

BRIEF REPORT

Developing a guideline for measuring the total number concentration of engineering nanomaterials in workplaces in China

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Abstract

Objectives: To provide a guideline for assessing the occupational exposure to nanomaterials in workplaces in China.

Methods: Based on the basic requirement for the sampling of harmful substances, condensation particle counter/optical particle counter (CPC/OPC) was selected as the tool and the total number concentration (TNC) was used as an index to measure engineering nanomaterials in workplaces.

Results: The strategy included instrument preparation, identification of particle-emission source, particle-property analysis, measurement of background concentration, concentration measurement based on working activity, concentration calculation and analysis, and recording of measurements.

Conclusions: The draft guideline based on traditional industrial hygiene practices can be used to identify the emission source of nanomaterials, qualitatively and quantitatively assess exposure to nanomaterials in workplaces.

KEYWORDS

guideline, measurement, nanomaterials, number concentration, workplaces

1 | INTRODUCTION

Nanotechnology has been developed rapidly worldwide, but the potential health effects associated with engineering nanomaterials remain unclear. Many engineering materials have already been shown to be toxic owing to their unique physicochemical characteristics (small size, large surface, active surface, etc).¹ Potential health problems include negative effects on the respiratory system, cardiovascular system, reproductive functions, alimentary system, and neural system,^{2,3} although these toxic effects still need to be verified

by epidemiological studies. So far, epidemiological studies on exposed workers have not identified specific effects of engineering nanomaterials linking them with a specific exposure.^{4,5} The engineering nanomaterials can be generated and released into the air during various production processes and downstream-use stages, and they can readily enter the body through inhalation.⁶

Engineering nanomaterials have already emerged as new occupational hazards in many developing countries including China. However, there is a lack of comprehensive guidelines for the measurement and evaluation of

engineering nanomaterials in workplaces in China. As a result, there are few concerted efforts to collect exposure data of engineering nanomaterials. It is therefore critical to develop guidelines for measuring engineering nanomaterials in the workplace to establish a scientific basis for the assessment of health risks involved and to perform further epidemiological investigations. The International Organization for Standardization (ISO) stipulates the measurement of the number concentration using a condensation particle counter (CPC).⁷ In addition, international organizations like the Organization for Economic Co-operation and Development (OECD) and the National Institute for Occupational Safety and Health (NIOSH) in the US have guidelines for the measurement of engineering nanomaterials to assess the emission level in the workplaces.^{8,9}

Here, we propose a new guideline for China based on existing recommendations of CPC/optical particle counter (OPC) utilization and the basic requirement for the sampling of harmful substances in accordance with the occupational health standard GB/Z 159 (<http://www.nhfpc.gov.cn/xxgk/pages/wsbzsearch.jsp>). This new guideline will stipulate a measurement method and technical benchmarks for the measurement of the total number concentration (TNC) of engineering nanomaterials in the workplace. The guideline can be used for identification of key locations of engineering nanomaterials, emission evaluation, effectiveness evaluation of control measures, and evaluation of equipment leakage.

2 | MATERIALS AND METHODS

2.1 | Terms and definitions of nanomaterials

Relevant terms and their definitions in this method are shown in Table 1.

2.2 | Selection of measurement indices

A progress has been made in the measuring techniques of engineering nanomaterials in recent years, especially the nanoparticle concentration measurement technique (real-time monitoring and cascade impact sampling) and the physicochemical characteristic identification technique. Figure 1 shows the overall scheme of the nanoparticle measuring technique.⁶ In the categories of indices,—particle number, mass, surface area, number distribution, and mass distribution—the use of the particle number concentration as the index offers some advantages, such as mature measuring technique, portable measuring instrument, and reflecting the exposure scenario associated with worker activities,^{12,13} which are expected to promote adoption and application. Recently, there have been new developments in particle concentration measurement techniques based on the concept of diffusion size classification. These novel devices measure charged particles

