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Inhalability for aerosols at ultra-low windspeeds

Darrah K. Sleeth and James H. Vincent

Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI, 48109, U.S.A.

jhv@umich.edu

Abstract. Most previous experimental studies of aerosol inhalability were conducted in wind tunnels for windspeeds greater than 0.5 ms^{-1} . While that body of work was used to establish a convention for the inhalable fraction, results from studies in calm air chambers (for essentially zero windspeed) are being discussed as the basis of a modified criterion. However, information is lacking for windspeeds in the intermediate range, which – it so happens – pertain to most actual workplaces. With this in mind, we have developed a new experimental system to assess inhalability – and, ultimately, personal sampler performance – for aerosols with particle aerodynamic diameter within the range from about 9 to 90 μm for ultra-low windspeed environments from about 0.1 to 0.5 ms^{-1} . This new system contains an aerosol test facility, fully described elsewhere, that combines the physical attributes and performance characteristics of moving air wind tunnels and calm air chambers, both of which have featured individually in previous research. It also contains a specially-designed breathing, heated, life-sized mannequin that allows for accurate recovery of test particulate material that has been inhaled. Procedures have been developed that employ test aerosols of well-defined particle size distribution generated mechanically from narrowly-graded powders of fused alumina. Using this new system, we have conducted an extensive set of new experiments to measure the inhalability of a human subject (as represented by the mannequin), aimed at filling the current knowledge gap for conditions that are more realistic than those embodied in most previous research. These data reveal that inhalability throughout the range of interest is significantly different based on windspeed, indicating a rise in aspiration efficiency as windspeed decreases. Breathing flowrate and mode of breathing (i.e. nose versus mouth breathing) did not show significant differences for the inhalability of aerosols. On the whole however, the data obtained here are within the range of inhalability data that exist from the large body of the previous experimental work performed at the higher windspeeds. These latest findings are an important contribution to the ongoing discussion in international standards-setting bodies about the possible adjustment of the quantitative definition of what constitutes the inhalable fraction.

1. Introduction

The entry of airborne particles into the noses and mouths of human subjects during breathing is strongly dependent on a number of factors, primarily particle aerodynamic diameter (d_{ae}), defined as the diameter of an equivalent spherical particle of density 10^3 kg/m^3 that has the same falling speed in air as the particle in question, the windspeed (U), orientation of the subject with respect to the wind, and breathing flowrate and pattern. Similar factors are influential in how airborne particles are drawn into aerosol sampling devices. These scenarios and their relevance to human exposures to aerosols in working and living environments have been discussed extensively in the literature[1]. The relationship

between the efficiency of aerosol aspiration during inhalation and the variables mentioned provide the basis of criteria by which to define what has become widely known as the *inhalable fraction*. This fraction provides a quantitative definition of the aerosol that can enter the human body through the nose and/or mouth during breathing, and so becomes a primary ingredient in health-related standards. It is therefore an important yardstick against which the performances of aerosol sampling instruments may be compared.

The development of health-related particle size-selective criteria for occupational aerosol sampling and standards remains of considerable interest to international standards-setting bodies, notably the International Standards Organization (ISO), the Comité Européen de Normalisation (CEN) and the American Conference of Governmental Industrial Hygienists (ACGIH), as well as to national regulatory bodies throughout the world. Previous experiments to characterize the *aspiration efficiency* (A) of the human head were carried out mostly in wind tunnels with windspeeds in excess of 0.5 ms^{-1} , based on the experiments with life-sized, breathing mannequins for orientation with respect to the wind averaged over all possible orientations [2, 3, 4]. Using this body of work from several laboratories, the experimentally-obtained data for aspiration efficiency were used to develop a convention for what has become known as '*inhalability*' (I). In its most general expression it is given by the empirical form [5].

$$I(d_{ae}) = 0.5\{1 + \exp(-0.06d_{ae})\} + f(d_{ae}, U) \quad (1)$$

where the term on the right hand side may be expressed as

$$f(d_{ae}, U) \equiv pU^q \exp(rd_{ae}) \quad (2)$$

in which d_{ae} is in [μm] and the windspeed U is in [ms^{-1}], and where the coefficients $p = 1 \times 10^{-5}$, $q = 2.75$ and $r = 0.055$ for windspeeds in the range $1 \leq U \leq 9 \text{ ms}^{-1}$. Thus it is seen that Equation (1) contains a windspeed dependency for large particle sizes and for higher windspeeds. But for lower windspeeds ($U < 4 \text{ ms}^{-1}$), Equation (1) reverts to the simpler (and more familiar)

$$I(d_{ae}) = 0.5\{1 + \exp(-0.06d_{ae})\} \quad (3)$$

which is the form that appears in the ACGIH definition of the inhalable fraction considered to this day as being applicable to most workplaces.[6]

