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Correlation between airborne particle concentrations in seven industrial plants and estimated respiratory tract deposition by number, mass and elemental composition

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ABSTRACT

The number and mass distribution of airborne particles were recorded in several industrial plants. From the data obtained, particle deposition was estimated in three regions of the respiratory tract using the ICRP grand average deposition model based on Hinds' (1999) parameterization. The median diameter was 30–70 nm (number distributions), and $>4\,\mu m$ (mass distributions) near most work activities, resulting in linear relationships between the deposited number/mass concentrations and the number/mass concentrations in the air. Welding and laser cutting produced particles in the 200–500-nm range; total deposition was small, not in accordance with the linear relationship observed for the other work activities. The elemental content varied between particle sizes in some workplaces, causing different elements to deposit in different respiratory regions. Iron was the most abundant element in the particles in many of the workplaces; in an iron foundry, however, Fe was most abundant only in the micron-sized particles whereas the nanoparticles mainly comprised Pb and Sb.

1. Introduction

The occupational exposure to airborne particles is often high in industrial plants (Elihn & Berg, 2009; Möhlmann, 2005), so accurate particle measurements are needed at these workplaces to determine the relationship between health effects and exposure levels. The best metric for particle exposure is not yet clear. Depending on the health endpoint, different characteristics of workplace aerosols may be germane, for example: (i) mass concentration, (ii) number concentration, (iii) particle surface area concentration, (iv) particle size, and (v) particle composition. Airborne particle size is one determinant of where particles may deposit in the respiratory tract upon inhalation, and is therefore a possible determinant of the health effect caused; however, different health endpoints may require measurements of different particle metrics (Maynard & Aitken, 2007).

Studies of workplace particle exposure often investigate the mass concentration of airborne particles. Kertész et al. (2002) determined the mass size distribution of cave aerosols, and calculated total and regional deposition efficiencies using a stochastic lung deposition model, and concluded that the extrathoracic deposition of these coarse particles was significant. Mass measurements, however, does often not reflect the concentration of airborne ultrafine particles. Increasing concern about nano-sized particles has led to more measurements of, for example, number concentrations and particle number size

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distributions that better reflect the level of exposure to ultrafine particles (<100 nm in diameter). Heitbrink et al. (2009) simultaneously measured particle number, surface area, and respirable mass concentrations in a foundry and an automotive engine manufacturing plant. They found that the surface area concentration was correlated with ultrafine particle number concentration (r^2=0.36–0.6) and weakly correlated with respirable mass concentration (r^2=0.09–0.28). A study by Wang, Tsai, Chen, Chen, & Hsu (2010) predicted the nanoparticle exposure in three regions of the respiratory tract for workers in a carbon black manufacturing industry. The deposition efficiency of the particle surface area and number concentrations that deposit in the alveolar region was concluded to be much higher than for the head airways and tracheobronchial regions. It has been suggested that some adverse health effects depend on exposure to ultrafine particles (Donaldson, Stone, Seaton, & MacNee, 2001; Seaton, MacNee, Donaldson, & Godden, 1995; Sjögren, Fossum, Lindh, & Weiner, 2002).

