

Proposed Modification to the Inhalable Aerosol Convention Applicable to Realistic Workplace Wind Speeds

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The current convention for sampling inhalable aerosols was based on several mannequin studies performed in wind tunnels at wind speeds between 0.5 and 4 m s⁻¹. In reality, as we now know, the wind speed in most modern indoor working environments is generally at or below ~0.2 m s⁻¹. Inhalability studies performed in calm air aerosol chambers have shown that human aspiration efficiency at essentially zero wind speed is not consistent with the existing inhalable aerosol convention, calling into question the universal applicability of the current standard. More recently, experiments were carried out in a new hybrid wind tunnel–calm air chamber at more representative workplace wind speeds, between ~0.1 and 0.5 m s⁻¹, to fill in this knowledge gap. Comparing these new data to both the existing inhalable aerosol convention and a recently proposed alternative for low wind movement suggests that, while the existing inhalable aerosol convention remains appropriate for wind speeds above ~0.2 m s⁻¹, the modified version is more appropriate for the range below ~0.2 m s⁻¹.

Keywords: aerosols; aspiration efficiency; inhalability; inhalable convention; low wind speed

INTRODUCTION

The evolution of criteria for aerosol sampling began many years ago with the desire to collect a sample of airborne particles uniformly across the entire particle size range. Strictly speaking, this required the aspiration efficiency of a sampler to be 100% for all particle sizes. In theory, this is what could be achieved using a thin-walled tube operated isokinetically and facing directly into the wind, as indeed is done for some aerosol sampling scenarios (e.g. in stacks and ducts) where the air movement is unidirectional and steady and the velocity is well known. These conditions, however, are ideal and are rarely—if ever—met in living and working environments. So isokinetic sampling cannot be used under such conditions and, as has been recognized for many years, sampling for so-called

‘total aerosol’ or ‘total suspended particulate’ is problematic for workplace air sampling. Nonetheless, it remains the case that, even to this day, many aerosol standards around the world are still written vaguely in terms of total aerosol or total suspended particulate.

In the 1970s, it was first suggested by W.H. Walton, one of the pioneers of particle size-selective aerosol sampling, that coarse aerosols would be better described in terms of what is actually inhaled by people. That is, what enters into the nose and/or mouth during breathing is most important. In this way, the human head would be treated as a sampler itself, thus acknowledging that the same principles governing aerosol transport into a sampling device also hold true for particles that are carried through the air and into the nose and/or mouth of a breathing person. The first experimental studies of what became known as human ‘inhalability’ were reported soon afterwards by Ogden and Birkett (1977, 1978), mainly for moving air but also with some data for calm air. These represented

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an important first step towards a quantitative health-based aerosol sampling criterion, which acknowledged that standards for aerosol sampling should better reflect human exposure.

Key earlier research that was carried out in relation to the measurement of this metric of aerosol exposure by humans, particularly in relation to sampling standards and criteria, has been described widely and in great detail in the literature (e.g. Vincent, 2007). It will be reviewed briefly in this paper in the process of proposing an important modification to the long-standing inhalable aerosol convention, one that takes account of realistic workplace environmental conditions.

INHALABILITY

Following Ogden and Birkett, other experimental studies of human inhalability were reported over the next two decades, all of which (like those of Ogden and Birkett) were carried out using life-sized breathing mannequins exposed to well-characterized aerosols in specially designed wind tunnels (Armbruster and Breuer, 1982; Vincent and Mark, 1982; Vincent *et al.*, 1990; Phalen *et al.*, 1992; Kennedy and Hinds, 2002). The use of inert mannequins in this body of work has consistently been justified on the basis of the fact that it is the aspiration efficiency of the human head that was the subject of interest, unaffected by internal properties of the human respiratory tract. That remains the case. In the studies cited, comprehensive sets of data were generated for the aspiration efficiency (A) of the human head for aerosols with particle aerodynamic diameters (d_{ae}) up to $\sim 90 \mu\text{m}$, mostly for wind speeds in the range from ~ 0.5 to 4 m s^{-1} . A few experiments were reported for even higher wind speeds—up to 9 m s^{-1} —considered to be relevant to outdoor scenarios. In all these studies, aspiration efficiency was averaged uniformly over all possible orientations of the mannequin with respect to the wind direction. The primary finding of this body of work was that the efficiency with which particles entered through the nose and/or mouth during breathing exhibited a consistent strong relationship with particle size, specifically decreasing with increasing particle size for particles in the range up to $\sim 30 \mu\text{m}$ and then levelling out for larger particles at $\sim 50\%$. The general consistency (for the most part) observed in the data from the various studies provided strong impetus to the development of a quantitative particle size-selective criterion for the inhalable aerosol fraction. As early as 1985, the American Conference of Governmental Industrial Hygienists (ACGIH, 1985) specified it in the form of the algebraic expression