TABLE 1 Relevant terms and their definitions

Terms	Definition
Ultrafine particles/ nanoparticles	Particles with nominal diameters (eg, geometric, aerodynamic, mobility-related, and projected-area diameters) of less than 100 nm. ¹⁰
Fine particles	The diameter is smaller than 2500 nm but larger than 100 nm. ¹⁰
Agglomerate	Collection of weakly bound particles or aggregates or a mixture of the two, where the resulting external surface area is similar to the sum of the surface areas of the individual components. ¹⁰
Aggregate	Particle comprising strongly bonded or fused particles, where the resulting external surface area may be significantly smaller than the sum of the calculated areas of the individual components. ¹¹
Nanomaterial	Material with any external dimension on the nanoscale or an internal structure or surface structure on the nanoscale. Compared with large-sized materials of the same chemical composition, the nanomaterials show special physicochemical properties. ¹¹
Condensation particle counter (CPC)	An instrument that can measure the total number concentration (TNC) of nanoparticles or ultrafine particles. Saturated steam condenses on the surface of ultrafine particles until the diameter of the particles reach the size that is suitable for optical detection. ¹⁰
Particle number concentration	Number of particles per unit volume of air, P/cm^3 . The TNC refers to the sum of ultrafine or fine particles. ¹⁰
Concentration ratio	The ratio of the particle concentration at the sampling location and that related to the background, which reflects the level of nanoparticles or ultrafine particles released from the particle-generation source. ¹²
Detection efficiency	The ratio of CPC-measured value and the real value; used as the CPC calibration factor. ¹⁰

by measuring the current induced from deposition on a filter grid or from passage through a Faraday cage.

This guideline encourages the application of other measurement indices, such as real-time mass concentration, surface area concentration, and particle size distribution by number or by mass, to simultaneously measure the exposure to nanomaterials, which can yield comparable results to evaluate the precision or accuracy of the method.¹⁴

2.3 | Requirement of measuring instrument

Since the size of the airborne engineering nanomaterials and degree of agglomeration may not be known at the time of the

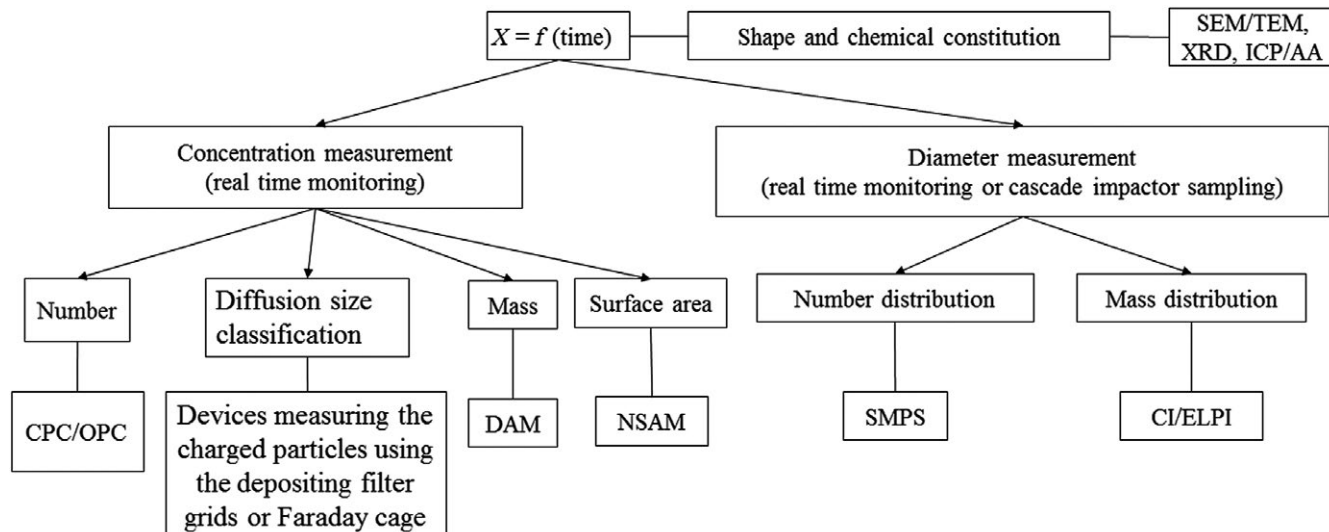


FIGURE 1 Outline of engineering nanomaterials measuring technique. (CPC, condensation particle counter; OPC, optical particle counter; DAM, dust/aerosol monitor; NSAM, nanoparticle surface area monitor; SMPS, scanning mobility particle spectrometer; CI, cascade impactor sampler; ELPI, electrical low pressure impactor; SEM, scanning electron microscope; TEM, transmission electron microscope; XRD, X-ray diffraction; ICP, inductively coupled plasma; AA, atomic absorption spectrophotometer)

sample collection, the direct-reading, particle sizing/counting instruments may provide a qualitative indication of the potential emissions. At present, a large number of literature were reported the use of CPC/OPC in measuring engineering nanoparticles in the workplaces. And there are many types of CPC/OPC instrument can be acquired in the market at a price less than 50,000 Chinese RMB (approximately 800 000 Japanese ¥ or 7000 US Dollar). The CPC and OPC can be used simultaneously to obtain a size differential evaluation. Most CPCs provide a measure of the TNC (particles per cubic centimeter, P/cm^3) within a size range of 5 ~ 1000 nm, while OPCs provide a TNC within a size range of 300 ~ 10 000 nm.

