Re-characterization of Some Factors Influencing Aerosol Sampling in the Workplace: Results from Field Studies

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Abstract: Re-characterization of Some Factors Influencing Aerosol Sampling in the Workplace: Results from Field Studies: Fengxia Hu, *et al*. Department of Occupational and Environmental Health, MOE Key Lab of Environment and Health, School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, China—Objective: Workplace aerosol sampling is challenged by its influencing factors and methodological limitations. Some factors, including blank setting, electrostatic effect, sample mass gain, and limit of detection (LOD), were studied to characterize them further and thereby to improve the sampling method. **Methods:** Through a field sampling in two shipyards and by an analysis of a large amount of dust data from different industries, the influencing factors were comparatively studied with emphasis on their effect on the final result. **Results:** After calibration with field blanks, the concentrations of most sample types in the shipyards decreased significantly, varying by as much as −24.3% of the final measurements. After laboratory blank calibration, dust concentrations increased or decreased without a definite change trend. With a variation of −1.8%, only the measurements of Chinese "total dust" sampled with polypropylene filters were significantly influenced by the electrostatic effect. The LOD coincidence rate was only 17.3% for American respirable dust in different industries and 12.2% for respirable particles collected by normal flow rate samplers (FSP2) in the shipyards. The latter increased to 73.9% when high flow samplers (FSP10) were used. **Conclusions:** It was suggested that field blank calibration was the predominant influencing factor in comparison with electrostatic effect and laboratory blank adjustment. The LOD coincidence rate was too low for reliable sampling, and this might be improved by use of high flow samplers.
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The terms dust and fumes are used in the present paper, although it has become popular to use the word aerosol to refer to solid and liquid particles. Dust sampling in the workplaces is perhaps a main occupational health task in both developing and industrialized countries. It is believed that dust exposure causes approximately 10,000 new pneumoconiosis cases per year in China nowadays. In Germany, 60% of samples from the raw material and chemistry industries are of inorganic dust. It is well known that new definitions of three health-related aerosol fractions (inhalable, thoracic and respirable) were conformably adopted by the European Committee for Standardization (CEN)[1], International Organization for Standardization (ISO)[2] and American Conference of Governmental Industrial Hygienists (ACGIH)[3] in the 1990s. The methods for size-selective dust sampling were correspondingly revised[4, 5]; for example, method 0600 of the National Institute for Occupational Safety and Health (NIOSH) was revised in 1998[5]. Technical requirements or influencing factors for dust measurement were revised in line with the new knowledge at that time. However, it seems that they will continue to require study with time and industry development.

In a recent study, the important factors influencing the accuracy of filter weighing were found to be air buoyancy variation and storage time[6], but in another study, the filter material itself was found to be important[7]. Furthermore, the emphasis of the studies was put on the weighing process and methods. More than a decade later, there might be some changes in the industry technology and dust production; for example, the respirable dust concentration in Chinese mines/factories has decreased significantly, from about 3 mg/m^3 in the 1950s to 0.5 mg/m^3 in the 1990s[8, 9]. Furthermore, the occupational limit value has been reduced step by step for the prevention of silicosis, e.g., to 0.025 mg/m^3 by the ACGIH[10] or 0.1 mg/m^3 by the UK[11] for respirable silica. As a result, it has become difficult to collect sufficient dust on filters and thereby fulfill the requirements with regard to the limit of detection (LOD) for the analysis of dust concentrations and silica content as well[12, 13]. Defined as the lowest concentration level that can be determined to be statistically different from a blank[14], the LOD is also an influence on aerosol sampling in the workplace.

China began dust sampling as early as in the 1950s with an open-face sampler to collect all airborne dust, referred to as "total dust", onto a filter at a high flow rate (15−30 *l*/min) over a short period of time (15−20 min) while production is in progress. In 2002, the Chinese Occupational Health Standard Committee decided to adopt the definition of respirable dust according to the Johannesburg convention and use the 8-h time-weighted average concentration in practice. In its sampling guide, however, some requirements like blank samples and the LOD are still absent[15].