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

which is shown graphically in Fig. 1. Here, I is inhalability, where the change in nomenclature represents that I is a convention, as opposed to aspiration efficiency, A , which is an actual measured physical quantity. Also, d_{ae} is the particle aerodynamic diameter, expressed in micrometre. Later, this form was endorsed and adopted by the International Organization for Standardization (ISO, 1992) and the Comité Européen de Normalization (CEN, 1992) [It is noted that ISO, bearing in mind its requirement (in this area) to provide standards relevant to both the workplaces and the ambient environment, included additional terms in the expression to take into account systematic wind speed-dependent departures in human aspiration efficiency that had been observed at higher wind speeds. The resultant expression reverts to the one shown in equation (1) for wind speeds below $\sim 4 \text{ m s}^{-1}$, and this is the one most relevant to the workplaces, which are of interest in this paper.]. It indicates that inhalability, and hence the desired performance of an aerosol sampling instrument to collect that fraction, may be described by a curve that passes through unity (equivalent to 100%) for the smallest particles and decreases exponentially until it levels off at 0.5 (equivalent to 50%) for particles bigger than $\sim 30 \mu\text{m}$ and up to $\sim 100 \mu\text{m}$. It is limited there only by the lack of available information for particle sizes beyond that, although it is understood that, practically speaking, aspiration efficiency must fall to zero for large particle sizes. Over time, this convention has become widely accepted around the world and provides the basis of aerosol standards in many countries.

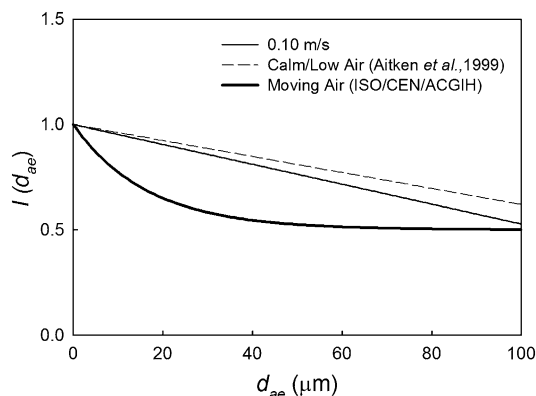


Fig. 1. Linear regression for data at 0.10 m s^{-1} (thin solid line) compared to the existing inhalable aerosol convention (thick solid line) and the proposed 'low air movement' (i.e. calm air) criterion (dashed line) shown for inhalability (I) as a function of particle aerodynamic diameter (d_{ae}).

It is important to note that the criterion embodied in equation (1) was established on the basis of the consensus of experts after reviewing the trends observed in the available experimental data. It does not specifically represent a scientific 'fit' to the available experimental data (any more than earlier criteria for the finer respirable aerosol fraction had been) but rather an agreement based on both scientific and other considerations, including the need for simplicity and—in turn—practical workability in the real world of occupational and environmental hygiene.

One of the primary uses of such a criterion is to provide a benchmark for the development of samplers that mimic human inhalability. Indeed, this was the intention from the very beginning, as reflected in the title of the 1977 paper of Ogden and Birkett, 'The human head as a dust sampler'. The criterion that emerged became the basis for several inhalable aerosol samplers used today, including the IOM sampler (originally developed at the Institute of Occupational Medicine in Edinburgh, Scotland, UK), which was designed specifically to match this curve. Therefore, it is of utmost interest to ensure that such sampling criteria are based on the most appropriate and relevant data so that worker exposures can be accurately assessed.

