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Estimating Factors to Convert Chinese 'Total Dust' Measurements to ACGIH Respirable Concentrations in Metal Mines and Pottery Industries

PENGFEI GAO†*, BEAN T. CHEN†, FRANK J. HEARL†, MICHAEL A. McCAWLEY†, DIANA J. SCHWERHA†, JOHN ODENCRANTZ†, WEIHONG CHEN‡, JINGQIONG CHEN‡ 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, *USA*; ‡*Department of Labor Health and Occupational Diseases, Tongji Medical University,*13 *Hangkong Road, Wuhan, Hubei, People's Republic of China*

Historical data on the dust exposures of Chinese workers in metal mines (iron/copper, tin, tungsten) and pottery industries are being used in an ongoing joint Chinese/United States epidemiological study to investigate the exposure–response relationship for the development of silicosis, lung cancer, and other diseases. The historical data include 'total dust' concentrations determined by a Chinese method. Information about particle size distribution and the chemical and mineralogical content of airborne particles is generally not available. In addition, the historical Chinese sampling strategy is different from a typical American eight-hour time-weighted average (TWA) sampling strategy, because the Chinese samples were collected for approximately 15 minutes during production so the sample could be compared to their maximum allowable concentration (MAC) standard. Therefore, in order to assess American respirable dust exposure standards in light of the Chinese experience, factors are needed to convert historical Chinese total dust concentrations to respirable dust concentrations. As a part of the joint study to estimate the conversion factors, airborne dust samples were collected in 20 metal mines and 9 pottery factories in China during 1988 and 1989 using three different samplers: 10 mm nylon cyclones, multi-stage 'cassette' impactors, and the traditional Chinese total dust samplers. More than 100 samples were collected and analysed for each of the three samplers. The study yielded two different estimates of the conversion factor from the Chinese total dust concentrations (measured during production processes) to respirable dust concentrations. The multivariate analysis of variance (MANOVA) reveals that, with a fixed sampling/analysis method, conversion factors were not statistically different among the different job titles within each industry. It also indicates that conversion factors among the industries were not statistically different. However, the two estimates consistently showed that conversion factors were the lowest in the pottery industry. Average conversion factors were then calculated for each of the estimates across the industries studied. A pooled mean conversion factor, 0.25 ± 0.04, was then derived for all the job titles and industries. Respirable dust levels were estimated from the historical 'total dust' concentrations collected between 1952 and 1992 by adopting the American standard. © 2000 British Occupational Hygiene Society. Published by Elsevier Science Ltd. All rights reserved

Keywords: conversion factor; mining dust; exposure estimates; respirable dust; metal mines; iron; copper; tin; tungsten; pottery; ACGIH definition

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*Author to whom correspondence should be addessed. Tel.: +1 304 285 6034; Fax: + 1 304 285 6041; E-mail: pcg9@cdc.gov

INTRODUCTION

Conversion factors are necessary for the exposure assessment component of an epidemiological study when past sampling methods and/or data expressions are inconsistent with current criteria. For instance, impinger sampling with particle counting using light-field microscopy with 100× magnification was the standard method used in the United States for quantifying exposure to mineral dusts from 1925 through the 1960s. These measurements were reported as millions of particles per cubic foot (mppcf) of air (Sutton and Reno, 1967). Since the 1960s, 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 concentration. The reports indicate that ratios of respirable dust concentration in mg m^{-3} to the impinger count concentrations in mppcf were remarkably consistent: 0.09 in Vermont granite sheds (Sutton and Reno, 1967) and in the North Carolina granite industry (Rice *et al.*, 1984); 0.13 in a 1920 granite shed industry (Ayer *et al.*, 1973); and 0.092–0.139 in Minnesota taconite plants (Sheehy and McJilton, 1987).

