



UNIVERSITY OF LEEDS

This is a repository copy of *A study of the size distribution of aerosol particles resuspended from clothing surfaces*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/79028/>

Version: Accepted Version

Article:

McDonagh, A and Byrne, MA (2014) A study of the size distribution of aerosol particles resuspended from clothing surfaces. *Journal of Aerosol Science*, 75. 94 - 103 (10). ISSN 0021-8502

<https://doi.org/10.1016/j.jaerosci.2014.05.007>

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

A Study of the Size Distribution of Aerosol Particles

Resuspended from Clothing Surfaces

A. McDonagh^{a,*} and M. A. Byrne^a

^a School of Physics and C-CAPS, The Ryan Institute,
National University of Ireland Galway (NUIG), Galway, Co. Galway, Ireland.

***Corresponding author details:**

Name: Dr Ann McDonagh

Present address: Pathogen Control Engineering (PaCE) Institute, School of Civil Engineering,
University of Leeds, Leeds LS2 9JT, United Kingdom.

Telephone: +44 (0) 113 343 1957

Fax: +44 (0) 113 343 2265

Email: mcdonagh.ann@gmail.com; A.McDonagh@leeds.ac.uk

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.

Keywords

Resuspension; Human physical activity; Clothing; Hazardous aerosol particles; Size distribution; Shedding.

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. 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 and 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 and 2005), 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 and Williams, 2003). These smaller particles ($< 3 \mu\text{m}$) 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 $> 5 \mu\text{m}$ 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 $0.3 - 25+ \mu\text{m}$). Abt et al. (2000) concluded that particle emission rates significantly increased (for $0.7 - 10 \mu\text{m}$ particles) with increasing particle size during cleaning and indoor work, due to the resuspension of particles greater than $1 \mu\text{m}$. 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) does compare the deposited and resuspended size distributions of 0.7 and $2.5 \mu\text{m}$, 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 x 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 and denim (the significance of the clothing type on particle resuspension is discussed in McDonagh and Byrne (2014)). Large contaminated samples of the clothing were attached to a volunteer on the chest (20 x 20 cm, located centrally on the upper chest), arms (15 x 30 cm, located on the outer arm, mid-way between the shoulder and wrist) and legs (25 x 40 cm, wrapped around each lower leg, thus covering almost all of the lower legs - front and back - between the knee and ankle). The large samples each had two smaller samples of the same material type pinned onto them and those smaller samples (ranging from 1 x 4 cm to 2 x 5 cm, depending on the material type) were removed for analysis, one each before and after the resuspension event, to determine the proportion of the deposited mass which became resuspended – the Resuspended Fraction (RF).

The volunteer wore a clean room suit (Macrobond hooded coverall from Caulfield Industrial) - chosen for its non-linting and anti-static properties, booties (Polylatex shoecover 4 g from Caulfield Industrial), gloves (powder free purple nitrile) and a mask (8835 FFP3D disposable mask from Anderco Safety). The volunteer had the contaminated clothing attached to them by

an assistant and entered the resuspension chamber - a purpose-built 15 m³ plywood test room. The volunteer engaged in one of two pre-defined physical activities: Low physical activity - walking at a pre-defined rate for 20 minutes, or high physical activity – Irish dancing to a Reel (Wikipedia, accessed Feb 2014) with added swinging of the arms for 10 minutes (chosen to facilitate the accurate reproduction of movement in each repeated experiment). The sampling equipment inside the chamber included: two Aerodynamic Particle Sizer's (APS)'s, one at ankle height (15 cm from the floor) and the other at waist height (90 cm from the floor), located approximately 30 cm from the physically-active contaminated person; two active open-face filters (at 5 L/min), one at ankle height (15 cm from the floor) and the second at head height (150 cm from the floor), located 75 cm from the source; three passive filters fixed to the chamber wall at ankle, waist and head height, located 120 cm from the source. The filter papers used in each case were Whatman 542 hardened ashless filter papers of 55 mm diameter, chosen because of their suitability for Neutron Activation Analysis (NAA). In the centre of the chamber floor was a grounded metal plate upon which the volunteer stood while performing the experiment. This was to ensure that any static charge generated by the movement of the volunteers' feet, would not influence the behaviour of the resuspended particles.

Three analysis techniques were used. The air within the deposition and resuspension chambers was continuously monitored using Aerodynamic Particle Sizer's (APS) [Model 3321 by Trust Science Innovation (TSI)]. The APS measures the concentration and size of airborne particles in the range of 0.5 to 20 µm in aerodynamic diameter, in real time. The second analysis technique employed was Neutron Activation Analysis (NAA). This allows for the specific detection of the three labelled particles on the clothing material or filter, with a detection limit of ~ 1 pg. The third was Scanning Electron Microscopy (SEM) imagery, which was employed

to visually confirm that the particles deposited onto the clothing surface in a monolayer and to assess the penetration of the particles into the weave of the clothing materials.

3 Results and Discussion

3.1 Comparison of the size distributions of deposited and resuspended particles

Following the experimental procedure as described in section 2, all three particle sizes were mixed together and collectively deposited on to the clothing samples. An APS sampled the chamber air every second during both deposition of the particles onto the clothing samples and resuspension of the particles from the clothing samples.

