



A study of the size distribution of aerosol particles resuspended from clothing surfaces



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ARTICLE INFO

Article history:

Received 24 February 2014

Received in revised form

9 April 2014

Accepted 6 May 2014

Available online 21 May 2014

Keywords:

Resuspension

Human physical activity

Clothing

Hazardous aerosol particles

Size distribution

Shedding

ABSTRACT

A primary factor governing the impact of hazardous aerosol particles on the human body is the size of the contaminant particles. Secondary exposure to humans can occur when initially deposited particles are re-entrained into the air via the transport process of resuspension. This study has experimentally investigated the size distributions of a mixture of monodisperse 3, 5, and 10 μm particles after they were collectively deposited on, and then resuspended from the clothing of a contaminated person engaged in varying degrees of physical activity. The generally accepted theory, that the likelihood of particles resuspending from a surface will increase with increasing particle size, has been verified in this study (i) by comparing the size distribution curves of airborne particles during deposition and during resuspension, (ii) by examination of the individual size distributions for each of the three particle sizes investigated, and (iii) by calculating the resuspended fraction of initially deposited particles, as determined via Neutron Activation Analysis (NAA).

A comparison of the size distribution curves for deposited and resuspended particles revealed that during resuspension, the highest peak in concentration occurred at $\sim 10 \mu\text{m}$, whereas the highest concentration peak occurred at $\sim 3 \mu\text{m}$ during deposition. When the three distributions were individually analysed, it revealed a shift towards a higher Mass Median Aerodynamic Diameter for the resuspended distribution. This was confirmed via NAA, which revealed that the percentage of particles resuspended increased with increasing particle size; during high physical activity, an average of $27 \pm 9\%$ of 3 μm particles, $30 \pm 6\%$ of 5 μm particles, and $34 \pm 5\%$ of 10 μm particles resuspended. Additionally, it was revealed that following the collective resuspension of 3, 5 and 10 μm sized particles, the larger sized particles were found at their highest concentrations at head height (in comparison to ankle or waist height). This has consequences for a person's potential inhalation exposure; larger particles are less likely to penetrate the lower airways of the lungs, and therefore resuspended aerosol particles do not pose a major threat for increased inhalation exposure.

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1. Introduction

Airborne hazardous particles are of major concern in today's society. These potentially dangerous particles include biological aerosol (for example by terrorist release), infectious diseases (transmission in hospitals) and radioactive particles.

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A major accident at a nuclear power plant (e.g. Fukushima) or an act of terrorism involving large quantities of radioactive material could result in this hazardous material being carried long distances in the atmosphere and affecting populations hundreds of miles away from the source, as was noted by [Mustonen \(2009\)](#) in relation to the spread of radioactive materials over much of Europe following the Chernobyl accident. A countries horticulture and livestock can become contaminated, which exposes the population to contamination by harvesting and ingestion. Inhabitants could also become exposed to the airborne particles through the process of deposition on their hair, skin and clothing ([Andersson et al., 2004](#); [Fogh et al., 1999](#)). [Andersson et al. \(2002\)](#) assumed that on average, 85% of the human body is covered with clothes.

While deposition and other primary exposure routes have been extensively studied, e.g. [Lai and Nazaroff \(2000, 2005\)](#) and [Thatcher et al. \(2002\)](#), less attention has been given to the subsequent fate of deposited particles. Unless a contaminated person then remains perfectly still, they will engage in some degree of human physical activity. This movement will cause particles to resuspend from their clothing and become airborne and thus there is a potential for secondary exposure.