In an ongoing collaborative epidemiological study between the National Institute for Occupational Safety and Health (NIOSH) and the Tongji Medical University in China, scientists are using an historical Chinese database to investigate the exposure–response relationship for the development of silicosis, lung cancer, and other diseases. This data source contains dust exposure records for approximately 60 000 workers who were employed from 1958 to 1992 in 29 metal mines and pottery factories in five provinces of south-central China. This historical database consists of more than two million measurements collected using the Chinese 'total dust' sampler. This is a battery-operated area sampler that collects airborne dust directly onto an open-face 40 mm filter at a flow rate as high as 25 l. min^{-1} for 15 min while the dust-producing tasks were in progress. Such a high sampling flow rate and a short sampling period were needed because the Chinese dust exposure standard has been based on a maximum allowable concentration (MAC). Therefore, a different sampling strategy from NIOSH's eight-hour time-weighted average (TWA) was needed in order to track 'maximum peak concentration' within a short period. During 1988 and 1989, a sampling campaign was mounted and more than 100 samples were collected and analysed using 10 mm nylon cyclones, multi-stage 'cassette' impactors (Jones *et al.*, 1983), and Chinese dust samplers, respectively. Total dust concentrations were determined gravimetrically from the filter samples collected using the Chinese dust sampler and sampling strategy. Respirable dust concentrations were estimated gravimetrically from 10 mm nylon cyclone samples and multi-stage cassette impactor samples, respectively, which had been collected over nearly a full shift.

The study yielded two different estimates of the conversion factor from the Chinese total dust concentrations measured during production—one for respirable dust concentrations estimated using cyclone and the other for those estimated using the multi-stage 'cassette' impactor. With this information, Chinese total dust concentrations can be converted to respirable dust concentrations and subsequently to respirable free silica concentrations in order to determine the adequacy of current American respirable dust standards relative to the incidence of occupational lung disease among Chinese workers. This study develops the conversion factors needed to estimate respirable dust without regard to chemical content. A separate study is currently under way that focuses on the conversion factors needed to estimate respirable free silica exposures (Zhuang *et al.*, 1999).

MATERIALS AND METHODS

Dust sampling and measurements

Sampling was conducted in 29 industries:10 tungsten mines, 6 iron/copper mines, 4 tin mines, and 9 pottery factories. There were three exposure-monitoring stations in each mine and factory. Their locations were based on two criteria: (1) each of the three sampling stations was chosen to be representative of a distinct exposure; and (2) sampling stations were previously sampled under the Chinese national dust monitoring programme. Dust levels were measured using three area samplers in parallel: the cyclone, the multi-stage 'cassette' impactor, and the Chinese dust sampler. Details in selecting the sampling sites were described by Wu *et al.* (1992).

For samples collected using a cyclone, respirable mass concentrations were measured gravimetrically. A 37 mm FWS-B filter mounted in a plastic cassette was placed downstream from the cyclone. Pre- and post-weighing with a balance were done after desiccant drying to determine the mass collected. Air was aspirated at 1.7 l. min^{-1} according to NIOSH dust sampling procedures. Respirable dust concentrations were obtained by taking the ratio of the respirable dust mass to the sampled air volume.

For samples collected using a multi-stage 'cassette' impactor, respirable dust concentrations were determined. The impactor was fabricated from 37 mm cassette pieces comprising four stages plus a back-up filter operating at 2.0 l. min^{-1} (Jones *et al.*, 1983). In order to focus on the respirable dust size range, the nozzle diameters were modified to have 50% cut-off diameters of 9.8, 7.4, 5.2 and 1.65 μm, corresponding to the respirable fractions 0.01, 0.032, 0.16 and 0.97 on the individual stages (Wu *et* *al.*,1992) based on the American Conference of Governmental Industrial Hygienists (ACGIH) definition (Soderholm, 1989; ACGIH, 1999). All the particles collected on the back-up filter were regarded as respirable. Thus, respirable dust mass was calculated as the sum of the products of dust mass on each stage and its corresponding respirable fraction plus the mass on the back-up filter. The respirable dust concentration was also obtained by taking the ratio of the respirable dust mass to the sampled air volume.