INHALABILITY IN CALM AIR

Much of the earlier work to evaluate inhalability was driven by interest in workers' aerosol exposures in well-ventilated situations, most notably in underground coal mines. In such environments, the range of wind speeds studied was generally considered to be appropriate. There was the added benefit that experiments at such wind speeds were relatively easy to execute in terms of the desired spatial uniformities of test aerosol concentration and air velocity in the wind tunnels that were used. This thinking was carried forward to later work, with application to the development of the inhalability criterion as described above and, in turn, to its implementation in standards. In the meantime, however, measurements of wind speeds in a range of workplaces, not including underground mining, taking into account not only actual air velocities *per se* but also relative motions between workers and the air, revealed that prevailing wind speeds were consistently much lower than anticipated, well below the range of the inhalability studies summarized above (Berry and Froude, 1989; Baldwin and Maynard, 1998). Indeed, wind speeds were found to be typically in the range from ~ 0.05 to 0.5 m s^{-1} , with median values $\sim 0.2 \text{ m s}^{-1}$

and below. With this knowledge came the realization that, in aerosol science terms, particle transport in such situations (and hence inhalability) is now likely to be influenced strongly by the role of gravitational settling in a way that was considered to be non-existent for the wind speeds of those earlier experiments. Although this reality has long been recognized in relation to aerosol sampling in perfectly calm air, it has been largely overlooked in the context of real world conditions.

The new realization spurred a small flurry of new experiments. In the first instance, to evaluate the aspiration efficiencies of breathing mannequins in chambers where wind speeds could be considered to be virtually negligible and with no net air movement (i.e. essentially 'calm air'). This was in contrast to the experiments carried out in wind tunnels where net horizontal air movement was mechanically generated by fans. With this in mind, it should be noted that the term calm air, as it is used here with respect to aerosol inhalability experiments, is meant to describe conditions where there is no net air movement (with wind speeds typically $< 0.05 \text{ m s}^{-1}$), whereas the 'ultra-low' wind speed experiments described in more detail later did include a net horizontal movement of air flow (with wind speeds between 0.05 and 0.5 m s^{-1}).

As part of their earlier work, Ogden and Birkett (1977, 1978) had reported results from limited experiments (for particles up to $30 \mu\text{m}$) under calm air conditions, but these were similar enough to the other inhalability data that specific mention about calm air conditions was not included in the adopted standards. It was not until 1999, in light of the new importance given to low wind speed situations, that Aitken *et al.* reported a definitive study comprising experiments conducted at two separate laboratories. The newer Aitken *et al.* data for A , with d_{ae} values up to $\sim 90 \mu\text{m}$, revealed human head aspiration efficiency values that lay significantly above the data trends that had been observed for the faster-moving air scenarios, with no dependence on mode of breathing (mouth versus nose) and minimal differences based on breathing rate (tested at 6, 10, and 20 l min^{-1} minute volumes). These trends were broadly similar (see Vincent, 2007) to those exhibited by the earlier data of Ogden and Birkett obtained using a quite different experimental set-up and methods. By contrast, another calm air study with a mannequin, reported by Hsu and Swift (1999) at around the same time, provided data that were strikingly different, suggesting that aspiration efficiency in calm air dropped off quite sharply with increasing particle size, actually falling to zero for

$d_{ac} \sim 80 \mu\text{m}$. Differences in these results are addressed in more detail below.

Based on their results, Aitken *et al.* went so far as to propose a new criterion for the inhalable aerosol fraction—based on their own data for mouth breathing at 20 l min^{-1} minute volume as a ‘worst case approach’—this time applicable to sampling coarse aerosol in ‘low air movement’ (e.g. calm air) situations. Again, it took the form of an empirical algebraic expression, given by

$$I(d_{ac}) = 1 - 0.0038d_{ac}. \quad (2)$$

In contrast to the original inhalability curve, the relationship shown in equation (2) is now described by a simple linear function, with I declining slowly as d_{ac} increases. It does imply that, if such an algorithm were to be used as a convention, I must eventually reach zero for large enough d_{ac} . With the current convention, the relationship levels off at an inhalability of 50% with the caveat that it is only valid up to a particle size of $100 \mu\text{m}$. Of course, it is absurd to think that inhalability immediately falls to zero for particles greater than this, but as it is presented, the current convention implies that inhalability will never reach zero for any particle size, an equally impractical situation. Therefore, practically speaking, the linear function appears to be more acceptable.

