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RETRACTED: Health risks and respiratory intake of submicron particles in the working environment: A case study

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Background: Powder-coating processes have been extensively used in various industries. The submicron particles generated during the powder-coating process in the workplace have complex compositions and can cause serious diseases. The purpose of this study was to better understand the health risks and respiratory intake of submicron particles during the powder coating process.

Methods: The concentrations of and variations in submicron particles were measured using real-time instruments. The health risks of submicron particles were analyzed using the Stoffenmanager Nano model. A new computational fluid dynamics model was used to assess the respiratory intake of ultrafine particles (UFPs), which was indicated by the deposited dosage of UFPs in the olfactory area, nasal cavity, and lungs. The deposited doses of UFPs were used to calculate the average daily doses (ADDs) of workers, according to the method described by the Environmental Protection Agency.

Results: The number concentration (NC), mass concentration, surface area concentration, personal NC, and lung-deposited surface area concentration of submicron particles were >10^5 pt/cm^3, 0.2–0.4 mg/m^3, 600–1,200 μm^2/cm^3, 0.7–1.4 pt/cm^3, and 100–700 μm^2/cm^3, respectively. The size distribution showed that the submicron particles mainly gathered between 30 and 200 nm. The health risk of submicron particles was high. Upon respiratory intake, most UFPs (111.5 mg) were inhaled into the lungs, a few UFPs (0.272 mg) were trapped in the nasal cavity, and a small minority of UFPs (0.292 mg) were deposited in the olfactory area. The ADD of male workers with 10 years of exposure in the olfactory area, nasal cavity, and lung were 1.192 × 10^{-3} mg/kg·d^{-1}, 1.11 × 10^{-3} mg/kg·d^{-1}, and 0.455 mg/kg·d^{-1}, respectively.

Conclusion: Owing to the high concentrations of submicron particles, the workers involved in the powder-coating process are at a high health risk. Moreover, the respiratory intake of UFPs by workers is high, which is

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suggested by the highly deposited dosage of UFPs in the lungs and the corresponding high ADD in workers. Control measures, including engineering control, management control, and personal protective equipment, must be improved for the protection of workers.

KEYWORDS

working environment, health risk, respiratory intake, submicron particles, average daily dose

1 Introduction

Powder-coating is a surface treatment process that enables different types of materials to be deposited on various substrates, such as metals, metal alloys, ceramics, and plastics (Society A T S, 2021). The powder-coating process not only has a higher deposition rate and can deposit coatings on refractory materials more easily than other spray-coating processes, but it can also maintain a low surface temperature. (Fauchais et al., 2014). Owing to these benefits, powder coatings are widely used in various industries as an effective technology to produce high-performance surfaces (Stöver and Funke, 1999; Rosso et al., 2001).

As the powder-coating process has been extensively used in various industries, the health risks of powder-coating workplaces have raised concerns. Coating powders, which are typically produced using resins, curing agents, pigments, and additives, present serious health hazards. Several studies have been conducted on the health effects of coating powders. It has been reported that the resin and curing agents could cause occupational contact dermatitis, occupational asthma (Pietranek, 2007; Suojalehto et al., 2019), and serious lung diseases (Pesonen et al., 2016). On the other hand, additives in coating powders, which are nanometers in size, include carbon nanotubes, metal oxides (e.g., Cr_2O_3, Fe_2O_3, and ZnO), and toxic metals (Ni, Fe, Al, and Pt) (West et al., 2021). Metals and metal oxides in additives can cause serious diseases such as lung carcinogens, metal fume fever, and siderosis (Antonini et al., 2021).

Extremely high emission rates and high concentrations of submicron particles are observed during the powder-coating process. Workers are the first group of people to be heavily exposed to submicron particles generated during the powder-coating process. The number of workers in the powder-coating industry is expected to grow significantly as the global spray-coating market expands (Research G V, 2020; Society A T S, 2020). Consequently, it is critical to evaluate the health risks of submicron particles during operations. There have been some studies on the characterization of exposure to submicron particles generated during the powder-coating process in the workplace. Bemer et al. (2010) observed extremely high emission rates and mass concentrations of submicron particles generated by the electric arc and flame spray processes. Similarly, Huang et al. (Hassan et al., 2016), who monitored the mass concentration of particles generated in a coating workshop without control measures, reported that the time-weighted average concentration of the particles was high (34.2 mg/m^3). The number concentration, mass concentration, and size distribution of particles generated during the atmospheric plasma spray process were characterized by Viana et al. (2017). In recent studies, the morphology, concentration (number and mass concentrations), size distribution, and compositions of particles generated during the thermal spray process have been described (Salmatonidis et al., 2019; Mikheev et al., 2020).