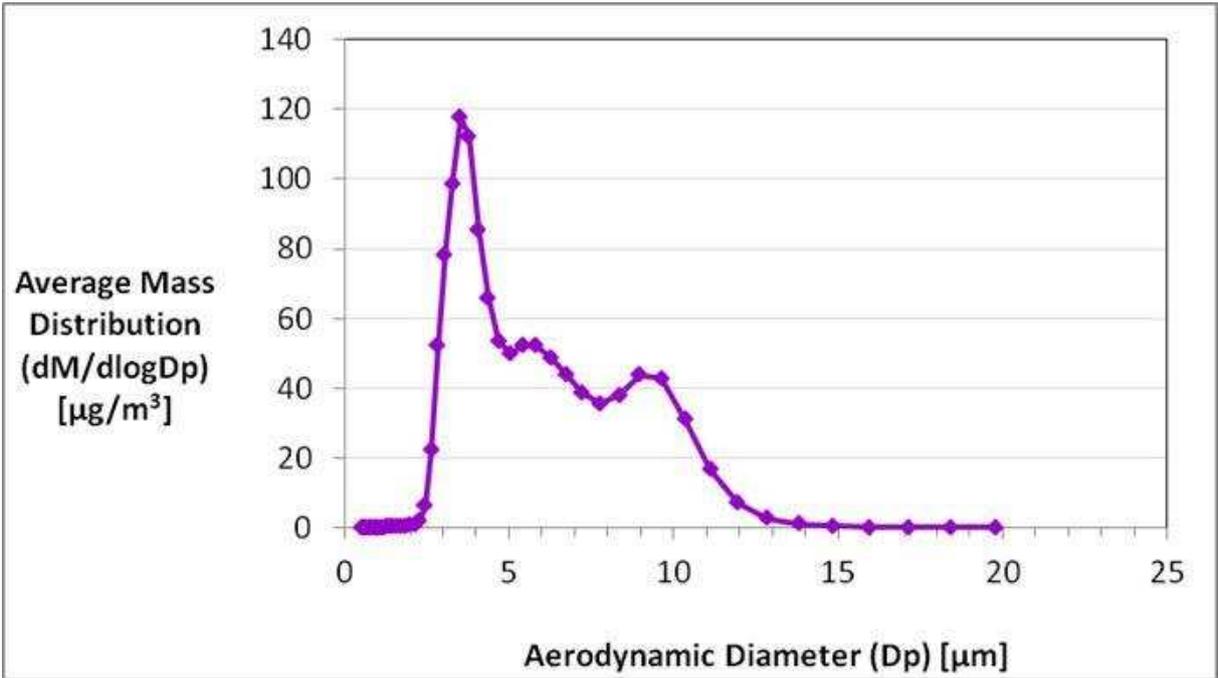


Figure 1. Average mass distribution of airborne particles in deposition chamber during deposition

Figure 1 shows the average airborne particle distribution, in terms of mass, as a function of particle diameter, as seen by an APS in the deposition chamber during deposition of all three particle sizes mixed together. It is clear that there is a mode at approximately 3, 5 and 10 µm.

Although the particles injected into the chamber are monodisperse, they each have a size distribution about their Mass Median Aerodynamic Diameter (MMAD) of approximately 3, 5 and 10 μm . These individual distributions overlap but their peak is evident and the remainder of their distributions can be estimated; this will be discussed further in section 3.1.2. For the remainder of this paper, when discussing particle size, the three individual size distributions will be referred to by their concentration peak (or MMAD) of approximately 3, 5 or 10 μm .

Figure 1 indicates that there were considerably more 3 μm sized particles in the deposition chamber than 5 or 10 μm . This may be due to the method used to mix the three particle sizes together before loading into the generator; the three powder samples were simply poured into a mixing container in similar quantities by eye. If the amount by volume of each particle size added was similar, there would be more of the smaller particles than larger particles in the same volume of particles. Any difference in the number of each particle size deposited is not significant, as the resuspended fraction is based on the quantity resuspended as a function of the quantity deposited.

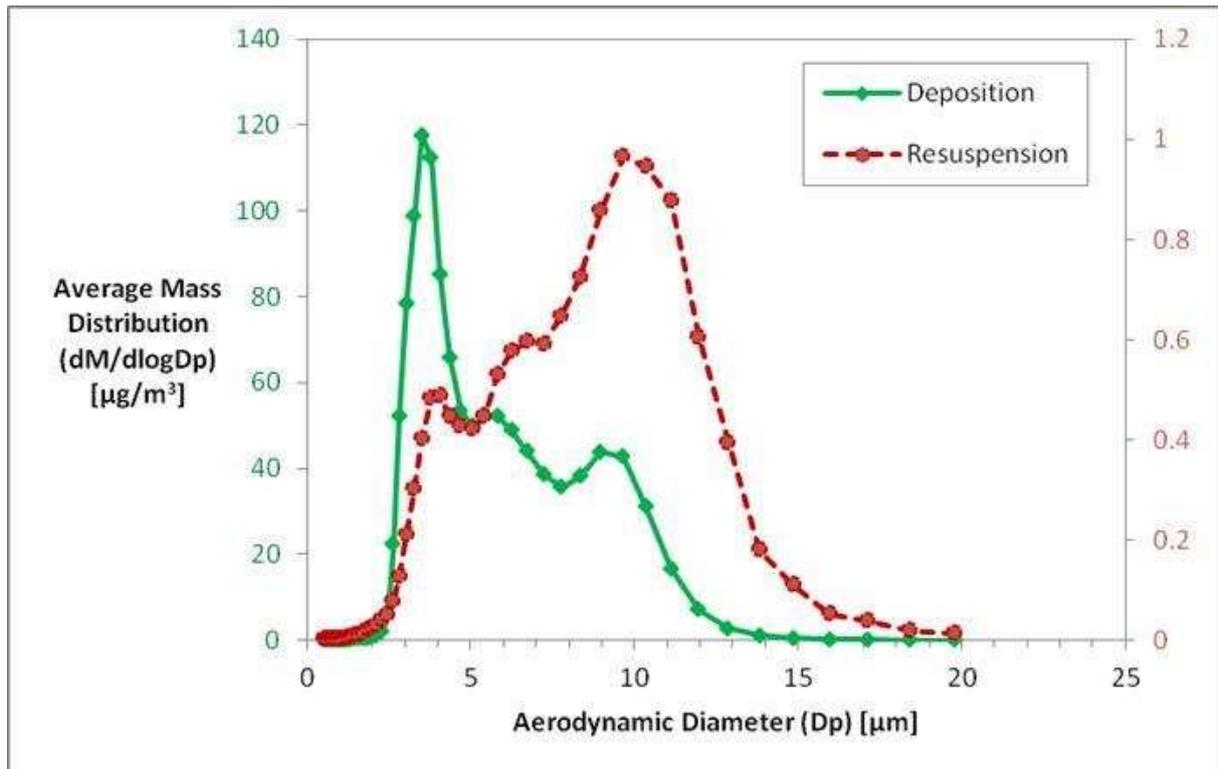


Figure 2. Size distribution of airborne particles in deposition and resuspension chambers to/from denim

When the size distributions of deposited and resuspended particles are compared, as shown in figure 2, two major differences can be observed. Firstly, the general shape of the size distribution curves for deposited and resuspended particles is markedly different (for all three sized particles mixed together). Secondly, the MMAD of each of the three individual size distributions changes when the deposited particles became resuspended. These differences will be discussed in the next sub-sections.

3.1.1 Change in shape of size distribution curve between deposition and resuspension

In this section, the difference in the general shape of the size distribution curve, between the deposition and resuspension events is examined. For the purposes of this discussion, the resuspension data chosen derives from the case of APS samples taken at waist level during resuspension from denim and under high physical activity conditions.