'Total dust' was collected using the Chinese dust sampler (Model FC-2, Wuhan Analytical Instrument Company, Wuhan, China). The sampler, with an open-face 40 mm polytetrachloroethylene filter (pore size 1.2–1.5 μm, thickness of 0.1 mm), was operated at a flow rate as high as 25 l. $\min^{-1}$ for periods of 15 min while the tasks were in progress. After sampling, the 'total dust' mass concentrations were determined. Additionally, particles were sized microscopically, a traditional method used in China. The filter was dissolved in butyl acetate. The solution was stirred thoroughly and a drop was put onto a glass microscope slide. The drop was spread out to form a thin film which dried quickly. Particles were categorized in four size ranges: ≤2 μm, 2–5 μm, 5–10 μm, and ≥10 μm. Approximately 200 particles were randomly selected on each slide. 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 log-normal density function (Gilbert, 1987). Two methods, one using volume contribution in each fraction, and the other using the Hatch–Choate equation, were developed to estimate the conversion factors (Gao *et al.*, 1999). However, the conversion factors estimated based on the microscopic data were only about one quarter the magnitude of those obtained using the cyclone and impactor data. There are several probable reasons for this. First, the Chinese sampling system was expected to collect greater quantities of large particles than the cyclone and impactor owing to the short-term sampling while the tasks were in progress. Second, only 200 particles on each filter were sized in only four size increments. Third, the lower conversion factors from the microscope sizing data could be caused by an inadequate dynamic shape factor which has a great impact on the calculation. For these reasons, the microscopic results will not be evaluated in the current study.

Calculations of the conversion factors

In this study, two sets of conversion factors were estimated using data collected from the cyclone and the multi-stage 'cassette' impactor sampler, respectively. Basically, conversion factors were obtained directly by taking the ratio of the respirable concentrations obtained from each instrument to the 'total dust' concentrations determined by the Chinese airborne dust sampler. The Chinese airborne dust sampling data were defined as 'total dust' in order to be consistent with the historical sampling strategy. This is consistent with a previous investigation in the iron and copper mines, where total dust concentrations measured by the Chinese dust sampler were compared to the multi-stage 'cassette' impactor (Wu *et al.*, 1992). The results of that study showed that although there was a tendency towards a positive bias when using the Chinese dust sampler (due to both the higher sampling flow and more dust being present while work was in progress), the total dust measurements between the multi-stage 'cassette' impactor and the Chinese dust sampler were highly correlated ($r^2 = 0.84$).

RESULTS AND DISCUSSION

Evaluation of the conversion factors

Table 1 presents the geometric means of the conversion factors averaged by job titles in the four different mines/factories. The geometric means were used to reduce the influence of a few high values. The ranges of the mean conversion factors in each industry were: 19.3–28.2% using the cyclone; and 31.3–52.4% using the impactor. Although three of the job-specific conversion factors were greater than 100%, they were not excluded from the analysis because they reflect random errors in sampling and analysis as well as differences in sampling strategy.

Results in Table 1 indicate that conversion factors were the lowest in the pottery industry, suggesting a difference between the mining and non-mining operations. It also indicates that the conversion factors were the highest in tin mines. Among the job titles, the lowest conversion factors were generally related to preparation workers in the pottery factory.

Statistical analyses of the conversion factors

The Statistical Analysis System (SAS version 6.12, SAS Institute, Inc., Cary, North Carolina) was used to investigate the conversion factors among the industries and job titles. The Shapiro–Wilk test indicated that the conversion factors were not normally distributed ($P < 0.0001$ for both factors). Therefore, an analysis of variance could not be directly used. Nevertheless, log-transformed conversion factors could be regarded as normally distributed (P equal to 0.06 and 0.57 for cyclone and impactor data, respectively). Multivariate analysis of variance (MANOVA) was applied to test the difference of the mean conversion factors using the log-transformed data. The test reveals that (1) with a fixed sampling/analysis method, conversion factors were not statistically different among the different job titles within each mine/industry ($P > 0.05$); and (2) conversion factors among the mines and industries were not statistically different ($P > 0.05$).

The lack of difference among the mean conversion factors could have resulted from a couple of reasons. It could have resulted from insufficient sampling data to distinguish the difference in the statistical inference. Secondly, it was demonstrated that the same respirable fraction could exist in different particle size distributions, thus having the same conversion factor. However, for a number of different distributions containing the same respirable fraction, one with a larger MMAD should have a larger GSD, and vice versa.