Although previous studies have characterized the physical and chemical properties of submicron particles in the work environment, they have not assessed the health risks of submicron particles. The concentration of submicron particles in the environment may not be equivalent to the concentration of submicron particles that workers are exposed to. The emission potential of submicron particles, characteristics of the submicron particles, production task, and control measures can influence the health risk of submicron particles. Therefore, it is necessary to assess the health risks associated with submicron particles. The complex composition and limited toxicological information of submicron particles limit our understanding of their health risks. A feasible risk-assessment strategy that can classify health risks with limited toxicological information is indispensable. The control banding (CB) tool, which can evaluate risk levels without toxicological or detailed exposure information, has been widely used in various environments (Eastlake et al., 2016; Sanchez Jimenez et al., 2016). Hence, in this study, the CB tool was introduced to assess the health risks of workers to submicron particles during work.

In addition to analyzing health risks, respiratory intake is indispensable for evaluating the potential health effects of substances. Inhalation is the principal pathway through which workers are exposed to submicron particles, and the concentration of submicron particles entering the human

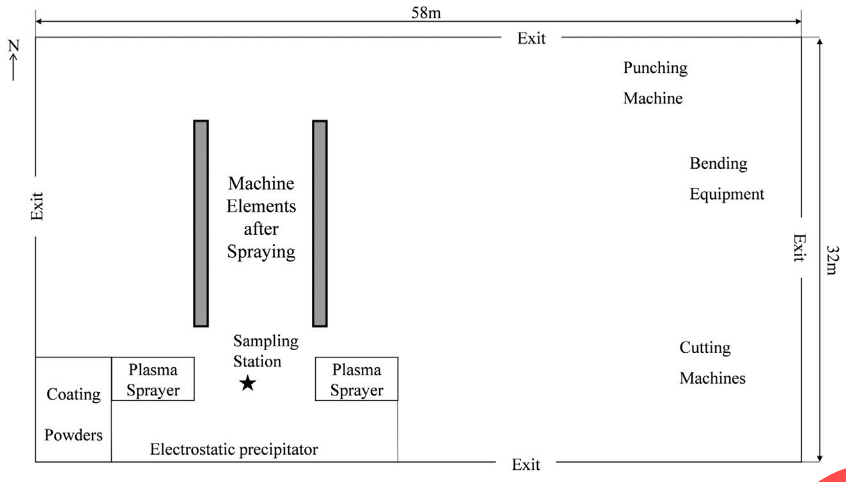

FIGURE 1
A schematic diagram of the powder-coating workshop. The star symbol represents the sampling location.

body through respiration is closely related to health effects. Therefore, in addition to health risks, it is crucial to analyze respiratory intake as a quantifiable indicator. Based on the rapid development of nanoparticle measurement methods, Tian et al. used computational fluid dynamics modeling and established a model that could assess the doses of ultrafine particles (UFPs) deposited in the olfactory area, nasal cavity, and lungs (Tian et al., 2017; Tian et al., 2019). On the basis of the model, the Institute of Urban Safety and Environmental Science at the Beijing Academy of Science and Technology developed a software named "ultrafine particle exposure evaluation (registration number: 2021SR1773659)," which can calculate the deposited dosage of UFPs in the olfactory area, nasal cavity, and lungs. In this study, software was used to evaluate the deposited dosages of the UFPs. Furthermore, the average daily doses (ADDs) of workers were calculated based on the deposited dosage of UFPs in different areas.

To shed light on the health risks and respiratory intake of submicron particles generated during the powder-coating process, this study mainly focuses on the following aspects: (Society A T S, 2021) the temporal variations in the concentrations of the submicron particles [i.e., number concentration (NC), mass concentration [MC], surface area concentration (SAC), personal NC, and lung-deposited surface area concentration (LDSA)]; (Fauchais et al., 2014) the health risks of the submicron particles; and (Rosso et al., 2001) the respiratory intake of UFPs, which is indicated by the dosage of UFPs deposited in the olfactory area and lungs, and the ADD of workers. The findings of this study can provide a basis for formulating risk management decisions to reduce the health risks of workers exposed to submicron particles during the powder-coating process.

2 Materials and methods

2.1 Descriptions of the working environment

A spray powder-coating process practiced in a machinery factory in Wenzhou City in Zhejiang Province, East China, was selected for the field investigation. The main production processes in this factory include cutting, bending, punching, welding, and powder coating. Among the processes, the welding and powder-coating processes are the ones that potentially release submicron particles. These two processes are conducted in two separate workshops. Figure 1 shows the layout of the powder-coating workshop. The workshop is 58 m long, 32 m wide, and 6 m high. Because the workshop is naturally ventilated, there is no mechanical ventilation system. The powder-coating position is equipped with an electrostatic precipitator system designed as a fume cupboard. There are no inspection or maintenance records of the electrostatic precipitator, and the workshop is not cleaned daily. Two types of sprayers are used to accomplish the powder-coating process, and there are four workers per work shift. One worker with 10 years of exposure operates the sprayer, and the other three workers are responsible for carrying products and placing products on the conveyor belt. The duration of the operation is 5 h on each workday, and the frequency is 7 days per week.