Figure 2 shows the particle mass distribution, as a function of size, during deposition (primary y-axis) and resuspension (secondary y-axis). There is a difference of approximately two orders of magnitude between the cumulative mass concentration of particles deposited ($1204.98 \mu\text{g m}^{-3}$) and resuspended ($12.84 \mu\text{g m}^{-3}$). This is expected as one would assume that not all deposited particles will resuspend and be detected by the APS. The most significant result from these data is that there is a higher concentration of larger sized particles airborne during resuspension than during deposition. The size distribution curve during deposition (in green) shows its highest mass concentration at approximately $3 \mu\text{m}$, with a second smaller peak approximately $5 \mu\text{m}$ and the smallest peak at approximately $10 \mu\text{m}$. These data are summarised in table 1. This illustrates that there are more small particles deposited to the denim than there are large particles, in terms of both mass and number concentrations. Conversely, the $3 \mu\text{m}$ mass concentration peak on the resuspension curve (shown in red) is the smallest, the second peak is at approximately $5 \mu\text{m}$ and the third and largest peak occurs at approximately $10 \mu\text{m}$. This indicates that more of the larger particles have resuspended from denim than the small particles, even though there were more of the smaller particles available for resuspension. However, in terms of number concentration during resuspension, the largest peak occurs at approximately $3 \mu\text{m}$ and the smallest at $10 \mu\text{m}$, which shows an opposite trend to the mass concentration data. However, it is the change in concentration during deposition relative to during resuspension which is important i.e. how many of those particles of a particular size which were available for resuspension, actually resuspended. This value is the same whether one considers the mass or number concentration data, as can be seen in table 1.

	Peak concentration about each distribution:					
	3 μm		5 μm		10 μm	
	Deposition	Resuspension	Deposition	Resuspension	Deposition	Resuspension
Mass Conc. ($\mu\text{g m}^{-3}$)	117.7	0.489	52.41	0.596	43.77	0.965
Number Conc. (# cm^{-3})	8290	34.4	800.8	9.11	83.59	1.84
Percentage change in conc.	- 99.6 %		- 98.8 %		- 97.8 %	

Table 1. Peak concentration in terms of number and mass, about each of the three size distributions, within the overall deposition and resuspension size distributions

The percentage difference in airborne mass concentration between deposition and resuspension, at each of the three particle sizes, is a percentage decrease in each case, as the overall mass concentration during deposition is approximately 100 times greater than during resuspension. This verifies that more of the larger sized particles are resuspending than are the smaller particles, when comparing the size distribution curve during resuspension to that during deposition.

While the authors of this paper have not found published papers directly comparing size distributions of deposited and resuspended particles from clothing due to human physical activity, Raunemaa et al. (1989) noted that there is a difference between the particle size distribution for deposition and re-emission and that the shift in size is towards the larger sizes. Furthermore, the conclusion that larger particles are easier to resuspend has been widely observed both theoretically and experimentally. Thatcher and Layton (1995) examined the increase in particle concentration indoors during various human activities, for four different particle size ranges. They concluded that particles between 0.5 and 1 μm in diameter were essentially non-resuspendable, whereas particles between 10 and 25 μm showed approximately a 6-fold increase in airborne particle concentration above background levels, with 2 minutes of continuous walking and sitting by one person in the living area of a house.

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 . Andersson et al. (2004) investigated the resuspension of particles from 0.4 to 7 μm from various surfaces (wood, plastic and wool), by dropping a weight onto the contaminated surface. They found that in the case of all three surfaces, there is a shift towards a larger count median diameter for the resuspended particles relative to the deposited particles. While the findings of these papers agree with the findings reported in the current work, these studies were quantifying the resuspension of particles based on a general change in airborne particle concentration, which was assumed to be due to resuspension but primarily from floors, and not specifically from a physically active contaminated person's clothing.

3.1.2 Mass Median Aerodynamic Diameter (MMAD) shift between deposition and resuspension, for each size spectrum

The Mass Median Aerodynamic Diameter (MMAD) for each particle distribution, during deposition and resuspension is summarised in table 2. The data are averaged over all material types and for airborne mass concentrations as measured during high physical activity.

	Median particle diameter (in μm) of each distribution:					
	3 μm		5 μm		10 μm	
	Deposition	Resuspension	Deposition	Resuspension	Deposition	Resuspension
MMAD	3.52	4.00	5.43	6.50	8.98	9.83
Percentage change in MMAD	+ 0.12 %		+ 0.16 %		+ 0.09 %	

Table 2. Mass Median Aerodynamic Diameter (MMAD) of each of the three particle size distributions, during both deposition and resuspension

As can be seen from table 2, for each of the three size distributions, for both mass and number concentrations, the MMAD of particles resuspended is greater than that of particles deposited. Figure 3 is a graphical representation of the mass concentration data from table 2 and confirms the findings in section 3.1.1; that the amount of particles resuspended increases with increasing particle size, and within the distribution of deposited particles of a particular size, the peak size of particles resuspended shifts slightly to the right or to a larger diameter, in comparison to the peak size of those deposited. So within a distribution, the larger particles resuspend more and thus the MMAD of the distribution is higher. This statement can be confirmed by separating the size distribution curves for each of the three particle sizes and forecasting their curve to complete the distributions from where the three curves overlap. This is done in figure 4, where the distribution for the 3 μm is separated from the full distribution and therefore its final point (before the distribution overlaps with the distribution about 5 μm) is at $\sim 4.1 \mu\text{m}$. The curve is then forecast forward to complete its estimated distribution. The curve is forecast using the knowledge that monodisperse airborne particles of this size range and generated by this method, are generally expected to follow a Gaussian distribution (Colbeck, 1998). Using the known portion of the distribution about the 3 μm peak, the remainder is estimated by hand, using a Gaussian curve with a sigma (standard deviation) of 1 (as this provided the best fit to the data) and is represented graphically in figure 4.