Estimation of the mean conversion factors

Assuming the data meet the usual assumptions for ordinary least-squares analysis, a straight-line model for respirable concentrations versus the total dust concentrations can be applied. For each set of the estimates, regression analysis using the least-squares method was employed based on the individual conversion factors. The following regression equation was used:

$$Y = \beta X \tag{1}$$

where Y is the respirable mass concentration in mg m^{-3}, and X is the total mass concentration measured using the Chinese dust sampler. β represents the slope as well as the mean conversion fac-

Table 1. Geometric means of the conversion factors[a] in per cent categorized by job titles[a]

Mine/Industry	Job title	Cyclone ($N = 100$)	Impactor ($N = 121$)
Tungsten mine	Crusher	8.7, $n = 2$	162.3 (2.4), $n = 3$
	Driller	21.1 (2.9), $n = 15$	31.5 (2.7), $n = 20$
	Loader	24.4, $n = 2$	21.2 (2.2), $n = 3$
	Mining	11.8 (2.3), $n = 5$	16.6 (2.9), $n = 6$
	Transport	119.0, $n = 2$	42.8 (2.0), $n = 7$
	Unloader	54.4 (5.3), $n = 9$	89.9 (3.6), $n = 11$
	Working lane	20.0, $n = 1$	72.7, $n = 1$
	All	26.0 (3.6), $n = 36$	41.8(3.2), $n = 51$
Copper/iron mine	Driller	20.2 (2.5), $n = 6$	29.5(2.0), $n = 6$
	Excavator	N.D.[b]	16.7, $n = 1$
	Face worker	N.D.	3.4, $n = 1$
	Loader	19.0 (1.7), $n = 3$	35.2(1.5), $n = 3$
	Transport	74.3, $n = 2$	52.7 (3.0), $n = 4$
	Tunnel	49.9, $n = 2$	51.1, $n = 2$
	Unloader	15.5, $n = 1$	23.9, $n = 1$
	All	26.8(2.4), $n = 14$	31.4(2.5), $n = 18$
Tin mine	Driller	33.8, $n = 2$	65.7, $n = 2$
	Excavator	41.4, $n = 2$	84.6, $n = 2$
	Pumper	N.D.	N.D.
	Unloader	9.1, $n = 1$	12.8, $n = 1$
	All	28.2(1.9), $n = 5$	52.4(2.3), $n = 5$
Pottery industry	Crusher	31.5, $n = 1$	40.5, $n = 1$
	Dragger	82.5, $n = 1$	44.7, $n = 1$
	Driller	2.9, $n = 1$	5.9, $n = 1$
	Forming	45.0 (6.6), $n = 6$	76.1 (6.2), $n = 6$
	Furnace	10.1 (4.0), $n = 3$	38.9 (1.9), $n = 3$
	Glazer	52.7 (2.2), $n = 3$	5.7 (20.5), $n = 3$
	Loader	15.8, $n = 2$	20.4 (2.2), $n = 3$
	Milling	33.3, $n = 2$	33.0, $n = 2$
	Mixer	15.5 (3.7), $n = 4$	21.8 (3.9), $n = 5$
	Molder	5.7, $n = 1$	10.4, $n = 1$
	Ore loader	19.2, $n = 2$	113.3, $n = 2$
	Polisher	19.4 (2.0), $n = 6$	27.7 (2.6), $n = 6$
	Preparation worker	6.0 (3.1), $n = 4$	12.8 (2.9), $n = 4$
	Raw material worker	15.8 (3.0), $n = 6$	20.2 (3.8), $n = 6$
	Transport	15.7, $n = 2$	38.5, $n = 2$
	Tunnel	82.0, $n = 1$	79.8, $n = 1$
	All	19.3(3.5), $n = 45$	31.3(3.6), $n = 47$

[a] Conversion factor is the ratio of respirable dust concentration (based upon the ACGIH definition) to the 'total' Chinese dust concentration. Values are the geometric means of the conversion factors in per cent (%); values in parentheses are the geometric standard deviations; N is the total number of measurements using each of the sampling and analysis methods for the four mines or industry, and n is the replicate sampling number.

[b] No determination.

tor based on the least-squares method. The non-intercept regression model was selected because it is reasonable to assume that no respirable dust would be collected when the total dust concentration was zero.