Few studies examine the relationships between various characteristics of aerosols in occupational environments and health effects. Ohlson et al. (2010) demonstrate a significant correlation between the level of several measured particle fractions and one inflammatory marker, i.e., interleukin 6 (IL-6), in blood samples of workers in industrial environments. Toxicological *in vitro* studies have addressed several aspects of the effect of particle characteristics on cells (Jeng & Swanson, 2006; Midander et al., 2009; Park et al., 2007). For example, a size dependant toxicity was observed for Cu and CuO particles, nano-sized particles being found to be more toxic than to micron-sized particles (Karlsson, Gustafsson, Cronholm, & Möller, 2009; Midander et al., 2009). A greater inflammatory response has also been reported for ultrafine in comparison with larger particles of the same material (i.e., TiO_2 and Ni) and mass dosage (Oberdörster, Ferin, Gelein, Soderholm, & Finkelstein, 1992; Zhang et al., 2003), though in the case of TiO_2, the crystal structure is of equal importance (Soto, Garza, & Murr, 2007). Nano-sized particles are generally more reactive than micron-sized particles are, and may therefore be more harmful to health. Particles of different sizes may also deposit in different compartments of the human respiratory tract upon inhalation, possibly affecting health in different ways. Ultrafine particles in the 10–100-nm size range deposit largely by diffusion in the alveolar region, whereas particles <10 nm and micron-sized particles mainly deposit in the nose and mouth regions. In addition, a substantial fraction of the 1–100-nm particles also deposit in the tracheobronchial region. For particles with a diffusion equivalent diameter >200 nm and an aerodynamic diameter <500 nm, however, a major portion of the particles is exhaled; in workplaces where most particles are in this size range, the particle deposition in the respiratory tract of workers may be less than in workplaces where smaller particles are dominant (even though the inhaled air contains a higher particle (number) concentration in the first case).

Cell exposure experiments have found that particle composition significantly influences the effect of particles on human health and toxicity. Metal fume fever, a phenomenon experienced by welders, is dependent on the composition of inhaled metal particles. Welding fumes of zinc oxide as well as presence of cadmium, copper, and tin can induce metal fume fever in welders (Antonini, Taylor, Zimmer, & Roberts, 2003). *In vitro* studies have demonstrated that CuO nanoparticles are more toxic than many other metal oxide nanoparticles, such as those of TiO_2, ZnO, and Fe_3O_4 (Karlsson, Cronholm, Gustafsson, & Möller, 2008).

Exposure is defined as the total concentration of airborne particles in a worker's breathing zone at a workplace. As the instruments used here are heavy and bulky, personal sampling could not be done. Instead, particle concentrations were measured at positions near one or more workers. This approximates a worker's occupational exposure to airborne particles, which in occupational hygiene is defined as the concentration of the airborne particles in the worker's breathing zone during a representative measuring period (usually a day). Stationary measurements of the number and mass size distributions of airborne particles are presented here for several work activities in seven Swedish industrial plants. From these data, the concentrations of particles deposited in various regions of the respiratory tract were estimated.

The deposited particle concentration varies with breathing pattern (i.e., exercise level, gender, and fractions of air inhaled through the nose and mouth). The basis of our calculations is the ICRP model of particle deposition in the respiratory tract (ICRP, 1994). Since its publication, several authors have published other models of particle deposition in various regions of the respiratory tract (e.g., Asgharian, Price, & Hofmann, 2006; Choi & Kim, 2007; Park & Wexler, 2008; Sturm & Hofmann, 2005). Here we will use Hinds' (1999) grand average parameterization for the regional deposition efficiencies, according to the ICRP (1994) model, to estimate the deposited particle concentrations in three regions of the respiratory tract. Each of Hinds' grand average model equations for the three regions of the respiratory tract is the average over gender and three typical breathing patterns/exercise levels. To determine the dose for specific workers, one must also either estimate each worker's breathing pattern from exercise levels or measure the inhaled minute volume for the workers. Based on these data and the full ICRP model, it is possible to calculate the deposited dose by taking the product of the estimated deposited concentration, the shift length, and the minute volume. However, such modelling using the full ICRP model was not done here, as the corresponding data were not determined/estimated for the workers at the workplaces where the particle concentrations were measured. Consequently, only average deposited particle concentrations could be calculated; the doses for individual workers working at the specific workplaces could not be assessed, but will differ according to individual breathing patterns.

The elemental composition of particles in the workplaces was also determined. Individual ultrafine particles were analysed using transmission electron microscopy/energy dispersive X-ray spectroscopy (TEM/EDS). Filter samples, in which the main contribution in terms of mass originates from micron-sized particles, were analysed using inductively coupled plasma mass spectrometry (ICP-MS). Since the particle composition was size dependant in some cases, these results provide a brief description of the distribution of deposited elements in the respiratory tract.