Lidén and Harper (2006) presented a synthesis of the research carried out for inhalability in calm air, including not only the large body of data for mannequins but also the more recent data of Dai *et al.* (2006) for nasal inhalation by actual human volunteer subjects. This led them to similarly suggest that a sampling convention for calm air should include an upper limit for inhalability; that is, the sampling efficiency would reach zero for larger particles. If the use of a linear model for an inhalable aerosol criterion in calm air can be agreed, then the major decision becomes the slope of that line. The suggestion of Aitken *et al.* implies 50% efficiency at $\sim 100 \mu\text{m}$ (in that respect similar to the current convention) and reaching zero efficiency at well $> 200 \mu\text{m}$. The mannequin study of Hsu and Swift and the human volunteer study of Dai *et al.* suggest a sharper cut-off than this, although it should be noted that these experiments were for nose breathing only. On the basis of their analysis of the Dai *et al.* results, Lidén and Harper also suggested that an inhalable aerosol sampling convention in calm air might need to reflect actual breathing patterns.

In view of the differences between results from the bodies of work described, much depends on what is learned from the new study reported here. We there-

fore now move on to describe these new experiments for wind speeds in the intermediate range between calm and moving air, which, it is now recognized, are the most representative of most workplaces.

INHALABILITY AT ULTRA-LOW WIND SPEEDS

As already mentioned, we now know that wind speeds in workplaces are typically well below those for which the original experiments to examine human inhalability were conducted. But perfectly calm air does not represent actual situations either. In reality, true conditions will usually lie somewhere in between these two scenarios, for which we have identified the range of ‘ultra-low’ wind speeds from ~ 0.05 to 0.5 m s^{-1} as being the most relevant to typical workplace scenarios, particularly indoor environments.

The new research was conducted in a purpose-built ultra-low wind speed wind tunnel, designed as a ‘hybrid’ facility combining the principles and modes of operation of both a conventional wind tunnel and a calm air aerosol chamber. In that way, a uniform distribution of aerosols—in terms of both concentration and particle size distribution—was generated within the working section for horizontal wind speeds between 0.10 and 0.42 m s^{-1} . Experimental details that were similar to many of the previous studies were utilized (e.g. the use of narrowly graded powders of fused alumina, a breathing mannequin and orientation-averaged results) in order to provide an adequate level of comparability.

Full details of the experimental set-up are described elsewhere (Schmees *et al.*, 2008a), as are some of the earlier results (Schmees *et al.*, 2008b; Sleeth and Vincent, 2009). Just a brief summary is given here. The new facility was quite different from anything previously used to evaluate inhalability in that it enabled the injection of aerosols both upstream of the working section—as in a conventional aerosol wind tunnel—and, simultaneously, from overhead—as in a calm air aerosol chamber. In this way, large particles that settled out of the airstream before reaching the mannequin were compensated for by particles that fell into the airstream from overhead. Similarly, the smaller aerosols that were carried away quickly once injected overhead were compensated for by the smaller particles that entered the working section horizontally from upstream. If the same aerosols were injected at both points, there should theoretically be a uniform particle size distribution in the working section. This was the starting basis for the wind tunnel design and, ultimately, after a certain amount of adjustment to the original design,

the desired conditions were satisfactorily realized in practice (see Schmees *et al.*, 2008a). For the experiments, it should be noted that the mannequin was positioned at an upstream location that ensured the aerosol concentration and particle size distributions were consistently uniform to within about $\pm 10\%$.

The mannequin was also unique in its design. Firstly, it was designed to rotate about a vertical axis in order to simulate orientation-averaged sampling. This was achieved by means of a reciprocating motor that allowed for full travel through 360° , followed by 360° in the opposite direction, and so on back and forth. In this way, tangling of wires and tubing were avoided. Secondly, the mannequin featured a breathing machine that was able to operate at a representative range of breathing flow rates through either the nose or the mouth. Here, the pathways of air during inspiration and expiration respectively were designed to be different so that there could be no re-entrainment losses of collected particulate material during expiration. Those pathways were also designed such that the expired air was injected back into the airstream near the mannequin in the same way as it would be in real human exposure situations. Thus, the role of the jet of expired air on the motion of air and particles near the body was incorporated directly into the experiments. Finally, the mannequin was also heated to typical human skin temperature (33°C) to simulate the possibility of thermal air movements associated with warm air rising off the body. In summary, the experimental design was intended to simulate as closely as possible actual human exposures. The test aerosols that were used were generated from narrowly graded powders of fused alumina of the type previously used widely in this area of research (Mark *et al.*, 1985). Electrostatic effects were not controlled, in that neither the aerosols nor the mannequin were neutralized during the experiments since these were not considered to be significantly influential (Vincent, 2007).