A regression diagnostic technique using Studentized residuals was performed to investigate outliers (Stevens, 1984; Kleinbaum *et al.*, 1988). As a result, two outliers were detected at the 0.05 significance level and then discarded in each set of conversion factors. Slopes and correlation coefficients, before and after the outliers were discarded, are compared in Table 2. The results demonstrate how sensitive regression coefficients can be to just one or two outliers, as pointed out by Stevens (1984). Steps in evaluating the outliers using Studentized residuals are summarized in the Appendix. Figure 1(a) and (b) illustrates the regressions of respirable and total dust concentrations after the outliers were discarded. Table 3 presents the mean conversion factors estimated using the least-squares method, as well as the corresponding geometric means. It is apparent that the least-squares method yielded comparable results with the geometric means of the conversion factors, especially for the cyclone data.

To determine whether or not the mean conversion factors obtained between cyclone and impactor were different, a *t*-test was used to compare the two slopes. The results showed that the calculated T of 0.213 was much smaller than the critical value ($t_{207,0.975} = 1.97$) for a two-sided test. Thus, the two slopes (mean conversion factors) were not significantly different. Consequently, a weighted average of the two separate slope estimates was calculated by the following formula (Kleinbaum *et al.*, 1988):

$$\beta_{\text{pooled}} = \frac{(n_{\text{C}} - 1)S^2_{X\text{-C}}\beta_{\text{C}} + (n_{\text{I}} - 1)S^2_{X\text{-I}}\beta_{\text{I}}}{(n_{\text{C}} - 1)S^2_{X\text{-C}} + (n_{\text{I}} - 1)S^2_{X\text{-I}}} \qquad (2)$$

where the subscripts C and I stand for cyclone and impactor, respectively; n is the number of measurements, and S_X is the standard deviation of the independent value and β is the slope, respectively. This relationship yielded a pooled slope of 0.25 with a 95% confidence interval of 0.21–0.29.

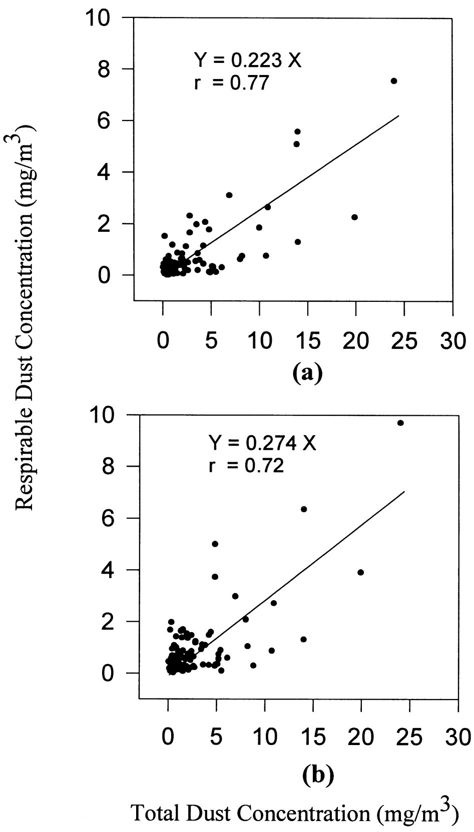

Fig. 1. Regression of the following respirable dust concentrations upon the total dust concentrations measured by the Chinese dust sampler: (a) respirable dust levels measured by a cyclone; (b) respirable dust levels measured by an impactor.

Table 2. Slopes and correlation coefficients before and after two outliers were discarded[a]

Method	n_{outlier}	Before discarding		After discarding		$\beta_{\text{a}}/\beta_{\text{b}}$
		r_{b}	β_{b}	r_{a}	β_{a}	
Cyclone	2	0.63	0.177	0.77	0.223	1.26
Impactor	2	0.53	0.247	0.72	0.274	1.11

[a] n_{outlier} is the number of the outlier points detected at the 0.05 significance level; r is the correlation coefficient, and β is the slope.