2.2 Sampling strategies

The real-time system for monitoring the concentration and size distribution of submicron particles is shown in

TABLE 1 Measuring systems for monitoring the concentrations and size distribution of the submicron particles.

Monitoring types	Exposure metrics	Instruments	Particle sizes (nm)	Measuring range	Sampling rate (L/min)	Log intervals (min)	Sampling time
Real-time monitoring	MC	DustTrak 8533 (TSI, United States)	100–15000 PM1.0:100~1000; RESP: 100~5000; PM2.5: 100~2500	0.01–150 mg/m^3	3	1	10:20–12:00
	NC	3007 (TSI, United States)	10–1000	0–100000 pt/cm^3	0.1	1	10:20–12:00
	SAC	AeroTrak 9000 (TSI, United States)	10–1000	1–10000 μm^2/cm^3	2.5	1	10:20–12:00
	Personal NC	DiSCmini (Testo, Germany)	20–700	0–5000000 pt/cm^3	1.0	1	10:20–12:00
	Size distribution by number	SMPS 3034 (TSI, United States)	10–487	1–2.4×10^6 pt/cm^3	1.0	3	9:41–11:59
		OPS 3330 (TSI, United States)	300–10000	0–3000 pt/cm^3	1.0	1	10:20–12:01

Table 1. The sampling process was performed in a machine factory in April 2019 on a sunny day, during which the outdoor temperature ranged from 17°C to 22°C. The outdoor air velocity was low (0.41 ± 0.04 m/s). According to the Chinese National Standard "Determination of dust in the air of workplaces, part 6: Total number concentration of ultrafine and fine particles" (China NHCotPsRo, 2019), the sampling schedule encompassed three main aspects. The first aspect was a field investigation, during which the processing technology, number of workers, work tasks, frequency and duration of operations, pre-sampling, and exposure-control devices were investigated. The second aspect was area sampling, in which the sampling facilities were located between the sprayers and 1.3 m above ground (Figure 1). Under regular production conditions, area sampling covering one complete work cycle consisting of a powder-coating period, powder-filling period, and non-activity period was carried out during and after the powder-coating process. The third aspect was personal sampling. During the field investigation, we measured the number concentration of submicron particles at different positions and found that the worker operating the sprayer had the highest exposure concentration. According to the Chinese standard of "Specifications of air sampling for hazardous substance monitoring in the workplace (GBZ159-2004)" (China NHCotPsRo, 2004), the worker operating the sprayer was selected for personal sampling in this study (n = 1). DiSCmini was placed close to the nose of the worker.

Capture velocity sampling based on an occupational health standard in China (Ministry of Emergency Management of the People's Republic of China, 2017) (Regulation on Technical Specifications for Capture Velocity for LEV Facilities, AQ/T4274-2016) was tested three times while the electrostatic precipitator system was operating, and the average value was used. The location was selected as the farthest particle source of release from the electrostatic precipitator hood, and the direction indicator on the digital anemometer was windward.

TABLE 2 The risk matrix of Stoffenmanager Nano model.

Exposure level \ Hazard level	A	B	C	D	E
1	3	3	3	2	1
2	3	3	2	2	1
3	3	2	2	1	1
4	2	1	1	1	1

2.3 Assessment of the health risk

The Stoffenmanager Nano model is effective for conducting risk assessment (Van Duuren-Stuurman et al., 2012; Gao et al., 2019). It follows a stepwise binary decision tree to classify the hazard risk into one of five hazard levels (levels A–E). A stepwise binary decision tree was described in a latter study (Van Duuren-Stuurman et al., 2012). Level A represents the lowest level of hazard, and level E represents the highest level of hazard. On the other hand, the model calculates the exposure score and then classifies the exposure risk into one of the four exposure levels (levels 1–4). Level 1 represents the lowest level of exposure (scores < 0.002), level 2 represents an average level (score range from 0.002 to 0.2), level 3 represents a high level (score range from 0.2 to 20), and level 4 represents the highest level of exposure (scores > 20). Hazard and exposure risks are used to construct a risk matrix that accommodates three risk levels (Table 2), of which level 1 represents the highest level of risk

TABLE 3 The multipliers used to calculate exposure scores.