The size of resuspended particles will have implications for a person's exposure type and severity. While the size distribution of hazardous aerosols in the environment is highly variable, in terms of human exposure, the risk varies with particle size. There are many routes for human exposure to hazardous particles including ingestion, inhalation and absorption through the skin. The size of the particles associated with these exposure routes varies. Particles of almost any size can be inhaled but will reach different parts of the lung, depending on their aerodynamic diameter. Particles greater than 10 μm in diameter cannot reach the alveolar region (the unciliated airways) of the lungs and particles greater than 30 μm will not penetrate the respiratory region past the larynx ([Cherrie et al., 2010](#)). For contamination deposited onto skin, particles greater than 10 μm cannot penetrate the skin, particles of 3–10 μm may reach deeper layers of the skin through the hair follicles but particles less than 3 μm can diffuse through the stratum corneum to be incorporated into the body's blood supply ([Shekunov et al., 2007](#); [Williams, 2003](#)). These smaller particles (< 3 μm) are therefore of high exposure risk as they cannot be safely removed if they have penetrated through the skin. As particle size determines the fate of particles on/in the human body which thus affects a person's exposure risk, it is necessary to fully understand the size distribution of resuspended aerosol particles when determining secondary exposure.

For a surface-residing particle to be resuspended, the lift forces acting on the particle must exceed the forces of attraction between the particle and its residing surface ([Hinds, 1999](#)). Particle size affects the forces acting on a particle, as the larger the diameter of the particle, the greater the particle surface area which is in contact with the residing surface and hence a greater lift force is applied to the larger particle. The 'effective area' is the area of contact between the particle and the surface on which lift forces can act ([Nicholson, 2009](#)). Increasing sizes of a particular species of particle will have an increase on the particles' effective area and hence, the potential for resuspension is likely to increase with increasing particle size. This will be the case until particle size reaches a threshold diameter at which point the gravitational force will be the dominant force and particles will be restricted from resuspending fully ([Hu et al., accessed February 2014](#)). This threshold diameter below which particles can be fully resuspended into the atmosphere (at normal wind speeds) is at approximately 100 μm ([Nicholson, 2009](#)).

Earlier studies have reported a particle size dependency of resuspended material observed indoors during human activity. [Ferro et al. \(2004\)](#) found that, of the volume of resuspended house dust in a home due to human activity, most of the resuspended particle mass was > 5 μm and submicron particles accounted for less than 1% of the indoor total suspended particle (TSP) volume. This agrees with the findings of [Thatcher and Layton \(1995\)](#) who concluded that with normal physical activity in a family home, resuspension rate increased with increasing particle size (for a particle size range of 0.3–25+ μm). [Abt et al. \(2000\)](#) concluded that particle emission rates significantly increased (for 0.7–10 μm particles) with increasing particle size during cleaning and indoor work, due to the resuspension of particles greater than 1 μm . However these studies all quantified the resuspension of particles due to human physical activity based on a general change in airborne particle concentration, which was assumed to be due to resuspension, but was primarily from floors, and not specifically from a contaminated person's clothing. Furthermore, these studies do not include a comparison of the size distributions of tracer particles during deposition to that during resuspension. Although [Andersson et al. \(2004\)](#) do compare the deposited and resuspended size distributions of 0.7 and 2.5 μm , indium and dysprosium labelled particles, as with previously cited papers, the particles were resuspended due to vacuuming the floors in a contaminated room and not from a contaminated person's clothing.

The aim of the present work is to quantify the size distribution of particles which resuspend from clothing surfaces during human physical activity and to compare the resuspended particle size distribution to the size distribution of the originally deposited particles.

2. Materials and methods

A full description of the materials and methods for this work is given in detail in [McDonagh and Byrne \(2014\)](#), but is summarised as follows.

Silica particles of 3, 5 and 10 μm in diameter were respectively labelled with the rare earth metals Europium (EuCl_3), Dysprosium (DyCl_3) and Indium (InCl_3). The three particle sizes were mixed together and collectively aerosolised within a 2.25 m^3 aluminium deposition chamber, using a dry powder particle generator (Palas RBG-1000) and an array of 12 \times 33 KBq Am241 radioactive sources, to neutralise any charge acquired by the particles during generation. The particles were allowed to deposit onto clothing samples located on the chamber floor. The clothing types included cotton, polyester, fleece

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