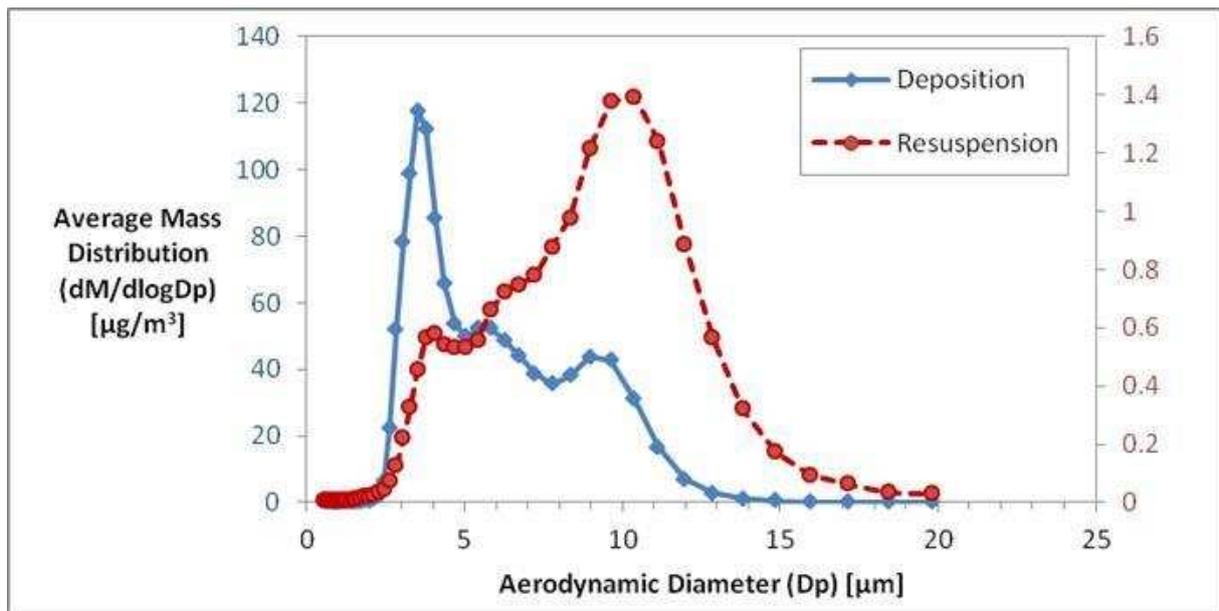


Figure 3. Average size distribution of airborne particles during deposition and resuspension at high physical activity

Figure 4 shows that the resuspension curve has shifted to the right in comparison to the deposition curve. This confirms that the mean particle diameter of resuspended particles was greater than that of the deposited particles, which implies that, of the deposited particles, those with a larger diameter were more likely to resuspend.

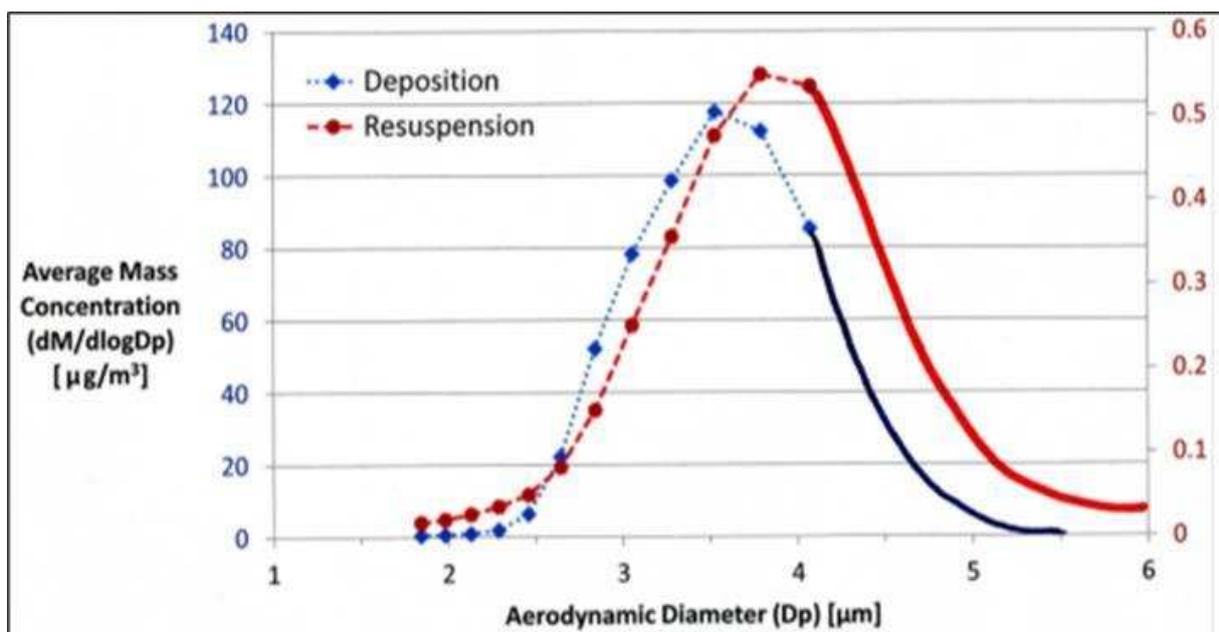


Figure 4. Forecast size distribution of airborne particles in deposition and resuspension chambers, to/from cotton (focus on 3 µm)

A shift in MMAD was also noted by Andersson et al. (2004) who examined the mean diameter of tracer particles released into a test room and compared it to the mean diameter of those deposited particles which became airborne after the room surfaces were agitated with a filter-less vacuum cleaner. Andersson et al. (2004) released tracer particles with two different size distributions and compared their mean diameter before and after resuspension events. Andersson concluded that the particle distribution with a mean diameter of 0.7 μm before agitation had a mean diameter of 2.8 μm after agitation, which occurred 24 hours after the deposition. However the particle distribution with a mean diameter of 2.5 μm before agitation showed no significant change in size distribution after any of the resuspension events. In contrast, the results presented in this paper show an increase in the MMAD following resuspension for all three particle sizes examined (3, 5 and 10 μm).

The greater tendency for large particles to resuspend than smaller particles, as evidenced in the current work, can be explained by examining the forces acting on a surface-residing particle. It has been extensively studied and generally understood that the magnitude of adhesive forces is directly proportional to the first power of particle diameter, but removal forces are proportional to the second (gravitational, vibrational and centrifugal forces) or third power (air currents) of diameter (Hinds, 1999). Thus particles of increasing size are easier to resuspend from a surface. The knowledge that particles with large diameters are more likely to resuspend, has implications for estimating the impact on a persons' exposure to hazardous particles. In terms of inhalation exposure, less than 2 % of large particles (> 10 μm) will pass the nose and upper airways of the lungs and thus it can be concluded that as resuspended particles are of a relatively large size, their significance for respiratory exposure is less than by other exposure routes (Byrne, 2009). Also larger particles (> 3 μm) are less likely to penetrate a person's skin and thus will not be readily absorbed into the body (Shekunov et al., 2007).

3.2 Relationship between particle size and the Resuspended Fraction (RF)

The purpose of this section is to examine the resuspended fraction (RF) data for each particle size, at low and high physical activity levels. The data are averaged over all material types and body locations. Low physical activity consisted of walking for 20 minutes and high physical activity was representative of running and simulated by modified Irish dancing to an Irish Reel for 10 minutes, as described in section 2.