In this paper, we present for the first time the full data set (Table 1) for the measured aspiration efficiency of the mannequin, as represented by the mean for all identical experimental conditions (with at least two repeat tests for each). These data are summarized graphically in Figs 2–4, for three wind speeds (0.10, 0.24, and 0.42 m s^{-1} , respectively), two breathing flow rates (minute volumes, i.e. the volume inhaled per minute, of 6 and 20 l min^{-1}), and three modes of breathing (in and out through the mouth only, in and out through the nose only, and in through the nose and out through the mouth). These breathing conditions were chosen to cover the

range of those considered likely to be found among workers, from ‘at rest’ to ‘hard work’. The results are shown for d_{ae} values up to $\sim 90\text{ }\mu\text{m}$. Also shown in each of the graphs is the inhalability curve (I) representing the currently accepted convention. First glance shows that the results are generally consistent with the convention for the higher wind speed of 0.42 m s^{-1} but show a tendency to drift upwards as wind speed decreases, to the point where the results for the lowest wind speed of 0.10 m s^{-1} lie significantly and unambiguously above the inhalability curve.

Statistical inspection by analysis of variance (ANOVA), which compared the aspiration efficiencies based on different wind speeds or different breathing combinations, supported these tendencies. Firstly, it was confirmed that there were highly significant dependences on wind speed. Specifically, the results for 0.10 m s^{-1} were greater than those for 0.24 m s^{-1} and those for 0.24 m s^{-1} were greater than for 0.42 m s^{-1} (all P -values < 0.0001). As for breathing conditions (represented by a combination of breathing flow rate and mode of breathing), there were no significant dependencies on these for the lower wind speeds of 0.10 and 0.24 m s^{-1} (P -values = 0.0866 and 0.6786, respectively), but such dependencies did become somewhat significant at 0.42 m s^{-1} (P -value = 0.0217).

A paired t -test was then used to examine how the results relate to the existing inhalability criterion. It was found that wind speed dependencies were reflected here too. At the lowest wind speed of 0.10 m s^{-1} , aspiration efficiency was significantly greater than the convention (P -value < 0.0001), yet there were no statistically significant differences for the data at 0.24 m s^{-1} (P -value = 0.0957), while at 0.42 m s^{-1} , the new aspiration efficiency was actually shown to be less—albeit slightly so—than the convention (P -value < 0.0001).

DISCUSSION

The single most important finding from the experiments described above is that the aspiration efficiency of the human head is reasonably consistent with the existing inhalability criterion for the higher wind speeds within much of the range we have studied. That is, down to $\sim 0.2\text{ m s}^{-1}$, it appears that the existing criterion—as defined by equation (1)—holds quite well, as we already knew it to be the case for wind speeds between 0.5 and 4 m s^{-1} . But, recalling from our earlier discussion that workplace wind speeds do typically tend towards the lower end of the range we have been discussing

Table 1. Entire data set of mean mannequin aspiration efficiency (A) at ultra-low wind speeds of 0.10, 0.24, and 0.42 m s^{-1} , for various breathing conditions and particle aerodynamic diameters (d_{ae}), shown with standard error (SE)

