MMD 很大程度上取决于对数概率图所提供的精确的 s_c 值。相对而言,体积法的变异波动较小,计算很大程度上取决于大颗粒数目的准确性。此外,转换系数的复杂性还在于矿工们很少每天都做同样的工作。故有人推荐每个类型厂矿用同一个均值的转换系数。使用体积法计算呼吸性粉尘所占百分率均值介于 5%~8%,用其它方法则为 4%~6%。假若粉尘样品的分散度很一致,则转换系数差异很小。

由于总粉尘采样是在高流速、短时间、工人操作时,易于采集到大于 10 μm 的尘粒。Wu 等^[9]曾研究表明:中国采样方法比美国以 2 L/min 采样速度采集在 37 mm 样品盒内的总粉尘要多收集到 38%。为此,我们应将转换系数调整 38% 后再估算其相应的水平。我们的计算结果与 Burkant 等^[10]对井下煤矿研究显示的呼吸性粉尘 SiO₂ 的百分含量大致相同。

总之,根据粉尘分散度资料将历史性的总

粉尘浓度转换成呼吸性粉尘浓度,在流行病学研究中是非常重要的。尽管两种方法计算的结果没有太大差异,但体积直接计算法可能更适用,因此法适用性较为广泛,条件要求也不太高。我们建议所有34个工种、4个类型厂矿的平均转换系数用6%,因为:(1)中国工人每天并不只从事单项工作,因此用平均值更现实、方便;(2)不同厂矿间转换系数变动较小,即5%~7%,与冲击采样的转换系数0.09(0.07~0.13)基本类似。

(感谢西弗及尼亚大学工程矿物学院的 Larry Nice 先生及其同事测定粉尘比重;感谢 NIOSH 的 Paul Baron 博士和 Texwipe LLC 公司的 Douglas Cooper 博士对本文给予有价值的讨论和建议)

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曲酒发酵池 CO₂ 气体急性中毒 4 例

张克维 王春娟

1997年3月24日下午5时30分,某酒厂曲酒固体发酵池倒塌,7时50分4名抢修工下池后即昏倒在池中。立即用电风扇向池内吹风,并由1人用湿衣扎住嘴跳下池救人,但仍感憋气,随即上来,1分钟后,相继下去4人,将中毒者救出。4例中毒者在池中约15分钟,救出后1例呼吸、心跳已停止,3例昏迷。

事故后立即进行现场调查。该厂曲酒发酵池两池轮换使用,发酵池容积为4m×2m×2.5m,以红高粱为原料,发酵过程中每分子葡萄糖可产生2分子乙醇和2分子CO₂。事故当日,阴雨天气,无风,池内风速0.1m/s。空气中CO₂气体采样测定:中毒池为8.2%,倒塌发酵池17.5%,密封发酵池37.4%。

临床表现:4例中毒者均为男性,除1例死亡者45岁外,余3例年龄20~24岁,入院时均呈昏迷状态,对声、光、语言刺激无反映,压迫眶上神经可见表情痛苦,角膜反射、瞳孔反射存在。3例呼吸缓慢(呼吸频率

11~13次/min),2例心动过缓(心电图检查:心率54~58次/min),1例血压偏低(11.7/7.5kPa)。实验室检查:尿常规正常。Hb 131g/L, RBC 4.7×10¹²/L, WBC 6.3×10⁹/L, N 0.68, L 0.27。血清ALT(GPT)、AST(GOT)、γ-GT均正常。胸片未见异常。患者醒后对事故经过已失去记忆,自述周身酸痛、沉重。

治疗:4例中毒病人,1例因当场呼吸、心跳停止,经人工复苏,抢救无效死亡外,余3例昏迷病人入院后立即进入多人舱行高压氧治疗(常规方案:2.5ATA,吸氧2次,每次30分钟,中间休息10分钟);20%甘露醇250ml,30分钟内静脉滴注完,地塞米松5mg/次,静脉注射,6小时1次,同时给予ATP 40mg/d,辅酶A 30mg/d, Vit C 2g/d加入10%葡萄糖液静脉滴注。经上述纠正缺氧和防治脑水肿等方法治疗后于次日上午6~8时先后清醒,经住院观察5天,无异常征象,痊愈出院。2个月后随访,情况良好。

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