Therefore, factors influencing dust measurement such as setting of blanks, flow rate calibration, electrostatic charge, sample mass gain and LOD were comparatively studied by field investigations with emphasis on their effect upon the final result.

Materials and Methods

Influencing factors were taken into consideration at the design phase and studied by a field investigation of aerosol sampling in two shipyards in 2012 and also by analysis of a large set of dust sampling data for different Chinese mines/factories collected from 2000 to 2009. With fume samples from the shipyards and mineral dust samples from different industries together, it will represent more appropriately the aerosol sampling at workplaces. Mass gain, LOD, and the coincidence rate were analyzed mainly by using of the large amount of data from early samples.

Sampling locations

Two shipyards (A and B) in Wuhan were chosen as sampling sites for welding fumes. Shipbuilding is one of the main industries for the city, which is located near the Yangtse River. Two shipyards with different production scales were selected for the purpose of being representative, as the welding tasks in shipyard B were generally heavier than those in shipyard A. Their welding workshop buildings were high and large, with many windows on two sides and without walls on the other two sides, and therefore they both had good natural ventilation. The workers performed gas metal arc welding with a normal welding shield, without local exhaust ventilation in the welding torch and in squatting body position in most cases. The workers faced the particle source while working and worked close to it. In accordance with the study purpose of influencing factors, side-by-side area sampling was employed in the study in the shipyards, although the authors are aware of the fact that the modern samplers that were used (FSP-BIA, 10-mm nylon cyclone) are intended to be used as personal samplers. This type of sampling was chosen also because the Chinese "total dust" sampler has been used for area sampling traditionally. In the respiratory zone, sampling took place outside of the shield but as close as possible to the workers at the welding site. The instruments were placed closely together in the workplaces for collecting the samples to be compared with each other, e.g., the two kind of German respirable dust samplers: FSP2 and FSP10.

Sampling and equipment

To collect Chinese "total dust", traditional samplers (FC-2, Wuhan Analytical Instrument Company, Wuhan, China) with an open-face 40-mm filter of polypropylene were used in the study. They were used to collect airborne dust directly onto the filter at a flow rate of 15−30 *l*/min for 20 or 30 minutes while production was in progress[16, 17]. Inhalable dust was collected with a German conical inhalable sampler (CIS) with a 37 mm filter of mixed cellulose esters (MCE). It was operated at a flow rate of 3.5 *l*/min for 3−4 h. Respirable dust was sampled with the two kind of cyclones, i.e., FSP2 at a normal flow rate and FSP10 at a high flow rate, with the same 37 mm filter of polyvinyl chloride (PVC) or glass fiber filters. The FSP2 samplers were operated at a flow rate of 2 *l*/min for 3−4 hours, while the FSP10 samplers were operated at a flow rate of 10 *l*/min for about 2 hours[18]. The sampling time of two hours was chosen in consideration of the fact that: two hours is the shortest time needed for filter dust sampling in the BG guidance[19] and in consideration of the fact that much more dust will be collected if sampling is performed for a longer period of time. The CIS and FSP2 were operated by a Gilian 5000 or GilAir-5 pump (Gilian, Sensidyne,

St. Petersburg, FL, USA), while the FSP10 samplers were operated by the same Chinese pump as the "total dust" samplers.

Flow rate of the pumps was calibrated by a Gilian airflow calibrator before use. Weighing was performed with an electronic balance (ME235S, Sartorius, Goettingen, Germany), with a resolution of 0.01 mg. The balance was equipped with a built-in N.I.C.E. (neutralization by ionic charge elimination) static eliminator. Weighing was performed with or without discharge of any electrostatic charge by turning on or off the device.