Table 3. Mean conversion factors

Method	Least-squares method		Geometric mean	
	Mean	95% Confidence interval	Mean	GSD
Cyclone	0.223	±0.040	0.229	3.2
Impactor	0.274	±0.037	0.363	3.3

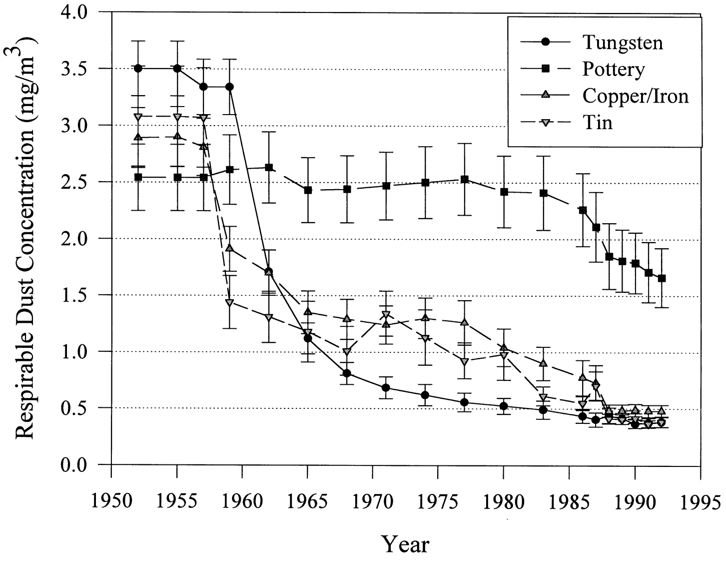

Fig. 2. Estimated respirable dust levels from the historical 'total dust' concentrations collected during 1952 and 1992. The error bars show the 95% confidence intervals.

Respirable dust levels based on the ACGIH definition for American dust exposure standards (ACGIH, 1999) were then estimated using the mean conversion factor for the historical 'total dust' concentrations collected during 1952 and 1992. Each data point shown in Fig. 2 represents the respirable dust level as a weighted average by the different plants and job titles in a given industry and year. The error bars show the 95% confidence intervals. Figure 2 indicates that respirable dust levels have been decreased historically, especially since 1958 when major control technologies (such as ventilation and dust suppression by wet methods) were applied in the three mining industries. Based upon these data it appears that the exposures of the Chinese workers have generally complied with the ACGIH guide for exposure to respirable particulates not otherwise classified (PNOC) since 1958 (ACGIH, 1999). Further exposure assessment for respirable free silica is being conducted (Zhuang *et al.*, 1999).

SUMMARY AND CONCLUSIONS

This study provides conversion factors between historical dust exposures and respirable dust concentrations in Chinese industries and mines. Since the conversion factors among the mines and industries were not significantly different, the factors were averaged to provide a single value of 0.25. Using this conversion factor, it appears that Chinese exposures have been in compliance with ACGIH recommendations for respirable PNOC standards since 1958.

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APPENDIX

Regression diagnostic statistics using Studentized residuals for detecting outliers

Steps for detecting outliers in regression analysis using Studentized residuals are summarized based on Kleinbaum *et al.* (1988) as follows:

1. Calculate predicted values ($\hat{Y}_i$) based on the independent variables (X_i) and the dependent values (Y_i) using the least-squares methods.
2. Determine unstandardized residuals $e_i = Y_i - \hat{Y}_i$.
3. Estimate population variance (S^2) from the sample of n unstandardized residuals:

$$S^2 = \frac{1}{n-k-1}\sum_{i=1}^{n} e_i^2 \qquad \text{(A1)}$$

where n is total sample size, and k is the number of independent variables ($k = 1$ for this study).

4. Determine the leverage value for the ith observation:

$$h_i = \frac{1}{n} + \frac{(X_i - \bar{X})^2}{(n-1)S_x^2} \qquad \text{(A2)}$$

where $\bar{X}$ in the numerator is the mean of the independent variables and S_x^2 is the variance of the independent variables.

5. Use e_i, S^2, and h_i to determine Studentized residuals (r_i):

$$r_i = \frac{e_i}{S\sqrt{1-h_i}} \qquad \text{(A3)}$$

6. Compare r_i with the critical values for Studentized residuals to determine outliers at an appropriate significance level.