Powder grade	Wind speed (m s^{-1})									
	0.10			0.24			0.42			
	d_{ae}	A	SE	d_{ae}	A	SE	d_{ae}	A	SE	
				6 l min^{-1} Mouth-only breathing						
F1200	9.6	1.37	0.09	9.5	0.80	0.03	9.3	0.80	0.10	
F800	13.9	0.93	0.04	12.8	0.76	0.00	12.4	0.69	0.02	
F500	28.8	1.03	0.14	32.7	0.86	0.09	28.7	0.79	0.05	
F400	37.7	0.80	0.04	44.3	0.55	0.14	40.0	0.52	0.08	
F280	74.0	0.84	0.32	62.4	0.38	0.11	66.9	0.43	0.04	
F240	89.5	0.38	^a	60.1	0.46	0.00	63.0	0.47	0.20	
				20 l min^{-1} Mouth-only breathing						
F1200	9.6	0.87	0.09	9.5	0.85	0.07	9.3	0.62	0.03	
F800	13.9	0.79	0.05	12.8	0.65	0.05	12.4	0.64	0.06	
F500	28.8	0.85	0.04	32.7	0.81	0.06	28.7	0.60	0.03	
F400	37.7	0.73	0.19	44.3	0.53	0.06	40.0	0.56	0.02	
F280	74.0	0.49	0.04	62.4	0.49	0.01	66.9	0.48	0.08	
F240	89.5	0.67	0.09	60.1	0.61	0.18	63.0	0.33	0.01	
				6 l min^{-1} Nose-only breathing						
F1200	9.6	1.23	0.19	9.5	0.76	0.04	9.3	0.61	0.03	
F800	13.9	0.98	0.08	12.8	0.85	0.09	12.4	0.68	0.01	
F500	28.8	0.57	0.10	32.7	0.76	0.24	28.7	0.68	0.09	
F400	37.7	0.49	0.02	44.3	0.53	0.00	40.0	0.48	0.03	
F280	74.0	0.93	0.07	62.4	0.63	0.18	66.9	0.44	0.05	
F240	89.5	0.59	0.27	60.1	0.47	0.05	63.0	0.33	0.04	
				6 l min^{-1} Nose-mouth breathing						
F1200	9.6	1.32	0.22	9.5	0.77	0.01	9.3	0.75	0.28	
F800	13.9	0.85	0.07	12.8	0.95	0.26	12.4	0.60	0.10	
F500	28.8	0.66	0.07	32.7	0.64	0.03	28.7	0.48	0.16	
F400	37.7	0.51	0.01	44.3	0.50	0.04	40.0	0.71	0.22	
F280	74.0	0.74	0.38	62.4	0.38	0.06	66.9	0.49	0.05	
F240	89.5	0.46	0.16	60.1	0.51	0.17	63.0	0.29	0.00	
				20 l min^{-1} Nose-mouth breathing						
F1200	9.6	0.89	0.01	9.5	0.54	0.02	9.3	0.41	0.05	
F800	13.9	0.62	0.10	12.8	0.52	0.08	12.4	0.47	0.01	
F500	28.8	0.62	0.12	32.7	0.71	0.01	28.7	0.54	0.03	
F400	37.7	0.62	0.06	44.3	0.55	0.12	40.0	0.41	0.02	
F280	74.0	0.94	0.04	62.4	0.41	0.00	66.9	0.48	0.05	
F240	89.5	0.59	0.02	60.1	0.69	0.20	63.0	0.35	0.04	

^aData not available.

(i.e. median values $\sim 0.2 \text{ m s}^{-1}$), our results for the lowest wind speed tested (0.10 m s^{-1}) become especially important.

In the first instance, a simple linear regression was carried out for the new data at 0.10 m s^{-1} (including all breathing conditions), guided by the form suggested earlier by Aitken *et al.*, again constraining the data to maximum aspiration efficiency at unity

for the smallest particles. A fair fit with our data was found with

$$A(d_{\text{ae}}) = 1 - 0.0047d_{\text{ae}}, \quad (3)$$

which is shown in Fig. 1 alongside the existing inhalability convention as described by equation (1) and the new one for calm air/low air movement' suggested by Aitken *et al.*, as shown in equation (2).

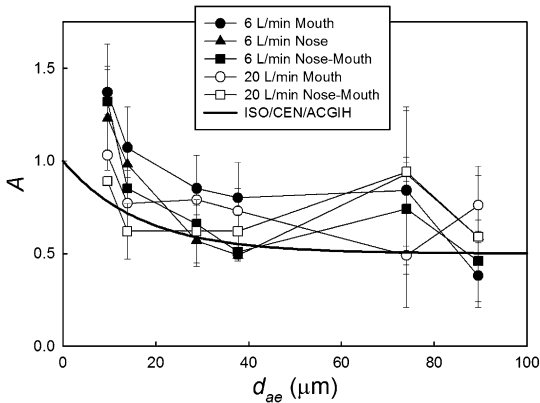


Fig. 2. Mean aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) for a life-sized mannequin with various breathing parameters at a wind speed of 0.10 m s^{-1} . Error bars represent 1 SD. The current inhalability convention (I from Fig. 1) is also shown for comparison.