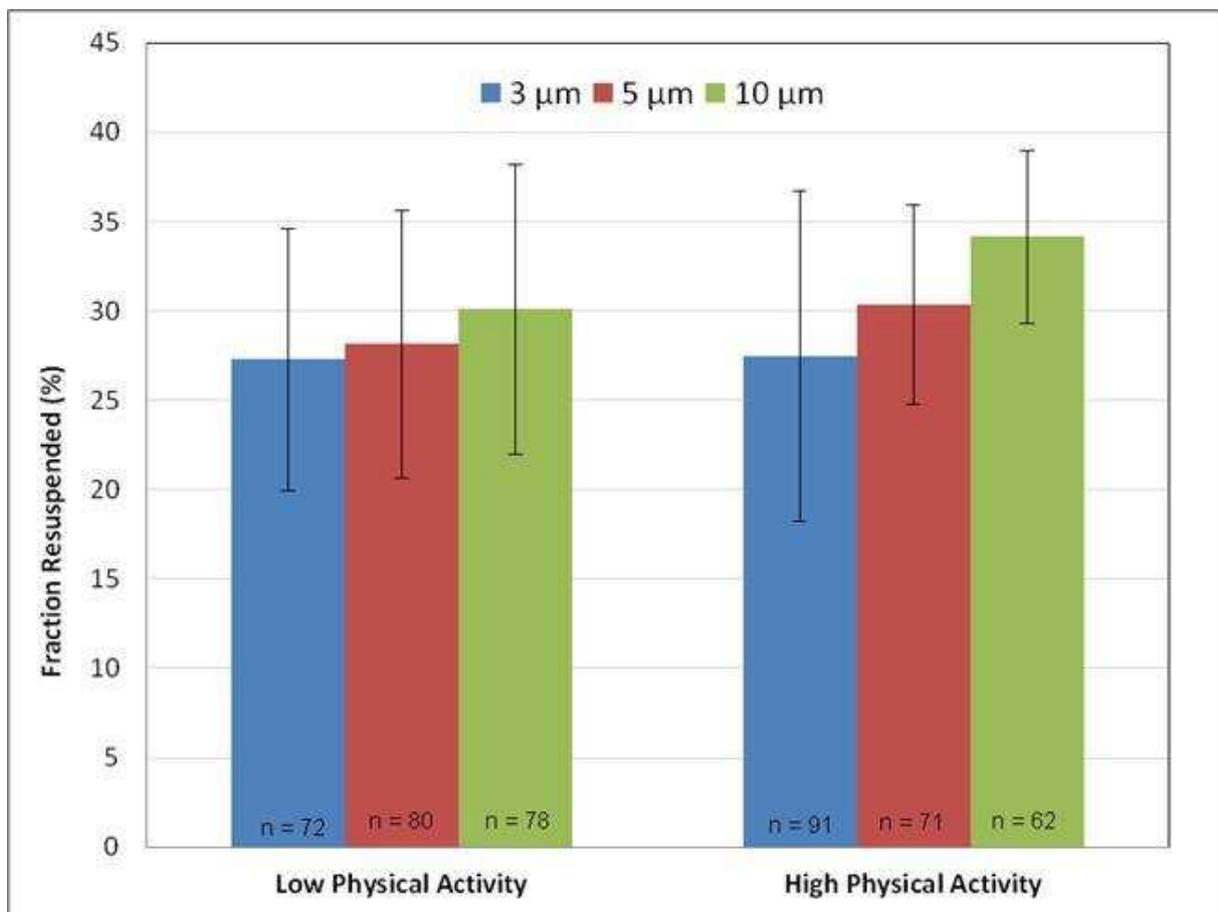


Figure 5. Percentage of the original deposit which has resuspended from all surface types, at low and high physical activity. The number of separate experimental values that were averaged is indicated on each bar. The error bars indicate one standard deviation above and below the average value in each data set.

Figure 5 shows the fraction of each particle size which becomes resuspended due to low and high physical activity. The height of the bars indicates the fraction of originally deposited particles of a specific size which have been resuspended. These data show that the fraction of

particles which become resuspended from the clothing of a person engaged in low physical activity, ranges from 8 to 52 % and with an average RF across all sized particles of 28 ± 8 %. The average RF from all body locations and material types for the 3 μm particles is 27 ± 7 %. For the 5 μm particles is 28 ± 7 % and for particles of 10 μm in size, an average of 30 ± 8 % of the originally deposited particles have resuspended.

During high physical activity, between 3 and 67 % of particles formerly deposited on various clothing types was found to resuspend, with an average RF value across all particle sizes of 30 ± 7 %. On average, 27 ± 9 % of 3 μm particles, 30 ± 6 % of 5 μm particles and 34 ± 5 % of 10 μm particles resuspended. As with the low physical activity, these data suggest that the fraction of particles resuspended increases as particle size increases. However, statistically analysing the data using a two-tailed t-test for samples of equal variance indicates that the differences in the RF between sizes for each physical activity level is not significant for $p = 0.05$. This apparent lack of difference in RF between the three sized particles is only seen on the samples analysed by NAA (figure 5) however, analysing the airborne mass concentration of particles in the air surrounding a person engaging in high physical activity as measured by an APS (figures 2 and 3), shows there is a significant difference in the distributions about each particle size, for a significance level of 0.05. This apparent contradiction is due to the capturing of different features of the resuspension process by the two different analytical techniques, as discussed below.

The APS data shows the airborne mass concentration as a function of particle size and thus measures all particles that are airborne, regardless of their origin. NAA data are used to determine the resuspended fraction (RF), which is calculated by measuring the difference in mass concentration of particles deposited on the material sample before and remaining on the material sample after the period of resuspension, as a percentage of the mass concentration

deposited on the material sample before resuspension. Hence the concentration of particles remaining on a sample after resuspension is the key variable in determining the RF from that sample. However, this value may be higher than expected due to an unquantified number of particles remaining on that sample after the resuspension event, caused mainly by three processes. The processes are discussed in detail in McDonagh and Byrne (2014) and are: 1. Impaction of resuspended particles back onto the material sample, as it passes through the particle laden air stream. 2. Enhanced deposition due to both increased air velocities around the moving person and the rate of displacements of the body parts (and hence the material samples) themselves. 3. Penetration of resuspended particles deep into the weave of the material. Because of the particles' increased velocities when they redeposit, they will have an increased kinetic energy and hence may penetrate deeper into the weave pattern of the material and therefore be more difficult to re-resuspend.