Since the adoption of Equation (3) as *the* definition of inhalable aerosol applicable to workplaces, questions have been posed about *what is* the appropriate range of windspeeds in working environments. Measurements of actual windspeeds prevailing in a wide range of workplaces have revealed that actual workplace windspeeds tend to be much lower than originally thought, typically in the range from about 0.05 to 0.5 ms^{-1} [7, 8]. This has produced interest in re-defining the inhalable fraction for what are now regarded as more realistic windspeeds. In one body of work, new experiments to measure inhalability with a breathing mannequin were carried out in a calm air chamber,[9] and revealed some systematic differences with what had been observed at the higher windspeeds of the previous studies. However, there has so far been no systematic research to determine the aspiration efficiency of the human head as a function of windspeed within the important low – or, as we call it, '*ultra-low*' – range of windspeeds that have been identified as most relevant to most workplaces. The current research therefore has set out to acquire new data with which this knowledge gap may be filled.

2. Methods

The challenge in conducting research at the very low windspeeds mentioned was to develop an experimental arrangement in which sufficiently uniform aerosol distribution could be achieved in a test system in order to allow valid measurements of aspiration efficiency for the human head. This was achieved by means of what might best be described as a 'hybrid' ultra-low windspeed facility, combining elements of both a wind tunnel and a calm air chamber. A full description of the facility that was designed and built in our laboratory has been described in detail elsewhere[10] and so the details will not be reproduced here. It is sufficient to refer to the schematic diagram in Figure 1. Figure 1a identifies the main features, indicating the provision to introduce test aerosol from upstream (as in a wind tunnel) and from above (as in a calm air chamber). In principle, each aerosol injection location may be adjusted with respect to the other to provide uniform spatial distribution of the aerosol in the working section. In particular, Figure 1a illustrates the higher windspeed situation where particle settling velocity is relatively negligible, so that all the airborne particles in the test section arrive there by horizontal convection. Figure 1b illustrates the calm air situation where all the airborne particles in the test section arrive there vertically by gravitational settling. Figure 1c is the most interesting in the context of the current work, showing how aerosol in the test section receives contributions from both upstream and above. It indicates the horizontal and vertical velocity vectors for particles of a given size, revealing the non-horizontal net trajectory. In principle it is thus possible to maintain uniform spatial distribution of both concentration and particle size distribution. As the work progressed, just one modification was made to the experimental system as shown in Figure 1.