Multipliers	Category/Description	Value
E	Dustiness = Granules/flakes	0.03
	Moisture content = Dry product (<5% moisture content)	1
	Weight fraction = Pure product	1
a	Regular inspections and maintenance of machines and equipment, no daily cleaning	0.01
H	Handling of products where, due to high pressure, speed, or force, large quantities of dust are generated and dispersed	100
t_h	4–8 h a day	1
f_h	4–5 days a week	1
η_{imm}	The worker does not work in a cabin	1
η_{ppe}	None	1
η_{lc}	Containment of the source without local exhaust ventilation	0.3
η_{gv_nf}	Volume > 1,000 m^3, mechanical and/or natural ventilation	1
η_{gv_ff}	Volume > 1,000 m^3, mechanical and/or natural ventilation	1

Note: E, Dustiness Moisture content Weight fraction, 0.03·1·1, 0.03.

and level 3 represents the lowest level of risk. The equations used to calculate the exposure score in the Stoffenmanager Nano model are as follows (Van Duuren-Stuurman et al., 2012):

$$B = \left[\left(C_{nf}\right) + \left(C_{ff}\right) + \left(C_{ds}\right)\right] \cdot \eta_{imm} \cdot \eta_{ppe} \cdot t_h \cdot f_h, \quad (1)$$

$$C_{nf} = E \cdot H \cdot \eta_{Ic\_nf} \cdot \eta_{gv\_nf}, \quad (2)$$

$$C_{ff} = E \cdot H \cdot \eta_{Ic\_ff} \cdot \eta_{gv\_ff}, \quad (3)$$

$$C_{ds} = E \cdot a \quad (4)$$

where B is exposure score, C_{nf} is the concentration (score) due to near-field sources, C_{ff} is the concentration (score) due to far-field sources, C_{ds} is the background concentration (score) due to diffusive sources, η_{imm} is the multiplier for the reduction of exposure due to control measures at the worker, η_{ppe} is the multiplier for the reduction of exposure due to use of personal protective equipment, t_h is the multiplier for the duration of the handling, f_h is the multiplier for frequency of the handling, E is intrinsic emission multiplier, H is handling (or task) multiplier, η_{lc} is the effect of local control measures multiplier, η_{gv_nf} is the multiplier for the effect of general ventilation in relation to the room size on the exposure due to near-field sources, η_{gv_ff} is the multiplier for the effect of general ventilation in relation to the room size on the exposure due to far-field sources, and a is a multiplier for the relative influence of background sources. The multipliers used in this study are presented in Table 3.

2.4 Methodology for respiratory intake assessment

The software named "ultrafine particle exposure evaluation (registration number: 2021SR1773659)," which requires MATLAB Runtime to run, was employed to assess the deposition dosage of UFPs in the olfactory area, nasal cavity, and lungs of the workers. Based on the size distribution and number concentrations of the UFPs (which were measured using SMPS), duration of the activity period, duration of the non-activity period, breathing rates of the workers, and exposure duration of the workers to the UFPs, the software calculates the daily dosage of the UFPs accumulated in different areas in the workers. The empirical equation used in the software to quantitatively predict the regional deposited dosage of UFPs in the human olfactory mucosa and lungs is as follows:

$$Dose_{mass} = \int_{t_1}^{t_2} \int_{d_1}^{d_2} \rho \frac{\pi}{6} d^3 \cdot n\left(d, \vec{r}, t\right) \cdot DE \cdot Q \quad (5)$$

where (t_1, t_2) is the exposure time, (d_1, d_2) is the size range of the UFPs, ρ is the density, d is the particle diameter, $n(d, \vec{r}, t)$ is the environmental particle size distribution by number concentration, DE is the regional deposition rate of inhaled UFPs, *and* Q is the breathing rate. Here the size of the UFPs ranges from 10.4 nm to 96.5 nm, and ρ and DE were assumed to be 1.2 g/cc and 12 L/min, respectively (Shang et al., 2021). The $n(d, \vec{r}, t)$ is the data measured by SMPS, and DE is calculated using the equation embedded in the software, as described in a previous study (Shang et al., 2021).

According to the method described in the Environmental Protection Agency's (EPA's) *Risk assessment guidance for superfund* (Environmental Protection Agency, 2009), the deposited concentrations evaluated using the software "2021SR1773659" were converted to ADD of workers. The ADD ($mg/kg \cdot d^{-1}$) was calculated using the following equation:

$$\mathrm{ADD} = \frac{D \cdot ED \cdot EF}{BW \cdot AT} \quad (6)$$

where D is the deposited dose calculated by equation (Suojalehto et al., 2019) (mg/day), ED is the exposure duration (year), and EF