Filter preparation and weighing

Besides the filters for sampling, sufficient numbers of filters for field and laboratory blanks were prepared for the four kinds of filters. After bringing them back to the laboratory, sampling and field blank filter samples were stored for at least 2 hours before weighing, according to the sampling convention in China[20]. Filters were weighed before and after sampling to obtain the tare weight (filter), gross weight (dust-loaded filter) and net weight (mass gain or mass of the dust sample) under the conditions of with and without elimination of electrostatic charges. This served as the normal step to determine the sample mass gain (or concentration) and also as a procedure to observe the electrostatic effect.

Field and laboratory blanks

Field blank filters were brought to the workplace and left open to the ambient air for the whole sampling period, but without active sampling[14, 21, 22]. Laboratory blanks were reference filters for every collection substrate to control the environment humidity and temperature, and they never left the laboratory. In this test, 5 field blanks and 5 laboratory blanks were prepared for every set of dust samples. Ultimately, the concentration was calculated with calibration by either field blanks (formula 1)[5] or laboratory blanks (formula 2)[23] using one of the following equations:

$$c1 = \frac{(W_2 - W_1) - (B_2 - B_1)}{Q \cdot t} \cdot 10^3 \qquad (1)$$

$$c2 = \frac{W_2 - (W_1 \cdot B_2 / B_1)}{Q \cdot t} \cdot 10^3 \qquad (2)$$

where:
c1=concentration calibrated with field blank (mg/m³),
c2=concentration calibrated with laboratory blank (mg/m³),
W_1=tare weight of filter before sampling (mg),
W_2=post-sampling weight of sample-containing filter (mg),
B_1=mean tare weight of blank filters (mg),
B_2=mean post-sampling weight of blank filters (mg),
Q=flow rate of sampling (*l*/min),
t=sampling time (min).

LOD and its coincidence rate

To determine the mass gain, filters were weighed, taken to the sampling locations and treated just like field blanks and then weighed again. Fifteen of such filters for every type (polypropylene, MCE, PVC and glass fiber) were prepared in the present study. The LOD was three times the standard deviation of the mass gain[14].

The coincidence rate with the LOD was the proportion of the dust samples with mass gains larger than the LOD to that of all the samples of a certain type.

Dust measurements from previous sampling in Chinese industries

As a cooperative effort with our German partner IGF of BG RCI (IGF - Institut für Gefahrstoff-Forschung der Berufsgenossenschaft Rohstoffe und chemische Industrie), many Chinese mines and factories were sampled for comparative measurements of Chinese "total dust" (CT), Chinese respirable dust (CR), German total dust (GT), German respirable dust (GR), American total dust (AT) and American respirable dust (AR) during 2000−2009. The selection of sampling locations was based on the criteria described by Wu *et al.*[16]: to be representative of an industry such as drillers underground and crushers in surface workplaces of a mine, and include exposures at different levels, especially the relatively higher exposures of historical times. Parallel sampling with different methods was performed in the same workplace and at the same time. The field survey of sampling in each industry lasted for several days. A total of 1,890 aerosols samples were collected (960 CT, 77 CR, 198 GT, 198 GR, 188 AT and 269 AR). The relationships between dust concentration measurements by different sampling methods and especially the conversion coefficients were studied by Yang *et al.*[9]. Using the data from that study, the calibration effect of field blanks on the dust concentration in an iron mine, mass gain of different samples and their LOD coincidence rates were analyzed in the present study.

Statistical analysis

Based on the same samples, the original and calibrated measurements were calculated and compared using the paired *t*-test or Wilcoxon signed-rank test. Both tests can be performed by using the same statistical analysis software (SAS 9.2, SAS Institute, Cary, NC, USA). When the differences showed a normal distribution, the paired *t*-test was used; otherwise, the

Wilcoxon signed-rank test was applied. In addition, it was desired in the present study to understand the variation in measurements before and after adjustment with different influencing factors. For that purpose, the following formula was used: percent of variation=(a−b)/b*100. In the formula, "b" refers to the original measurement, and "a" refers to the calibrated measurement. All the data were analyzed by use of the SAS software.