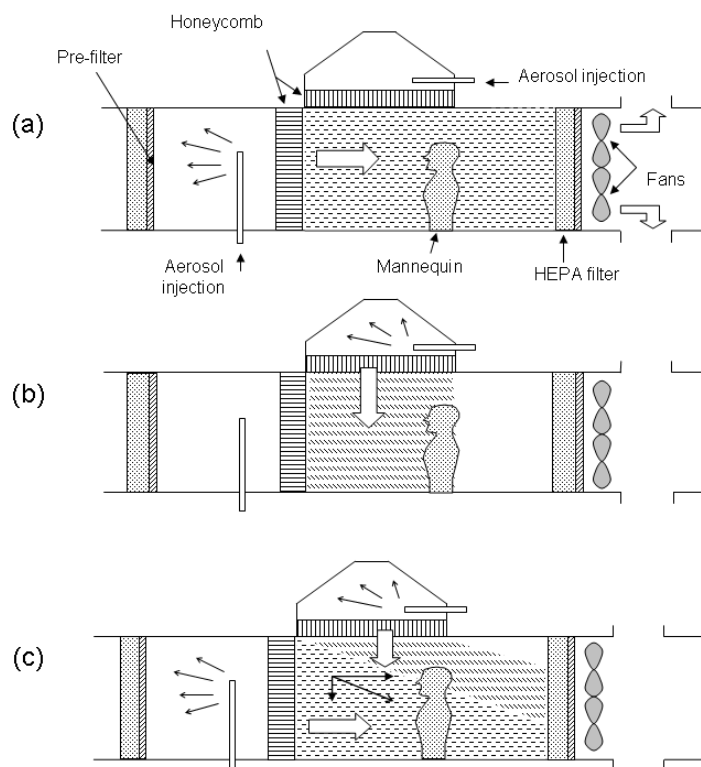


Figure 1. Schematic diagrams to show the concept of the new ultralow-speed wind tunnel: (a) the higher windspeed situation where particle settling velocity is relatively negligible; (b) the calm air situation where all the airborne particles in the test section arrive there vertically by gravitational settling; and (c) the ultra-low windspeed situation where aerosol in the test section receives contributions from both upstream and above.[10]

In the earliest experiments it was found that, under certain conditions, there were significant losses of particles during transport into the working section. To overcome this, the honeycomb flow

straighteners at the entrance to the working section were replaced by a perforated metal screen, and this was the experimental arrangement used for most of the results that will be described below. It suffices to say here that the modification produced no observable impact on the results for inhalability.

Test aerosol, mechanically generated from the same narrowly-graded powders of fused alumina that were featured widely in previous such research, was dispersed into the working section of the facility, which measured approximately 3 m in length and 1.2 m by 1.2 m in cross section. The particle size distribution was measured using 5 modified Marple-type cascade impactors fitted with foam plugs to extend the size collection range[11] and the aerosol concentration was measured using IOM inhalable samplers acting as static samplers. It was shown that spatial uniformity – for both particle size distribution and concentration – was achieved to within $\pm 10\%$ across the range of windspeeds of interest. However, unlike in the previous work, where it was possible to assume the original calibrations of particle size distribution first tabulated by Mark *et al.* (1985) [12], the enhanced losses of particles by gravitational effects at the very low windspeeds in the present work required that particle size distributions of the test aerosol needed to be actually measured for each and every combination of starting powder grade and windspeed. The results are summarized in Table 1, and provide the desired information about particle size for each set of experimental conditions. Here it is important to note that, for many of the experimental conditions of interest, the particle size distribution was significantly modified in comparison to what might have been expected for higher windspeeds, in terms of both mass median aerodynamic diameter (*MMAD*) and geometric standard deviation (σ_g). In fact, for the latter, the experimentally-measured σ_g -values were significantly greater than for the original 'parent' aerosol.

Table 1. Particle size distributions measured using modified Marple-type cascade impactors in ultra-low windspeed environments, as represented by mass median aerodynamic (*MMAD* in μm) and geometric standard deviation (σ_g).

Powder Grade	Windspeed (ms^{-1})						Nominal Size	
	0.10		0.24		0.42		<i>MMAD</i>	σ_g
	<i>MMAD</i>	σ_g	<i>MMAD</i>	σ_g	<i>MMAD</i>	σ_g	<i>MMAD</i>	σ_g
F1200	9.6	1.28	9.5	1.32	9.3	1.34	6.0	1.36
F800	13.9	1.49	12.8	1.47	12.4	1.56	13.0	1.38
F500	28.8	1.62	32.7	1.71	28.7	1.93	26.0	1.30
F400	37.7	1.62	44.3	1.59	40.0	1.74	34.0	1.20
F280	74.0 ^a	1.19 ^a	62.4	1.42	66.9	1.45	74.0	1.19
F240	89.5 ^a	1.29 ^a	60.1	1.45	63.0	1.49	89.5	1.29

^a Nominal value used for this condition

As already mentioned, the subject of measurement is the *aspiration efficiency* of the human head, as represented by the life-sized mannequin shown in Figure 2. This mannequin was designed to incorporate not only breathing through the nose and/or mouth (in whatever combination – in through the nose/out through the mouth, in through the nose/out through the nose, etc. – is desired to be tested) but also body heat. For the latter, however, previous research described by Schmees *et al.* (2008) [13] showed that elevated body temperature had no appreciable effect on the motion of air near the human body, even at the very low windspeeds of interest. So this aspect will not feature further in this paper.