As a consequence of the above three events occurring during resuspension, the mass of particles calculated to be on the clothing sample after the period of resuspension may be higher than would be the case if all particles which initially resuspended were removed and not available to re-deposit. Therefore a lower RF than is actually the case is calculated but it should be noted that this RF is representative of a real-life scenario where impaction and secondary resuspension would be continuously occurring.

3.3 Relationship between particle size and the height reached by resuspended particles

Figures 6 and 7 show the concentration of each element – Europium (Eu), Dysprosium (Dy) and Indium (In) – detected by NAA, on filters placed at specific heights from the

resuspension chamber floor. It is the average concentration over all material types and physical activity levels, on passive and active filters. The concentration values are in units of $\mu\text{g kg}^{-1}$ which is the mass of the element detected in micro-grams divided by the mass of the sample (filter paper plus particles) in kilograms i.e. the concentration in parts per billion. This ensures that any difference in the size (and hence mass) of the samples is taken into account. The Eu, Dy and In are labels chemically bonded onto particles of diameter 3, 5 and 10 μm respectively and hence the mass of the element detected on the filter paper, is representative of the mass of that sized particle on the filter paper.

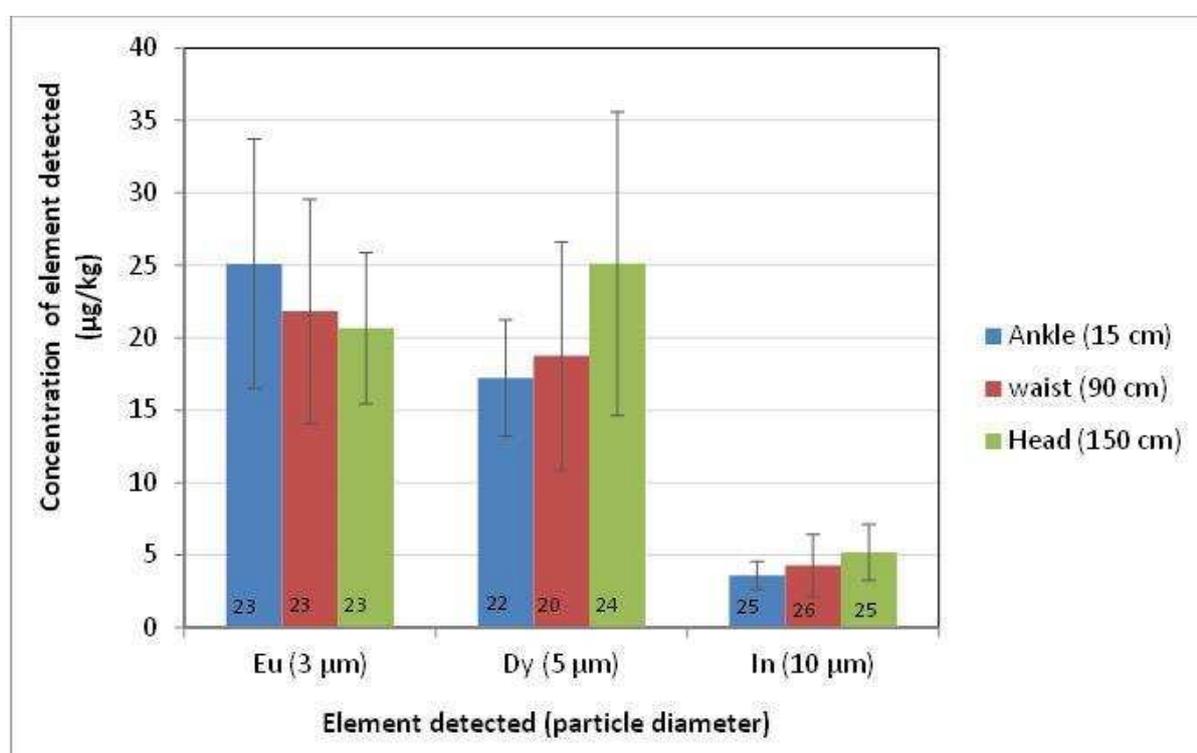


Figure 6. Concentration of 3, 5 and 10 μm particles as detected on Passive filters at various heights, from all material types and physical activity levels. The value shown at the bottom of each bar indicates the number of experimental values averaged. The error bars show one standard deviation above and below the average value.

Figure 6 shows the concentration of each element (and thus mass concentration of each particle size) detected on the passive filters at ankle (15 cm from the floor), waist (at 90 cm) and head height (at 150 cm). By examining the distribution of 3 μm sized particles, across the

three passive filter heights, it can be observed that the mass concentration of the particles captured decreases as the filter height above the ground increases, with an $18 \pm 5 \%$ decrease in the mass of resuspended $3 \mu\text{m}$ particles between filters at ankle and head height.

A different trend is observed for the larger particles. Specifically for $5 \mu\text{m}$ and $10 \mu\text{m}$ particles; as the filter height above the ground increases, the mass concentration of particles captured also increases, with $46 \pm 15 \%$ increase in the mass of resuspended particles between ankle and head height for particles of $5 \mu\text{m}$ and a corresponding increase of $44 \pm 14 \%$ for $10 \mu\text{m}$.