Results

Electrostatic effect

As shown in Table 1, only the results of Chinese "total dust" sampling were significantly influenced by electrostatic effects, with a significant decrease in concentration after discharge. Although there may be an increase or decrease in each of the collected samples as a result of discharge, no significant decrease or increase trend was observed among any of the other collected dust samples. In addition, the differential mass gain between samples with and without discharge ranged from 2.1 to 38.8 μg, accounting for a variation of 1.0% to −2.1% of the final measurement in all samples.

Calibration with blanks

Dust concentrations of all the samples changed significantly after adjustment with field blanks (Table 2), with only the exception of the FSP10 cyclone sample in shipyard A. They decreased in most cases with a variation range of 9.3% to −24.3%. After recalculation with laboratory blanks, the dust concentrations in most samples also changed significantly with a variation of 8.8% to −23.1%, but the direction of change, i.e., increase or decrease, showed no definite trend of change.

As shown by the samples from the iron mine (results not presented in detail), the concentrations of all the samples changed significantly after calibration with field blanks (Wilcoxon signed-rank test, $p<0.05$), with a variation from −3.5% to 8.3%. In addition, the Chinese "total dust" and German inhalable and respirable dust concentrations were reduced, while the concentrations of US inhalable and respirable dust were increased after calibration. Among the significant changes as a result of calibration with field blanks, the concentrations were reduced in most cases. Compared with the electrostatic effects on the welding particle samples (from 1.0% to −2.1%), calibration with field blanks changed the final concentration by a greater magnitude (9.3% to −24.3%).

LOD

The LODs in the survey were determined to be 0.36, 0.75, 0.51 and 0.78 mg for the glass fiber, PVC, MCE and polypropylene filters, respectively. The LOD of the polypropylene filter for Chinese "total dust" sampling was the largest.

Coincidence with LOD

As shown in Figure 1, the coincidence rate (mass gain greater than LOD) was relatively low, with the lowest rate, only 12.2%, in the German respirable samples obtained with the FSP2 samplers.

Discussion

The concentrations of most samples in the shipyard and iron mine changed significantly after calibration with field blanks in the present results. Therefore, this indicates that it is necessary to set field blanks for accurate mass concentration measurement in the workplace. Furthermore, the aerosol concentrations in our study decreased significantly after adjustment with field blanks in most cases, which implied that contamination is universal. This additional part of particles was estimated to be in the range of 9.3% to

Table 1. Electrostatic effect on the concentrations of different dust samples

| Sample (Sampling media)	n	Concentration (mg/m³)		Variation (%, IQR)
		Without discharge	Discharged	
Chinese "total dust" (Polypropylene filter)	105	2.50 ± 1.23	2.44 ± 1.23*	−1.8 (−6.2, 2.9)
German inhalable dust (MCE)	65	1.89 ± 0.96	1.92 ± 0.93	1.0 (−5.7, 5.1)
FSP10 sampler (PVC)	23	1.09 ± 0.51	1.07 ± 0.52	0.0 (−4.9, 2.7)
FSP2 sampler (PVC)	57	1.04 ± 0.63	1.04 ± 0.71	−2.1 (−15.6, 8.5)

Variation (%) was calculated with the formula variation percent=(a−b)/b*100, and the median was used as the average. IQR means interquartile range. The paired *t*-test (the first group) or Wilcoxon signed-rank test (three remaining groups) was used to compare the results by the different weighing methods of with and without discharge. *$p<0.05$.