In our experiments, inhaled aerosol was collected on the 47-mm glass fibre filter that was located just inside the nose and/or mouth entry, and on other inside surfaces between the entry and the filter. The latter deposits were recovered at the end of each experiment by swabbing with isopropyl alcohol-impregnated cotton balls. It is also important to note that special care was taken to design the air pathways inside the mannequin such that expired air did not pass through the same filter, or over the

same surfaces, as during inspiration, thus eliminating any risk of re-entraining particulate material already collected. For each experiment, both the filter and cotton were conditioned overnight in a desiccator to stabilize the mass, after which it was then weighed. After sample collection, the filter and cotton balls were similarly conditioned again and re-weighed. The resultant filter and wall particulate masses were combined to provide the total inhaled aerosol mass. From knowledge of the corresponding total volume of air sampled, the inhaled aerosol mass concentration (c_I) was obtained directly.

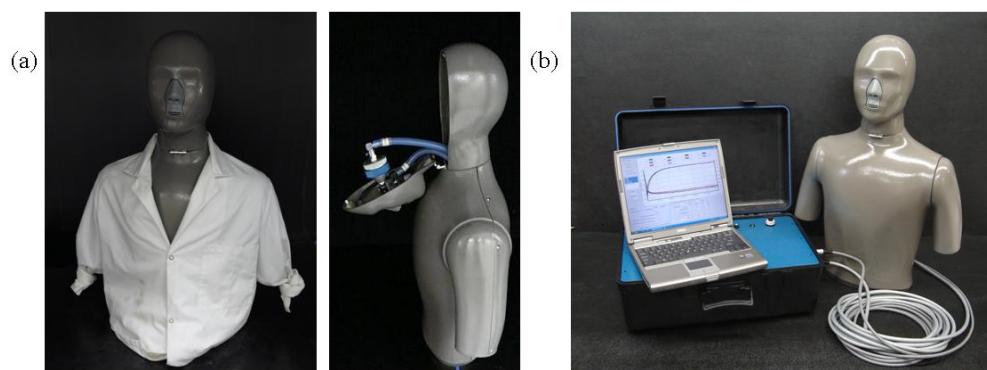


Figure 2. Photographs of the mannequin: (a) both assembled and disassembled (face manifold dropped down) to reveal aerosol collection filter and internal connections; and (b) the mannequin system, including the breathing machine and control lap-top computer.

The reference concentration was obtained from samples taken 0.75 m upstream of the mannequin using thin-walled isokinetic samplers. Here, provided that conditions were truly isokinetic, the particulate material entering through the plane of the sampler was indeed representative of the total airborne concentration. Similarly, as for the mannequin, the aspirated particulate material was recovered from both the filter and the inside walls of the thin-walled sampling tube, and combined to provide the reference concentration (c_0). Finally, aspiration efficiency (A) was determined from the ratio c_I/c_0 .

Experiments were conducted for particle size (as represented by $MMAD$) in the range from approximately 9 to 90 μm (represented by 6 different powder grades), windspeed values of 0.10, 0.24 and 0.42 ms^{-1} , breathing flowrate values (as represented by minute volume, V) of 6 and 20 lmin^{-1} , and breathing modes of 'mouth-only' (M), 'nose-only' (N), and 'in through nose/out through mouth' (NM) (with 'nose-only' breathing not tested for the higher breathing flowrate). Each sampling run lasted for 20 minutes and employed the breathing mannequin heated to typical skin temperature (33 $^{\circ}\text{C}$) while dressed in a laboratory coat. Each set of conditions was tested twice, for a total of 180 experiments.

3. Results

The experimental results shown here for the aspiration efficiency of the human head (A) represent an important contribution to the ongoing discussion in the international community about how to define the inhalable fraction. Figures 3, 4 and 5 show a summary of the results, all plotted graphically as A versus d_{ae} for each windspeed, breathing flowrate and mode of breathing, respectively. Each data point represents a mean for the pooled data at that aerosol particle size, containing between 2 and 18 values, across all experimental conditions. The data shown include those for the earlier experimental set-up as well as those for the later arrangement (and which, as already mentioned, exhibited no observable differences). It should also be noted that the values for d_{ae} represent the mass median aerodynamic diameter and so were obtained as part of a distribution, the spread of which can be assessed by the σ_g values shown in Table 1. The current inhalable convention, as adopted by ACGIH, ISO and CEN, is

also displayed on the graphs for comparison. Overall, Figures 3, 4 and 5 reveal a very comprehensive picture, providing aspiration efficiency data for the full range of conditions mentioned above.