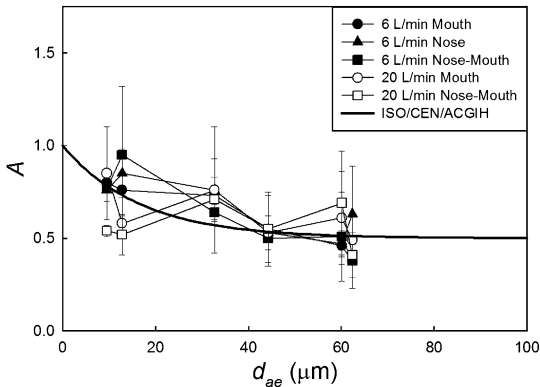


Fig. 3. Mean aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) for a life-sized mannequin with various breathing parameters at a wind speed of 0.24 m s^{-1} . Error bars represent 1 SD. The current inhalability convention (I from Fig. 1) is also shown for comparison.

This new expression is a candidate for an alternative criterion for the inhalable fraction, applicable at the very lowest non-zero wind speeds. Although the curve described by equation (3) is somewhat steeper than the one proposed by Aitken *et al.* for essentially calm air, it is nonetheless quite close, and indeed, the difference is not statistically significant (95% confidence interval of slope: 0.0027–0.0067). So, for practical purposes, it may arguably be regarded as no different. In fact, a more thorough ANOVA comparison between our results at 0.10 m s^{-1} and those of Aitken *et al.* (this time including only those experiments where the same breathing conditions were used: 6 and 20 l min^{-1} mouth breathing) also showed no significant difference (P -value = 0.4225).

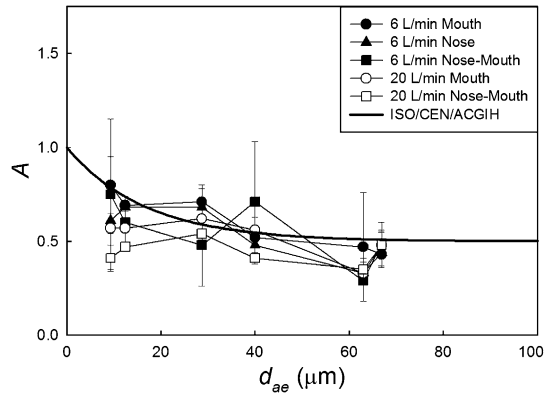


Fig. 4. Mean aspiration efficiency (A) as a function of particle aerodynamic diameter (d_{ae}) for a life-sized mannequin with various breathing parameters at a wind speed of 0.42 m s^{-1} . Error bars represent 1 SD. The current inhalability convention (I from Fig. 1) is also shown for comparison.

Next, our data provide the means to determine where to place the point that distinguishes air that is effectively moving from air that is effectively calm. This is especially important if there is to be one standard for essentially moving air and another for essentially calm air. From analysis of our data, a transition point of 0.2 m s^{-1} is suggested. But there is then the question of how to determine which standard should apply in each given situation. Possible options are discussed below when we come to make actual recommendations.

As we review our data in the light of what has gone before in other studies, it is important to note that each of those other reported experiments was different. There is no standard procedure for measuring inhalability for the human head, either for mannequins or for actual human subjects. Perhaps, the single biggest challenge for everyone has been the establishment of test aerosol conditions where concentrations and the particle size distribution are acceptably uniform in the working section of the wind tunnel or test chamber in question. In the work described here, we went to great lengths to achieve such conditions. With this in mind, we need to confront significant differences in the results reported from other bodies of work. Specifically, the calm air studies of Hsu and Swift (1999) for mannequins and Dai *et al.* (2006) for actual human subjects suggest markedly smaller cut-off particle sizes than do all the other work reported. Also, unlike in our study, they reported significant differences as a function of breathing flow rate. It is notable that those studies were all for nose breathing and important differences in the reference concentration measurements had also been identified previously. Other than that there

is no clear explanation for the dichotomy given the available information.