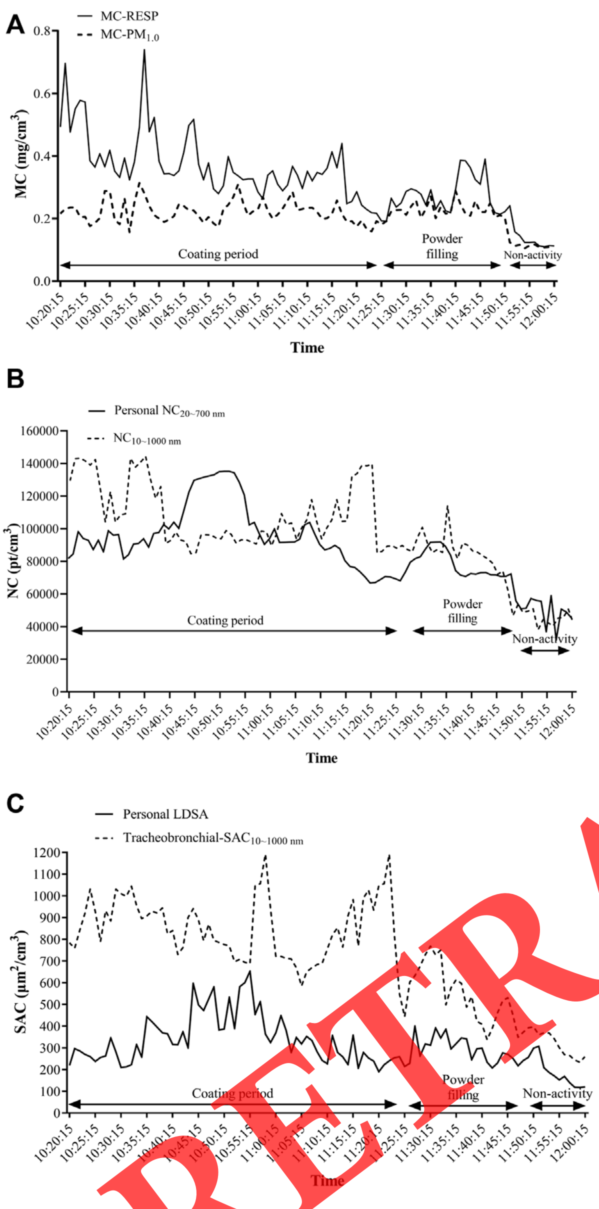

FIGURE 2
Temporal variations in the concentrations of the UFPs covering one complete work cycle. **(A)** Temporal variations in the MC; **(B)** Temporal variations in the NC and personal NC of particles; **(C)** Temporal variations in the SAC and personal SAC of particles.

is the exposure frequency (days/year). According to the investigation, the *ED* is 10 years, and the *EF* is assumed to be 288 days/year for the worker in this study. *BW* is body weight (kg), which is typically assumed to be 70 kg for adult males and 60 kg for adult females (Hussain et al., 2009). *AT* is the average time (days), which was approximately 10,080 days according to the field investigation.

3 Results

3.1 Temporal variations in the concentrations of submicron particles

The temporal variations in the concentrations of the submicron particles generated during and after the powder coating process are shown in Figure 2. As shown in Figure 2A, in the powder-coating period, the MC of respirable particles (RESP, size < 5 μm) reaches 0.8 mg/m³, which is approximately eight times as high as that in the non-activity period. The MC of RESP in the powder-filling period, which ranges from 0.2 mg/m³ to 0.4 mg/m³, is higher than that in the no-activity period (lower than 0.2 mg/m³). The MC of the particles whose diameter is smaller than 1.0 μm ($PM_{1.0}$), which ranges from 0.1 mg/m³ to 0.3 mg/m³, is less than the MC of RESP. Compared to the MC of RESP, the variation in $PM_{1.0}$ is relatively steady. After the cessation of the powder-coating or powder-filling activity, the MC of both RESP and $PM_{1.0}$ decreased sharply to 0.1 mg/m³. Figure 2B shows that in the powder-coating and powder-filling periods, the NC of the submicron particles with sizes ranging from 10 to 1,000 nm is higher than 1 × 10⁵ pt/cm³. The highest NC, which is approximately 1.5 × 10⁵ pt/cm³, occurs three times in the powder-coating period. The highest NC was three times higher than the NC during the no-activity period. In the powder-coating period, the trend of personal NC ranged from 0.7 × 10⁵ pt/cm³ to 1.4 × 10⁵ pt/cm³, which is similar to that of NC. As shown in Figure 2C, the SAC of the submicron particles fluctuated significantly from 600 μm²/cm³ to 1,200 μm²/cm³ in the powder-coating period and decreased to 300 μm²/cm³ in the no-activity period. The personal LDSA of the particles ranged from 100 to 700 μm²/cm³ during the powder coating period, which fluctuated sharply when the personal NC was high and decreased to 100 μm²/cm³ in the non-activity period.