Table 2. Comparison of the original concentration to the concentration calibrated using blanks (mg/m³, AM ± SD) in different shipyard dust samples

Shipyard	Sample	n	Concentration	Concentration-f	Variation-f (%, IQR)	Concentration-l	Variation-l (%, IQR)
A	Chinese "total dust"	48	1.99 ± 0.80	1.76 ± 0.76*	−8.7 (−21.4, −0.4)	1.81 ± 0.76*	−5.1 (−17.9, 1.9)
	German inhalable dust	22	1.09 ± 0.35	0.98 ± 0.34*	−8.9 (−13.8, −7.6)	1.11 ± 0.35*	1.8 (1.6, 2.8)
	FSP10 cyclone	11	0.81 ± 0.34	0.82 ± 0.31	9.3 (−6.4, 16.5)	0.81 ± 0.33	2.2 (−0.9, 4.3)
	FSP2 cyclone	29	0.61 ± 0.24	0.62 ± 0.33*	−24.3 (−29.0, 30.3)	0.62 ± 0.25*	−3.4 (−4.4, 7.3)
B	Chinese "total dust"	57	2.81 ± 1.39	2.68 ± 1.39*	−4.8 (−7.8, −4.1)	2.80 ± 1.39	−4.5 (−7.1, 8.2)
	German inhalable dust	43	2.35 ± 0.84	2.20 ± 0.80*	−5.3 (−17.8, 8.4)	2.41 ± 0.98	8.8 (−14.5, 10.5)
	FSP10 cyclone	18	1.13 ± 0.54	1.05 ± 0.49*	−8.6 (−13.4, 4.9)	1.04 ± 0.51*	−7.3 (−10.9, −5.4)
	FSP2 cyclone	42	1.31 ± 0.68	1.08 ± 0.52*	−22.5 (−30.5, 19.5)	1.01 ± 0.59*	−23.1 (−30.7, −13.9)

Concentration means the original one without adjustment by blanks, and concentration-f and concentration-l refer to the concentrations calibrated by field and laboratory blanks, respectively. IQR means interquartile range. Variation-f (%) was calculated with the formula variation-f percent=(a−b)/b*100, and the median was used as the average. Variation-l (%) was estimated in the same way. Comparisons were made between the original and adjusted concentrations by the Wilcoxon signed-rank test. *$p<0.05$.

−24.3% of the final measurements of welding fumes in the shipyard and −3.5% to 8.3% of the mineral dust concentrations in the iron mine. Field blanks are unused loaded samplers or loaded cassettes taken to workplaces and handled as far as possible in the same manner as those actually used for sampling with in respect to transport to and from the sampling site, except that no air is drawn through them[4, 14, 21]. The usage of field blank is defined clearly in principle but not so in detail. For example, different lengths of time have been suggested for how long field blanks should be left open to the air in workplaces, such as for about 30 seconds[24], just prior to sampling[25], for a predetermined amount of time[26] and for the same times as samples[7, 27]. The latter is more reasonable because they are used as a control to record the contamination introduced during sampling, handling and analysis[28]. This should be clarified in the new version of the NIOSH Manual of Analytical Methods[29]. As field blank filters are left open to the air, some people worry that some aerosol from the transiting air can deposit onto the filter to cause contamination. Fortunately, an environmental investigation found this fraction to be small, ranging from <0.0003% to 2% of the net sample, as estimated from particles with diameters ranging from 0.1 to 10 μm and settling velocities ranging from <0.0001 to 0.5 cm/s[30]. The deposition might be larger for aero-
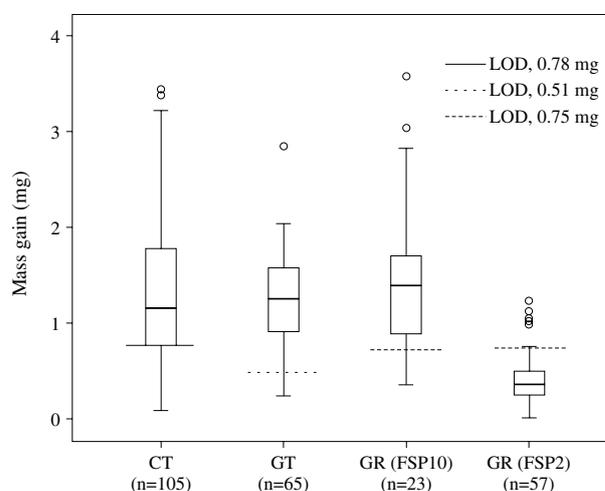
Fig. 1. Coincidence rate of mass gain with LOD by different samples in the shipyard survey