3 | RESULTS

3.1 | Measuring procedure

The measuring procedure includes instrument preparation, identification of particle-emission source, particle-property analysis, measurement of background concentration, concentration measurement based on working activity, concentration calculation and analysis, and recording of measurements.

3.1.1 | Instrument preparation before use

Clean the filtering device at the aerosol inlet to prevent contamination by large particle, or fibers. Before use, correct the aerosol flow at the inlet with a flow meter to ensure that the error rate is within 5%. Conduct zero setting with a built-in zero-setting filter film in a clean environment rather than the workplace. Replace the condensate wick; it should be replaced for every 4 hours during continuous measurement.

Set the measuring mode. Set the continuous measuring time and data-recording interval with the recording mode. The data display mode (direct-reading) can be used during concentration screening to help recognize the particle-generation source and mixed-particle-emission source.

3.1.2 | Identification of particle-emission source

The source of particle emission can be identified in three ways, including the information acquisition, field investigation, and concentration screening: (1) Information acquisition: the goal was to learn about the technological process, raw materials, auxiliary materials, products, by-products, and intermediate products. If the measured particles are nanomaterials, the corresponding safety data sheet should also be obtained to learn about its physicochemical properties, particle size, shape, solubility, surface activity, etc. (2) Field investigation: the production area and process, including the technical process, the usage amount and output of raw materials, engineering control, maintenance of engineering control measure, by-products, and intermediate products, should be investigated. In addition, the operating frequency and time of each procedure, production equipment that process and store nanomaterials, number of workers, engineering control, general ventilation, and local ventilation should be investigated. Attention should be paid to the following key links, such as the production and processing of nanomaterials, use of solid particles, abrasive machining of substances containing nanomaterials, packaging and sampling test, cleaning, maintenance, and repair of production equipment. (3) Concentration screening: a direct-reading CPC and an OPC should be used

to measure the TNC of particles generated instantaneously at the potential particle source. A particle generation source is likely located at a certain position if the TNC of particles at that position is evidently higher than that of background particles after eliminating the effect of mixed-particle-emission sources.

3.1.3 | Analysis of particle properties

The following methods can be applied in combination to determine the property of particles measured: (1) Field investigation: The type and physicochemical properties of particles are obtained through information acquisition and field investigation. (2) Scanning electron microscopy (SEM): One of the sampling filters, such as a quartz-fiber filter, mixed-cellulose acetate nitrate filter, polypropylene fiber filter, and other dust-measuring filter, can be selected for collecting particles with a respirable dust sampler or an aerosol impact sampler. The particle samples are sent to the laboratory for qualitative analysis with the SEM. The analysis indices include the chemical composition and morphology.

3.1.4 | Measurement of background particles

(a) Sampling location: Based on the descriptions of workplace exposure to nanomaterials from NIOSH, OECD, and German institutions, background particles can be divided into two categories: control particles, namely the background particles inside the workplace; atmospheric background particles outside the workplace.^{7,9,15}

The background particles inside a workplace serve as the preferred background particles.¹⁴ The measuring location of background particles can be far away from the operating area, with less activity of workers. It is necessary to measure various kinds of background concentrations in order to exclude the effects of mixed-particle-emission sources in the area. If these effects cannot be excluded, or if the work activity is not interrupted within 24 hours, the atmospheric background particles outside the workplace should be selected instead as the control particles.

The atmospheric background particles outside the workplace serve as the alternative background particles. If mechanical ventilation is adopted in the workplace, the measuring location can be selected as the position measuring 1 m from the air intake; if natural ventilation is adopted in the workplace, the measuring location can be selected as the position measuring 1 m outside the upwind window of the workplace.

(b) Measuring duration: The background particles inside or outside the workplace should be measured continuously for more than 0.5 hours on the same day, with at least 30 automatically recorded data points. The measurement of

background particles inside the workplace should be carried out before work commences.

(c) Consideration on the variance of background particle:

1. Before the start of the measurements, a reference number concentration of the engineered nanomaterials to be measured should be defined based on toxicological studies. This reference concentration should be at or below the lowest derived adverse effect concentration.
2. In case of natural (non-filtered) ventilation and/or the presence of other sources indoors, information needs to be gathered about the temporal pattern of these sources.
3. The background levels need to be determined during the phases where low concentrations are expected. This includes determining the temporal pattern and the extent of fluctuations in number concentrations. If the background level is above the required reference concentration as defined in step (1), alternative methods (eg, SEM) that allow characterizing the nature of the particles need to be considered. In such a situation, the measurement report should state that elevated concentrations of background particles interfere with the measurement of the particles of interest.
4. If there are no important sources of background particles or background particle concentrations are sufficiently low, the measurements can proceed. It will be important to document the pattern of background sources if they were found to be relevant.