3.2 Particle size distribution in the working environment

Figure 3 shows the particle size distribution by number determined using the SMPS and OPS. As shown in Figure 3A, the number of particles smaller than 200 nm increased significantly, as the powder-coating activity began at 10:20 am and decreased significantly at 11:50 am, at which time the activity stopped. Figure 3C shows that predominant size of the particles in the activity period ranged between 30 nm and 200 nm, and Figure 3A shows that the highest number of particles was 1.75 × 10⁵ pt/cm³, which occurred at approximately 11:10 am. Analysis of the particle size distribution using the OPS showed that the number of particles larger than 374 nm was lower than 2 × 10⁴ pt/cm³ (Figure 3B). The number of particles larger than 500 nm was less than 5 × 10³ pt/cm³, which remained constant throughout

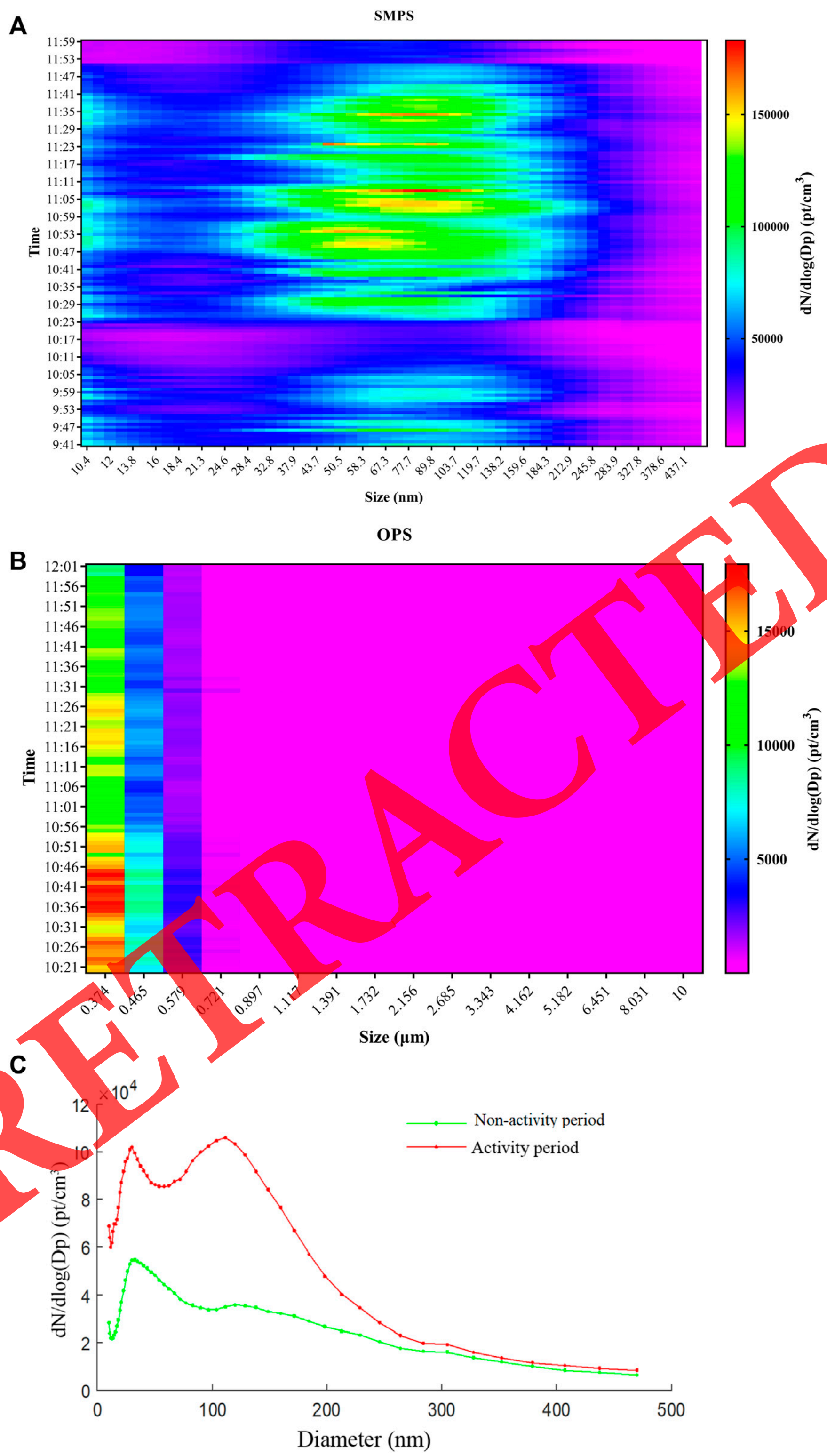

FIGURE 3
Temporal variations of particle size distribution by number. **(A)** Real-time particle size spectrum of scanning mobility particle sizer (SMPS); **(B)** Real-time particle size spectrum of optical particle sizer (OPS); **(C)** The temporal variations in mode size of SMPS.

TABLE 4 Dosage of UFPs deposited in olfactory, nasal cavity, and lung in a typical working day and the ADD of workers.