CT, Chinese "total dust" samples; GT, German inhalable dust; GR (FSP10) and GR (FSP2), German respirable dust by FSP10 and FSP2 cyclone samplers respectively. The LOD coincidence rate was the proportion of the dust samples, whose mass gains were larger than the LOD, to all the samples of a certain type. The rates for the CT, GT, GR (FSP10) and GR (FSP2) samples were found to be 77.1, 96.9, 73.9 and 12.2%, respectively.

sols with larger diameters and those generated locally by high winds. In rare cases, the concentrations of samples in the shipyards and iron mine became significantly higher after calibration with field blanks, which means that the blank filters became lighter after travelling from the sampling sites. This might suggest that bias from sources other than contamination and deposition could exist.

After calibration with laboratory blanks, the concentration changed in most cases. Thus, it seems also necessary to set up laboratory blanks to control the environmental conditions. Moisture sorption is the most common factor affecting the stability of filter weighing. Use of laboratory blanks is one of the ways of controlling environment factors but also doubles the error caused by balance random variation and filter handling contamination[6]. So it is optimal to provide an artificial microclimate either in weighing rooms as required by the NIOSH[5] or in a special weighing chamber[31]. It is worth noting that the latter is easier to realize. The present study was performed in May at an ambient temperature of 20–26°C and relative humidity of 40–60% (as recorded daily). Under such conditions, the concentration change after calibration showed no definite relation to the local humidity. In addition, the environmental conditions in the laboratory were actually controlled already by field blanks according to their method of setting (as described above).

After elimination of electrostatic charge, only the results for Chinese "total dust" sampling with polypropylene filters were influenced, showing a significant decrease in the final concentration (Table 1). Other samples of the present study showed a decrease in dust concentration sampling with PVC filters and an increase with MCE membranes, although their differences were not significant statistically. A similar change tendency, i.e., a decrease with PVC filters and increase with MCE filters, was also found by Tsai *et al.*[7]. The charge on filters produced an electrostatic interaction between the filter and the metal casing of the can, resulting in erroneous gravimetric measurements. However, whether this leads to a decrease or an increase in the final result is not clear, at least to our knowledge. In a previous study, the electrostatic charge could not be entirely eliminated by just passing over a ^{210}Po source, with a residual influence observed for two to three weeks[32]. Fortunately, the electrostatic effect was not as larger as expected. The mass difference caused by the filter static charge varied between −200 and +1,000 μg, however, it merely added a random variance of 20–40 μg to the final measurement[6]. Our study showed a differential mass gain of 2.1 to 38.8 μg, a variation from 1.0% to −2.1% of the final result. In contrast, calibration with field blanks

changed the final concentration by a greater magnitude (9.3% to −24.3%), and therefore might serve as a control measure more predominant than static charge elimination.

When the static charge effect was observed with the filter weight as the indicator instead of the mass gain, charge elimination resulted in a significant decrease in filter weight in all the samples, with a small variation range of −0.04 to −0.31% (details not presented here, but as supplementary material available from the journal). This highlights the weighing method but not the influence on the final sampling results. In addition, the variation increases stepwise when comparing the weight in the sequence of filter, dust-loaded filter, and dust mass gain (compare the supplementary table S1 and table S2 with Table 1). This indicates that the bias source becomes complicated during such a process. On the other hand, it makes the picture of static charge effect more clearly from different sides.

The LOD for the shipyards in the present study varied for different types of filters, ranging from 0.36 to 0.78 mg. It is desirable for the LOD to be no more than 0.5 mg. The magnitude of a LOD is determined mainly by the weighing precision of blank samples. The stability of blank samples might be affected by several factors, most commonly moisture sorption but also electrostatic effects and contamination from handling. All these factors need to be controlled to lower LOD values, and low hygroscopic filters in particular might be used as an improvement measure. Another way would be the use a proper amount of blanks[33].