Another issue that has been discussed many times before with respect to human inhalation is the possible effect of body heat. The theory is that, due to its warmth, the human body will generate buoyant air that may cause updraught in the vicinity of the body, thereby impacting inhalation. Dai *et al.* (2006) suggested that updraught due to human body heat were a possible reason for the noted discrepancy between their results in humans and previous work performed with mannequins. However, it is important to note that in their study using humans, Dai *et al.* did not allow the subjects to exhale back into the chamber, instead using a mouthpiece connected to a dry gas meter. Based on previous work in the low speed wind tunnel described here, this jet of expired air is quite influential on the air flow around the body and would very likely negate any effect from body heat (Schmees *et al.*, 2008b). In the mannequin study reported here, it is important to remember that we did include both the body heat and the expired air jet in order to better simulate actual breathing conditions.

Bearing in mind the similarity between the Ogden and Birkett and Aitken *et al.* results, the Hsu and Swift results appear to be less persuasive and hence, they are considered to be less applicable to the current discussion. Overall, and for the purpose of moving forward, we are persuaded by the consistency shown between the earliest calm air data of Ogden and Birkett (1977, 1978), the subsequent ones of Aitken *et al.* (1999), and now our own data. All these experiments were carried out by independent investigators using quite different experimental methods. It is these data, therefore, that we will apply towards suggesting a modified standard for inhalable aerosol.

CONCLUSIONS AND RECOMMENDATIONS

Our extensive new data set describing the results of experiments for the aspiration efficiency of the human head under ultra-low wind speed conditions leads to the conclusion that the existing criterion for the inhalable fraction does not adequately represent particle size-selective inhalation of aerosols at the very low wind speeds that we now know to be characteristic of a large proportion of workplaces. The results of our experiments for 0.10 m s^{-1} are strikingly consistent with those reported by Aitken *et al.* for nominally calm air conditions. Indeed, it might be said that that these two independent data sets strongly support one another, despite the very different experimental procedures that were adopted. Although minor differences have been noted be-

tween our results and theirs, these are small and may be neglected for the purposes of practical standards setting.

The preceding discussion provides a solid basis for recommending firm action by standards setting bodies. In this regards, therefore, we are confident in making the following conclusions:

1. The existing inhalability criterion, as described by equation (1), is appropriate for wind speeds over the range from 0.2 to 4 m s^{-1} and upwards, extending the lower end of the range of applicability from what was previously acknowledged.
2. For wind speeds in the range $<0.2 \text{ m s}^{-1}$, an alternative inhalability criterion is suggested, taking the form

$$I(d_{ac}) = 1 - 0.0038d_{ac}, [\text{from equation (2)}]$$

as had already been proposed by Aitken *et al.*; based on our results, we see no reason to suggest anything different.

Therefore, as far as the assessment of workers' exposures to inhalable aerosol is concerned, a dual approach is being suggested. That is, for wind speed environments where air velocities are generally considered to be greater than about 0.2 m s^{-1} , the existing criterion may continue to be applied. But for very low wind speeds (e.g. in typical indoor working environments), the alternative criterion should be applied. In each workplace situation where inhalable aerosol is considered to be the fraction of health-related interest, a decision is therefore required. Experience suggests that, at the outset, some occupational hygienists may resist a standard that contains more than one component, requiring a choice to be made. But we argue that a well-educated and professionally certified occupational hygienist should be able to make the necessary decision, even without needing to resort to actual wind speed measurement (which, in any case, is very difficult at such low values). For example, the qualitative smoke tube assessments familiar to all practicing professional hygienists should be able to provide the necessary guidance.

Of course, the purpose of such a criterion—the choice of one or other of the two options—is to guide the choice of sampling instrumentation that best reflects the actual exposures of workers. This takes discussion into the area of sampler technology and performance. This lies outside the scope of the present paper, but suffice to say here that a number of laboratories—including ours—have recently been conducting studies of aerosol sampler performance under conditions like those described here, in particular for

a range of personal samplers like those that are currently commercially available.

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