ANOVA results indicated that aspiration efficiency in the lowest windspeed (0.10 ms^{-1}) was significantly different from aspiration efficiency measured at both higher windspeeds (p -value < 0.0001). By contrast, the results for different breathing flowrates (p -value = 0.066) and modes of breathing (p -value = 0.155) showed no statistically significant differences. Overall, it is evident that the results all appear to be close – within the scatter – to the inhalability curve that was derived from the original bodies of experimental work at higher windspeeds.

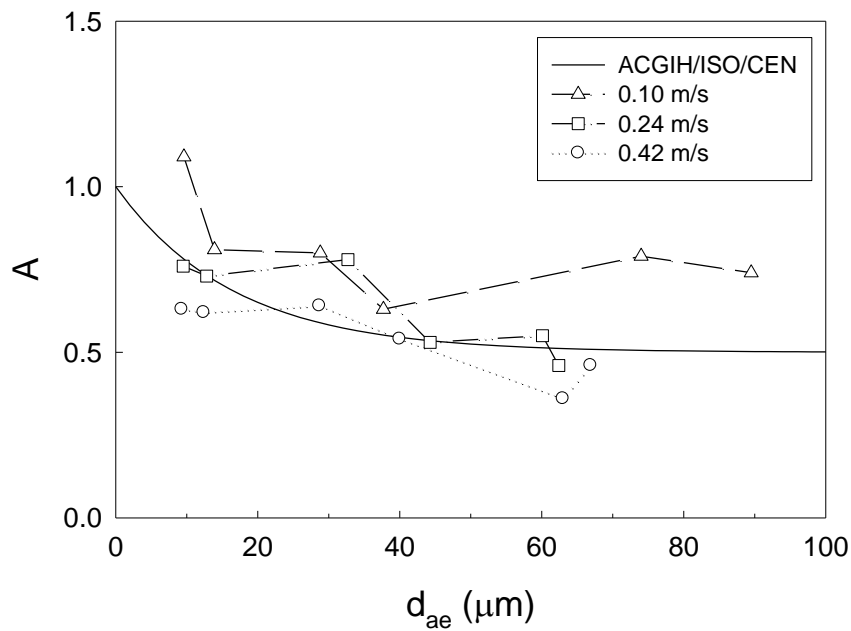


Figure 3. Mean human aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) at different windspeeds, across all breathing flowrates and modes. Also shown is the current inhalable convention as adopted by ACGIH, ISO and CEN.

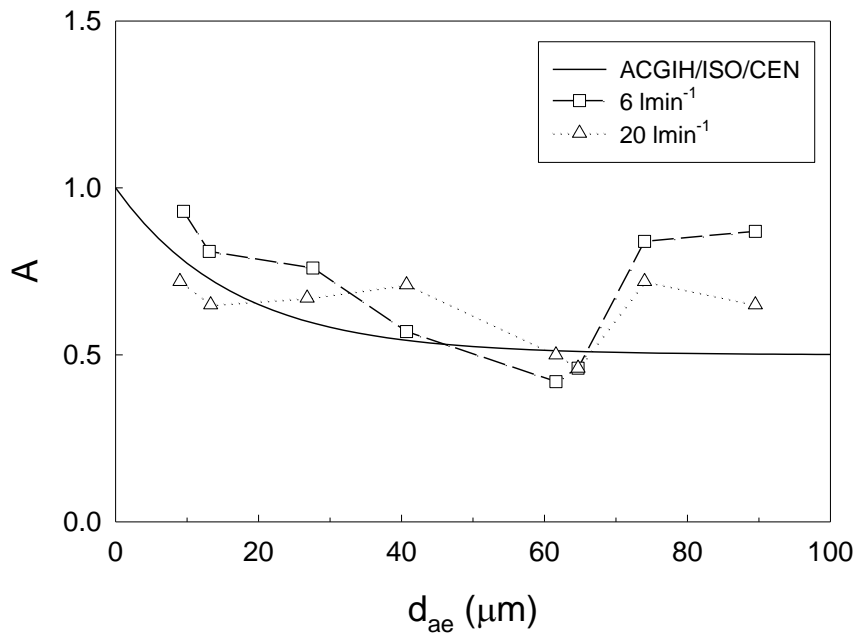


Figure 4. Mean human aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) at different breathing flowrates, across all windspeeds and modes of breathing. Also shown is the current inhalable convention as adopted by ACGIH, ISO and CEN.