3.1.5 | Area sampling based on working activity

(a) Selection principle of sampling location: The setting of the sampling point and the selection of sampled objects (workers) are executed according to GB/Z 159. A portable CPC and an OPC are used for fixed-point sampling, and the sampler is fixed in the place where engineering nanoparticles escape and workers have the longest exposure time. The sampling head should be placed at the height of the breathing zone of the worker. One sampling point is set up at each working place when the workers are working at multiple engineering nanomaterials emission points. Individual samples are collected by individual CPCs, and the sampling head is carried on the chest of the worker so that the air inlet is in the respiratory zone.

(b) Measuring duration: The measurement should be implemented based on the changes in working hours and job activity. Long-term measurement should be adopted (not less than 1 hour), covering at least one complete job activity, with more than 60 automatically recorded data points. If the job activity takes less than 15 minutes, short-term measurements can be adopted (not less than 15 minutes), including more than 15 automatically recorded data points.

The effect of mixed-particle-emission sources or non-related activities must be excluded in the measurement based on activities. When the production status in the workplace is unstable or the TNC of particles fluctuates, the measurement activity should continue for 3 days. It is advisable to continuously perform the measurements in different seasons to better understand the TNC variations of nanoparticles or ultrafine particles in the workplace.

3.1.6 | Calculation and analysis of TNC

If the TNC of nanoparticles meets the normal distribution or is steady, the arithmetic mean of TNC can be calculated. If the concentration is a skewed distribution or fluctuates greatly, the median or geometrical mean can be calculated. The TNC of nanoparticles can be analyzed from the following points of view: (1) If there are no corresponding occupational exposure limits for nanoparticles, their concentration ratio (CR) values can be calculated. If $CR > 1$, it indicates the release of particles; (2) Conduct a statistical analysis between the sampling location and the background; if there is statistical difference; it means particles were released; (3) Make a figure based on the variation in the time–number concentration, analyze the temporal–spatial distribution of particle TNC, and observe the relation between working activity and TNC dynamically; (4) Compare the exposure levels among different workplaces or different types of work.

3.1.7 | Measuring record

The quality-control record should be tabulated before CPC measurements. These records cover whether or not the filtering device at the aerosol inlet has been cleaned, whether the aerosol flow at the inlet has been corrected, whether zero setting has been conducted, and whether the old condensate wick has been replaced. At the same time, the meteorological conditions (temperature, barometric pressure, and relative humidity), the relative location of source, measurement point and exhaust, type of particles under test, equipment type and parameter setting, process operation, number and roles of workers associated with process, work patterns of workers (shift duration, work tasks and duration, work location), current particle emission and exposure controls used (engineering control measures and personal protective equipment), ventilation assessment (flow rates, air velocities and pressure),¹⁵ measurement date, starting time and location of measurements, time–activity of the particles under test and unidentified particles, and the TNC of particles should be recorded.

4 | CONCLUSIONS

This report provides a draft guideline for assessing exposure to nanomaterials in China. This standard can be used

to identify the emission source of nanomaterials, qualitatively and quantitatively assess exposure to nanomaterials. Furthermore, this standard can be applied for enterprises involved in the manufacture, handling, and disposal of nanomaterials to manage and mitigate workplace exposure to airborne nanomaterials. The proposed standard is based on traditional industrial hygiene practices, plus some new nanoparticle monitoring practices that have been developed in the aerosol science field. Thus, industrial hygienists will be able to apply their experience in particle monitoring technology with mass-based concentrations when using the proposed standard for qualitative exposure assessment in identifying emission sources, characterizing nanomaterials exposure, and mitigating nanomaterials exposure.

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DISCLOSURE

Approval of the research protocol: N/A. *Informed consent:* N/A. *Registry and the registration no. of the study/trial:* N/A. *Animal studies:* N/A. *Conflict of interest:* no.

AUTHOR CONTRIBUTIONS

Xiangjing Gao designed the research, analysed the data, and wrote the manuscript; Hua Zou and Lifang Zhou collected the data; Xiaohui Xu, Shichuan Tang, and Weiming Yuan analysed the data; Meibian Zhang designed the research and revised the manuscript.

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