It is becoming more difficult to collect a sufficient amount of dust on filters. From the large amount of data from different samples in Chinese mines and factories, the mean mass gain for most samples was in the range of micrograms, with only one exception, inhalable dust collected by German samplers, which showed a mean mass gain in the range of milligrams (Table 3). A small mass gain reduces the LOD coincidence rate. As shown in the present study, the LOD coincidence rate for samples of respirable particles was only 12.2% in the shipyards (Fig. 1). At welding workplaces in German industries, the rates were found to be 63% for all respirable particle samples and 28.8% for such samples during tungsten inert gas welding and no measurement higher than the LOD was obtained when welding was performed with personal ventilators[12]. The welding fume concentrations in the present study (inhalable particles 1.92 ± 0.933 mg/m³ and respirable fraction 1.04 ± 0.707 mg/m³) were found to be similar to or even a little lower than those determined in German industries (2.48 and 1.29 mg/m³ for inhalable and respirable particles respectively), although it is generally believed that the

Table 3. The mass gains and coincidence rates of different samples

Sample	n	Mass gain (mg)	Rate$_1$ (%)	Rate$_2$ (%)
AR	269	0.24 ± 2.35	17.3	0.4
AT	288	0.79 ± 2.66	69.9	20.5
CR	77	0.27 ± 2.81	33.3	0.0
CT	967	0.69 ± 2.87	62.1	17.5
GR	198	0.39 ± 2.55	36.3	4.0
GT	198	1.47 ± 2.62	91.4	36.9

Data from the sampling survey of Chinese industries during 2000–2009. An LOD of 0.50 mg was used, and the LOQ was 1.67 mg. Rate1 is the percentage of the samples with a mass gain>the LOD relative to all the samples of a certain type. Rate2 is the percentage of the samples with a mass gain>the LOQ relative to all the samples of a certain type.

exposure level in the workplaces in China is high[15]. When looking at the large amount of data from different Chinese industries (Table 3), the LOD coincidence rates were low, generally about thirty percent for German and Chinese respirable dust samples and even 17.3% for American respirable samples. Regarding the limit of quantitation (LOQ), the coincidence rates were much lower, only 4.0% and 0.4% for German and American respirable dust samples respectively. It is well known that the LOQ is ten times the estimated standard deviation of the mass of an aerosol sample and can be used as a threshold value to assure accurate measurement of a substance[14].

Certainly a low coincidence rate will influence the measurement reliability of either the dust concentration or quartz analysis. This might be improved through various means, such as by using a lower LOD, longer sampling time and higher flow rate for samplers. The sampling of respirable dust (GR and AR) in different industries in the present study was performed for 265 and 251 minutes (on average, respectively), and it would be difficult in practice to prolong it further. Samplers with a high flow rate might be used as a solution to this problem. With this increased collection of particles by high flow rate samplers, it was found that the LOD coincidence rate could be increased from 12.2% (FSP2) to 73.9% (FSP10, Fig. 1). However, it should be noted that the FSP10 and FSP2 samplers were operated for different amounts of time. In addition, the present study only reports the results from a sampling survey of two shipyards, and it should be extended to other industries in the future. By putting samplers in a calm air chamber, a laboratory study showed that high flow rate samplers FSP10, CIP10-R and GK2.69, collected 7.99, 6.42 and 2.78 times more coal dust than a normal 10-mm nylon cyclone, respectively,

although the increase was not proportional to their increased sampling flow rate exactly. It also indicated that the increased mass of quartz (from the sample by high flow samplers) would provide precise analytical results, i.e., significantly above the LOD by Fourier transform infrared (FTIR) and X-ray diffraction (XRD) analyses[34, 35]. However the FSP10 high flow rate sampler, with a 50% cutoff size (50 d$_{ae}$) of 4.8 μm, was found to overestimate the exposure to respirable fraction by up to 40% compared with the ISO/CEN/ACGIH respirable convention[34]. This needs to be studied further, especially with respect to its sampling efficiency.

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