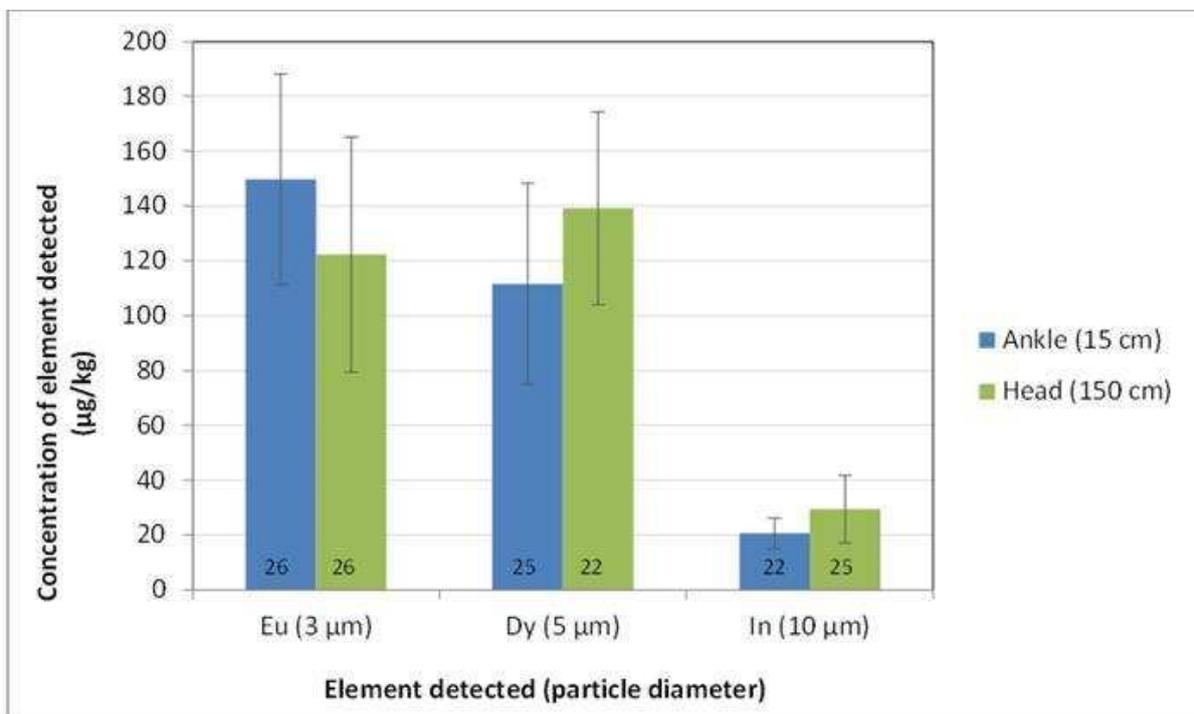


Figure 7. Concentration of 3, 5 and $10 \mu\text{m}$ particles as detected on Active filters at various heights, from all material types and physical activity levels. The number at the bottom of each bar indicates the number of experimental values averaged. The error bars show one standard deviation above and below the average value.

Figure 7 shows the concentration of each element (and thus mass concentration of each sized particle) detected on the active filters at ankle and head height. For the $3 \mu\text{m}$ particles, as the filter height above the ground increases, the mass concentration of particles captured

decreases, with an 18 ± 5 % decrease in the mass of resuspended $3 \mu\text{m}$ particles which deposited onto filters at ankle and head height. However, for 5 and $10 \mu\text{m}$ particles; as the filter height above the ground increases, the mass concentration of particles captured increases, with a 25 ± 7 % and 43 ± 14 % increase in the mass of resuspended particles between ankle and head height for particles of 5 and $10 \mu\text{m}$, respectively.

In summary, there are less $3 \mu\text{m}$ particles at head than at ankle height but the opposite is true for particles of 5 and $10 \mu\text{m}$ in diameter where a higher concentration is seen at head height. This may be due to larger particles being subjected to greater lift forces from their residing surface (Hinds, 1999) due to their larger effective area and thus being resuspended higher into the air. Therefore the larger particles will be captured by the higher filters before they deposit to the chamber floor. Correspondingly, the smaller particle size of $3 \mu\text{m}$ will be subjected to a smaller lift force and will therefore fall to the lower filter for capture. This phenomenon might not have been seen if the filters were located further from the source of the particles as, once they have been resuspended from the source, the larger particles would deposit to the ground quickly due to their large mass and therefore not reach the head height filters if they were located further from the source.

While there were far more particles (a 6.5 fold difference) captured by the active filters ($286.5 \mu\text{g kg}^{-1}$) than by the passive filters ($44.3 \mu\text{g kg}^{-1}$), the percentage change in particle concentration between ankle and head height is almost identical for the 3 and $10 \mu\text{m}$ particles, regardless of filter capture type. Between the ankle and head regions, there is an 18 ± 5 % decrease in the concentration of $3 \mu\text{m}$ particles for both passive and active filters, with a 44 ± 14 % and 43 ± 14 % increase in the case of $10 \mu\text{m}$ particles on passive and active filters respectively. For the $5 \mu\text{m}$ particles both filter types show a percentage increase in particle concentration between the ankle and head heights. While these percentage differences have

values of $+ 46 \pm 15 \%$ on passive filters and $+ 25 \pm 7 \%$ on active filters, they are not significantly different (according to a t-test).

This observation of an increase in the concentration of larger particles at head height relative to other locations has implications for the potential inhalation exposure resulting from resuspended hazardous particles, as particles with a diameter of $10 \mu\text{m}$ or greater are less likely ($< 2 \%$) to penetrate to the lower airways of the lungs. Also, if the smaller sized resuspended particles - which are more hazardous in terms of inhalation exposure - are found in higher concentrations at ankle height, they are likely to deposit to the ground and thus could be more easily removed from the environment by cleaning etc. They therefore do not pose a major threat for increased inhalation exposure. In summary these results indicate that; while resuspension will significantly increase airborne particle concentrations, which has implications for general exposure risk, current findings regarding the size of the resuspended particles and the height that the various sizes can reach indicates that resuspended material has a lesser consequence in respect of inhalation exposure, than it has by other routes.

4 Conclusions

When the size distributions of deposited and resuspended particles were compared, two major differences were observed. Firstly, the general shape of the size distribution curves for deposited and resuspended particles was markedly different (for all three sized particles mixed together). There was a difference of approximately two orders of magnitude between the concentration of particles deposited and resuspended. Also, more of the larger sized particles resuspended than did smaller particles, following comparison of the size distribution curve during resuspension to that during deposition.

Secondly, the Mass Median Aerodynamic Diameter (MMAD) of each of the three individual size distributions changed when the deposited particles became resuspended. The peak size of particles resuspended shifted slightly to the right or to a larger diameter, in comparison to the peak size of those deposited. Furthermore, the entire resuspension curve shifted to the right in comparison to the deposition curve. This confirms that the mean particle diameter of resuspended particles was greater than that of the deposited particles, which implies that, of the deposited particles, those with a larger diameter were more likely to resuspend.

The fraction of deposited particles which resuspended (the resuspended fraction (RF)) from a person's clothing was examined for two different physical activity levels. The RF from the clothing of a person engaged in low physical activity, ranged from 8 to 52 % and with an average RF across all sized particles of 28 ± 8 %. During high physical activity, between 3 and 67 % of particles formerly deposited on various clothing types was found to resuspend, with an average value across all particle sizes of 30 ± 7 %. These percentages are significant in terms of the transport of hazardous aerosol particles in the environment and hence resuspension from contaminated clothing is potentially a large source of secondary exposure to humans.

The relationship between particle size and the height reached by resuspended particles was also examined, as this can have an effect on the type and severity of a person's exposure. By examining the distribution of 3 μm sized particles, across the three filter heights (ankle, waist and head), it was observed that the mass concentration of the particles captured decreased as the filter height above the ground increased, with an 18 ± 5 % decrease in the mass of resuspended 3 μm particles between filters at ankle and head height. The opposite trend was observed for the larger 5 μm and 10 μm particles; as the filter height above the ground increased, the mass concentration of particles captured also increased. For particles of 5 μm , a

46 ± 15 % increase in the mass of resuspended particles between ankle and head height was observed on passive filters and a corresponding increase of 44 ± 14 % for $10 \mu\text{m}$ particles. Further studies could repeat these experiments but with the sampling locations at varied distances from the source, to examine if filters at a greater distance would exhibit the same trends as revealed here.