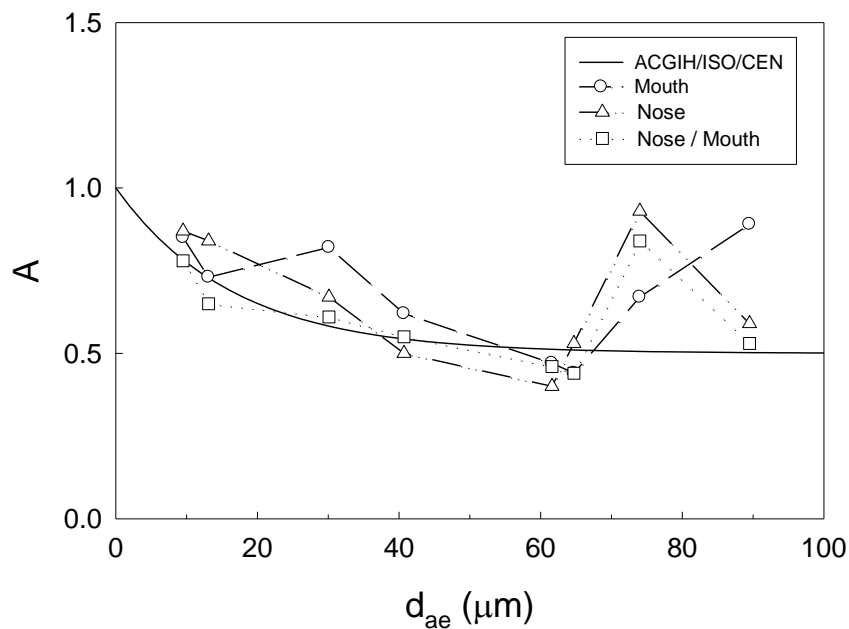


Figure 5. Mean human aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) at different modes of breathing, across all windspeeds and breathing flowrates. Also shown is the current inhalable convention as adopted by ACGIH, ISO and CEN.

4. Discussion

The aspiration efficiency of the human head (i.e. inhalability) has been successfully assessed at ultra-low windspeeds. The difficulty in performing experiments at such low windspeeds was overcome by the development of novel facilities and methods, and thus enabled the inhalability of aerosols to be assessed under realistic working conditions – at windspeeds between 0.1 and 0.5 ms⁻¹. While mannequin breathing flowrate and mode of breathing did not appear to be important factors in determining inhalability, windspeed did have an impact on the inhalability of the coarse aerosols tested here.

It should be noted that the current inhalable convention was established based on general trends in the large body of work that was performed for aspiration efficiency in fast moving air, without regard to rigorous statistical models. Bearing in mind that those earlier data were all obtained for windspeeds ranging from 0.5 to 9 ms⁻¹, it is interesting to observe that the set of inhalability data obtained in this research at the ultra-low windspeeds indicated lies within the range of those values previously measured.

As mentioned earlier, studies performed in essentially calm air have shown that inhalability in those environments is typically somewhat higher than what was seen in the previous data for higher windspeeds[9]. Taking a closer look at the importance of windspeed as it might relate to human aspiration efficiency will therefore be instructive. In the comprehensive analyses of workplace windspeeds discussed before, it was observed that approximately 85% of measured windspeeds were below 0.3 ms⁻¹, with 50% of values lower than 0.1 ms⁻¹ [8]. When one considers the widespread use of ventilation systems in most working environments, especially where inhalable hazards are known to be present, it is difficult to imagine many workplaces having windspeed conditions close to ‘calm’. In addition, workers who are not stationary will create additional air movements that would further limit the applicability of actual calm air results. Although our results were limited to environments with windspeeds at 0.1 ms⁻¹ and greater, the similarities seen between the set of data obtained here and those data used to set the inhalable convention, coupled with the limited applicability of true calm air models, windspeed – even ultra-low – does not appear to be a significant factor in determining the inhalability of aerosols.

Overall, these data provide an important assessment of human aspiration efficiency under realistic workplace environments and will be important for filling the gap between calm air and moving air with respect to human inhalability. It should also be noted that the preliminary analyses performed here have been purely statistical. The results of a more rigorous analysis, also incorporating ideas taken from the physical theories of aerosol aspiration, will be reported in a later paper.

5. Acknowledgements

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