Dosage	Area	Olfactory	Nasal cavity	Lung
	One working day (mg)	0.292	0.272	111.5
ADD (mg/kg·d^{-1})	The worker in this study (male with 10 years of ED)	1.192×10^{-3}	1.11×10^{-3}	0.455
	Male with 1 year of ED	1.192×10^{-4}	1.110×10^{-4}	0.046
	Female with 1 year of ED	1.390×10^{-4}	1.295×10^{-4}	0.053
	Male with 5 years of ED	5.959×10^{-4}	5.551×10^{-4}	0.228
	Female with 5 years of ED	6.952×10^{-4}	6.476×10^{-4}	0.265
	Female with 10 years of ED	1.390×10^{-3}	1.295×10^{-3}	0.531

the activity and non-activity periods. Figure 3C shows that in the activity period, the number of particles smaller than 200 nm was higher than that in the non-activity period. This pattern was similar to that shown in Figure 3A. For particles larger than 200 nm, there was no significant difference between the activity and non-activity periods.

3.3 The health risk of submicron particles

Based on the field investigation and material safety data sheet, the coating powders are a mixture of unknown composition, and hazard data are not available. Therefore, the hazard classification belonged to "manufactured nano objects containing unknown parent material" which is level E (a high level). Applying the equations from the Stoffenmanager Nano model resulted in an exposure score of 1.8003. Based on the exposure score, exposure risk was assigned a high level of 3. According to the risk matrix, health risk was high (Level 1). The capture velocity of the existing electrostatic precipitator was 0.6 m/s, which is far lower than the limit value (1.2 m/s) established in the occupational health standard of China (AQ/T4274-2016) (Ministry of Emergency Management of the People's Republic of China, 2017). In addition to engineering controls, numerous occupational health management measures including regular occupational health training and occupational health examinations for workers were implemented in the plant. However, the workers did not provide respiratory-protective equipment.

3.4 The respiratory intake of UFPs

The raw data recorded by the SMPS were imported into the software, and the powder-coating and powder-filling periods were selected as the activity period, while the non-activity period was selected as the background. According to the field investigation, the duration of the activity period was 5 h per day and the duration of the non-activity period was 3 h. In the powder-coating scenario, workers were assumed to breathe at a rate of 12 L/min. The dosages of UFPs deposited in the olfactory area, nasal cavity, and lung were 0.292 mg, 0.272 mg, and 111.5 mg, respectively, on a typical working day, as described in this study (Table 4). The deposited dosage of UFPs was used as *D* to calculate the ADD of workers. For the operating worker in this study, the ADDs in the olfactory cavity, nasal cavity, and lung were 1.192×10^{-3} mg/kg·d^{-1}, 1.11×10^{-3} mg/kg·d^{-1}, and 0.455 mg/kg·d^{-1}, respectively. The ADDs of assumed workers of different sexes and *ED* were calculated (Table 4). The results of ADD showed that the ADDs of female workers were higher than that of male workers with the same *ED*.

4 Discussion

In recent years, the number of reports on the generation and release of submicron particles during powder coating has increased. Previous studies have mainly focused on the environmental concentrations, size distribution, components, and emission rates of submicron particles. In this study, the detailed environmental concentrations and size distribution of submicron particles were investigated, and the health risk and respiratory intake of submicron particles were also evaluated. To the best of our knowledge, this is the first study to identify the health risks and respiratory intake of submicron particles during the powder-coating process.

The concentrations of submicron particles (including NC, MC, and SAC) generated during the activity period were higher than those of submicron particles generated during the non-activity period. NC, MC, and SAC were multimodal, increased immediately after the start of the activity, and decreased when the activity was halted or completed. The maximum MC, NC, and SAC appeared during the powder-coating period. The MC, NC, and SAC of the submicron particles in the activity period were significantly higher than the MC, NC, and SAC of the submicron particles in the non-activity period. These results were confirmed by previous studies on workshop exposure of submicron particles during spraying, which characterized high concentrations of submicron particles generated during the powder-coating process (Viana et al., 2017; Salmatonidis et al., 2019). Personal

NC measured in the breathing zone was lower than that measured in the environment, but the variation trend of personal NC was similar to that of NC. One of the reasons for the difference between NC and personal NC is the different particle size measuring ranges of the instruments, as the range of CPC measured was 10–1,000 nm and the range of Discmini measured was 20–700 nm. Previous *in vitro* studies have shown that the toxicity of insoluble particles correlates with their surface area (Hussain et al., 2009; Golbamaki et al., 2018). Therefore, LDSA is an important metric for quantifying the exposure risk of particles. The LDSA of personnel measured by DiSCmini suggested that there would be a significant deposition of submicron particles in the lungs of workers, which is supported by the results of personal NC. Therefore, the results of personal NC and LDSA provided direct evidence that workers may be exposed to high concentrations of submicron particles. Size distribution analysis revealed that the predominant size of the submicron particles in the workshop air during the activity period ranged between 30 and 200 nm. The size distribution of the submicron particles during the activity period was bimodal (Figure 3C), which is in agreement with our previous study that reported a bimodal size distribution of submicron particles in a steelmaking plant (Gao et al., 2021).