In conclusion, the generally accepted theory that larger particles are more likely to resuspend, has been confirmed in this study. The extent of which formerly deposited particles will resuspend from a person's clothing during physical activity, has been quantified for three specific particle sizes, 3, 5 and $10 \mu\text{m}$. Future work could extend the scope of this study by including submicron sized particles, as this category of particles are prevalent in many different types of exposure scenarios (e.g., virion transmission, large nuclear power plant accidents or malicious release via radioactive dispersion device's), and these particles may be more readily incorporated in the human body following exposure.

5 Acknowledgements

This work has been sponsored by the Radiological Protection Institute of Ireland (RPII) and supported by the European Commission under the 7th Framework Programme through the 'Research Infrastructures' action of the 'Capacities' Programme, Contract No: CP-CSA_INFRA-2008-1.1.1 Number 226507-NMI3. Support was also received from The Aerosol Society in the form of a research scholarship: The C.N. Davies award.

6 References

Abt, E., Suh, H. H., Catalano, P., & Koutrakis, P. (2000). Relative Contribution of Outdoor and Indoor Particle Sources to Indoor Concentrations. *Environmental Science & Technology*, 34(17), 3579-3587.

Andersson, K. G., Fogh, C. L., Byrne, M. A., Roed, J., Goddard, A. J. H., & Hotchkiss, S. A. M. (2002). Radiation Dose Implications of Airborne Contaminant Deposition to Humans. *Health Physics*, 82(2), 226-232.

Andersson, K. G., Roed, J., Byrne, M. A., Hession, H., Clark, P., & Elahi, E., et al. (2004). Airborne contamination in the indoor environment and its implications for dose. Riso National Laboratory, Roskilde; April 2004. Riso-R-1462(EN). Contract No.: FIKR-CT-2000-00043. ISSN: 0106-2840. ISBN: 87-550-3318-0 (internet).

Byrne, M. A. (2009). Airborne contamination inside dwellings. In: Andersson, K. G. Airborne radioactive contamination in inhabited areas. Elsevier B.V. ISSN: 1569-4860. DOI: 10.1016/S1569-4860(09)00403-3.

Byrne, M. A. (1995). An experimental study of the deposition of aerosol on indoor surfaces [Ph.D. thesis]. Imperial College of Science, Technology and Medicine, London, SW7 2BP, UK.

Cherrie, J., Howie, R., & Semple, S. (2010). Monitoring for health hazards at work. (4th edition). Wiley-Blackwell. ISBN 978-1-4051-5962-3.

Colbeck, I. (1998). Physical and Chemical Properties of Aersols. Blackie Academic & Professional, an imprint of Thomson Science. ISBN: 0-7514-0402-0.

Ferro, A. R., Kopperud, R. J., & Hildemann, L. M. (2004). Source Strengths for Indoor Human Activities that Resuspend Particulate Matter. *Environmental Science & Technology*, 38(6), 1759-1764.

Fogh, C. L., Byrne, M. A., Andersson, K. G., Bell, K. F., Roed, J., & Goddard, A. J. H., et al. (1999). Quantitative measurement of aerosol deposition on skin, hair and clothing for dosimetric assessment. Final report. Riso National Laboratory, Roskilde; 1999 June. Riso-r-1075(en). ISSN: 0106-2840. ISBN: 87-550-2360-6.

Hinds, W. C. (1999). *Aerosol Technology: Properties, behaviour, and measurement of airborne particles*. (2nd edition). A Wiley-Interscience Publication. ISBN 0-471-19410-7.

Hu, B., Freihaut, J. D., Bahnfleth, W., Gomes, C. A. S., & Thran, B. Literature review and parametric study: Indoor particle resuspension by human activity. http://www.engr.psu.edu/ae/iec/publications/papers/Lit_Review.pdf (accessed Feb 2014).

Lai, A. C. K., & Nazaroff, W. W. (2000). Modelling indoor particle deposition from turbulent flow onto smooth surfaces. *Journal of Aerosol Science*, 31(4), 463-476.

Lai, A. C. K., & Nazaroff, W. W. (2005). Supermicron particles deposition from turbulent chamber flow onto smooth and rough vertical surfaces. *Atmospheric Environment*, 39(27), 4893-4900.

McDonagh, A. & Byrne, M. A. (2014). The Influence of Human Physical Activity and Contaminated Clothing Type on Particle Resuspension. *Journal of Environmental Radioactivity*, 127, 119–126.

Mustonen, R. (2009). Potential sources of contamination in inhabited areas. In: Andersson, K. G. Airborne radioactive contamination in inhabited areas. Elsevier B.V. ISSN: 1569-4860. DOI: 10.1016/S1569-4860(09)00401-X.

Nicholson, K. W. (2009). The dispersion, deposition and resuspension of atmospheric contamination in the outdoor urban environment. In: Andersson, K. G. Airborne radioactive contamination in inhabited areas. Elsevier B.V. ISSN: 1569-4860. DOI: 10.1016/S1569-4860(09)00402-1.

Raunemaa, T., Kulmala, M., Saari, H., Olin, M., & Kulmala, M. H. (1989). Indoor Air Aerosol Model: Transport Indoors and Deposition of Fine and Coarse Particles. *Aerosol Science and Technology*, 11, 11-25.

Shekunov, B. Y., Chattopadhyay, P., Tong, H., & Chow, A. (2007). Particle Size Analysis in Pharmaceuticals: Principles, Methods and Applications. *Pharmaceutical Research*, 24(2).

Thatcher, T. L., Lai, A. C. K., Moreno-Jackson, R., Sextro, R. G., & Nazaroff, W. W. (2002). Effects of room furnishings and air speed on particle deposition rates indoors. *Atmospheric Environment*, 36(11), 1811-1819.

Thatcher, T. L., & Layton, D. W. (1995). Deposition, resuspension and penetration of particles within a residence. *Atmospheric Environment*, 29(3), 1487-1497.

Wikipedia, [http://en.wikipedia.org/wiki/Reel_\(dance\)](http://en.wikipedia.org/wiki/Reel_(dance)) (accessed February 2014).

Williams, A. C. (2003). *Transdermal and Topical Drug Delivery*. Pharmaceutical Press.