The exposure risk was level 3, and the corresponding health risk was level 1, both of which were high. The high health risk is consistent with the high NC, MC, SAC, and personal NC, which indicates that the workers are at a high risk of being exposed to high concentrations of submicron particles during the powder-coating process. According to the results of the field investigation and monitoring, the unorganized work environment, unavailable personal protective equipment, and low capture velocity of the electrostatic precipitator may explain the high health risks of workers to submicron particles.

The results of respiratory intake showed that a small portion of the UFPs were deposited on the olfactory mucosa or intercepted in the nasal cavity at dosages of 0.292 mg and 0.272 mg, respectively. Under the same exposure scenario and the same exposure duration, the ADD of female workers was higher than that of male workers because of their lower weight. For the worker in this study, the ADDs in the olfactory area and nasal cavity were 1.192×10^{-3} mg/kg·d^{-1} and 1.11×10^{-3} mg/kg·d^{-1}, respectively. UFPs in the nasal cavity were removed, and the health effects were negligible. Through an animal study, De Lorenzo (De Lorenzo, 1970) suggested that the olfactory pathway is a viable route for the brain to absorb environmental UFPs. Furthermore, Oberdörster et al. estimated that 20% of inhaled UFPs could be translocated into the brain through the olfactory bulb (Oberdörster et al., 2004). Based on the above hypothesis, the UFPs deposited on the olfactory mucosa may be translocated to the brain and lead to high potential hazards to the central nervous system (CNS), and this needs to draw attention. In addition, most of the UFPs were deposited in the lungs (111.5 mg), and the ADD in the lungs reached 0.455 mg/kg·d^{-1}. The UFPs deposited in the lung may not only be retained in the alveolus but also translocated to other tissues and cause damage (Kreyling et al., 2009; Geraets et al., 2012; Bakand and Hayes, 2016; Buckley et al., 2017). These results suggest that most of the inhaled UFPs were deposited in the lungs of workers. Therefore, UFPs deposited in the lungs require immediate attention.

Both the high health risk level and the high dosages of UFPs deposited in the lungs and olfactory mucosa require the urgent need for a series of additional control measures to protect workers. According to the NIOSH regulation, the BCF Code of Safe Practice (British Coatings Federation, 2015), and the Safe Powder-coating Guideline (European Council for Paint and Printing Ink Manufacturers, 2020), several additional measures should be implemented. First, the capture velocity of the electrostatic precipitator should be increased to higher than 1.2 m/s, or the sources of dust and submicron particles should be enclosed in a booth without workers. Moreover, the airflow across the face of the booth should be uniform (±20% of the average airflow). Air should flow from the backs of workers. Second, the effectiveness of the dust extraction and ventilation systems should be inspected, tested, and maintained. The workshop should be cleaned every day using the wet cleaning method, while dry sweeping or the compressed air method should not be permitted. Third, a regular inspection should be conducted to ensure that workers wear certified personal protective equipment properly (such as filter mask P3). The above measures can reduce the values of the corresponding parameters of the Stoffenmanager Nano model. For example, the first improvement can reduce the value of ηlc to 0.001, the daily cleaning measure can decrease the value of a to 0, and properly wearing the filter mask P3 can decrease the value of η_{ppe} to 0.2. The implementation of the above three measures could reduce the exposure risk to the lowest level, according to the Stoffenmanager Nano model.

This study had several limitations. First, the sampling lasted 1 day under standard working conditions. The results can only represent health risks under the same conditions, including the same operating model, working conditions, meteorological conditions, sex, age, exposure duration, and exposure frequency. Second, clearance efficiency should be considered when evaluating the regional deposition of UFPs. Third, researchers should evaluate the risks of workers to submicron particles *via* dermal contact and ingestion pathways. Fourth, all input parameters in the equations were fixed constants without given probability distributions, thus limiting the results on health risk and respiratory intake. Future studies should conduct a more scientific and comprehensive assessment of workers' risks during work.

5 Conclusion

In the powder-coating workplace, workers are at high risk due to exposure to high levels of submicron particles and high respiratory intake of UFPs. Significantly, a large quantity of UFPs can be deposited in the lungs, with a small portion of UFPs deposited on the olfactory mucosa. This study provides a scientific basis for reducing the health risks and respiratory intake of submicron particles by workers. Management should improve existing risk-control strategies including engineering, management, and personal protective equipment implementation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XG designed and performed the investigation, analyzed data, provided funding, and wrote part of the original draft. RC and HF contributed to investigation, supervision, and quality control. HZ and YC contributed to quality control and provide funding. YH, YL, WY, and CQ contributed to formal analysis and data curation. ZZ, XL, and XZ designed and supervised the project, reviewed and edited the article.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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