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Air quality — Particle size fraction definitions for health-related sampling

This Technical Report was drawn up by Technical Committee ISO/TC 146, *Air quality*, and approved by the majority of its members. The reasons which led to the decision to publish the document in the form of a Technical Report are the following.

— It was considered that the document could only define conventions for particle size fractions to be collected for assessing possible health effects.

— The choice of a cut at 10 µm of aerodynamic diameter at the larynx as the basis for these conventions.

— Publication as a Technical Report will encourage further experience with and acceptance of the conventions.

0 Introduction

The biological effects of particles inspired into the human body depend on the nature of the particles and where they deposit, although very little is known about the relationships either for the whole respiratory tract or for individual regions. Nor is much known about the effect in one region of deposition in another.

Inspired droplets or soluble components of inspired solid particles may be absorbed by the tissues wherever they deposit, or the particles may cause damage close to the deposition site if they are corrosive or active. For other inspired particles, biological effects may depend on the region of deposition and on the clearance mechanism and route. For example inspired particles depositing extrathoracically which are not expelled through the nose or mouth are likely to be swallowed and may cause a hazard by absorption in the gastro-intestinal tract. Inspired particles depositing in the tracheobronchial region and cleared by the mucociliary escalator are likely to be swallowed, so that gastro-intestinal absorption is a possible route for these particles also. Inspired particles depositing in the alveolar region may also be cleared by this route, or through the lymphatic system, or may cause a reaction in the alveolar region itself. All the factors considered — inspiration, deposition and clearance — may vary considerably from individual to individual.

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1 Scope and field of application

This Technical Report defines conventions for particle size fractions which should be collected for assessing possible health effects of ambient (see 2.20) airborne particles. A cut of 10 µm aerodynamic diameter at the larynx is assumed.

The conventions are intended to be used in occupational or non-occupational environments where particles that deposit in some part of the respiratory tract are considered potentially hazardous. Limitations of the conventions are given in 5.1.

It is assumed that any health effect is proportional to the mass of particles deposited, either in the whole respiratory tract or in individual regions.

The sampling convention chosen for collection and analysis will depend on the source of the biological effect for the chemical constituents of interest (see 5.2).

2 Definitions

For the purpose of this Technical Report, the following definitions apply. (A list of symbols is given in table 1.)

2.1 particle aerodynamic diameter, ϕ : The diameter of a sphere of density 1 g/cm^3 with the same terminal velocity as the particle under the prevailing conditions of temperature and relative humidity.

NOTE — For particles of aerodynamic diameter less than 0,5 µm, the particle diffusion diameter replaces the particle aerodynamic diameter. The particle diffusion diameter means the diameter of a sphere with the same diffusion coefficient as the particle under the prevailing conditions of temperature and relative humidity.

2.2 mass distribution function, M : The mass concentration of ambient airborne particles per aerodynamic diameter interval.

2.3 total mass concentration (of ambient airborne particles), M_{tot} :

$$M_{tot} = \int_0^\infty M(\phi)\, d\phi$$

2.4 aspiration rate of the respiratory tract, q_R : The air volume inspired per unit time averaged over one or more breathing cycles.

2.5 aspiration rate of sampling instrument, q_s : The air volume per unit time passing into a sampler.

2.6 inspirability, ξ : The mass concentration of ambient airborne particles of aerodynamic diameter, ϕ, inspired though the nose and mouth, as a fraction of the ambient airborne mass concentration of those particles before the air is affected by the presence of the exposed individual and inspiration, under the prevailing conditions of air movement.

2.7 inspirable mass fraction (of ambient airborne particles), I : The mass concentration of inspirable particles as a fraction of the total mass concentration

$$I = \frac{\int_0^\infty M(\phi)\, \xi(\phi)\, d\phi}{M_{tot}}$$

2.8 deposition probability; depositability (deprecated), ψ : The probability of an inspired particle being deposited in the respiratory tract.

2.9 regional deposition probability, ψ_X : The probability of an inspired particle being deposited in region X of the respiratory tract.

2.10 extrathoracic deposition probability, ψ_E : The probability of an inspired particle being deposited in the head and pharynx, down to and including the larynx.

2.11 tracheobronchial deposition probability, ψ_B : The probability of an inspired particle being deposited between the larynx and the unciliated airways.

2.12 alveolar deposition probability, ψ_A : The probability of an inspired particle being deposited in the unciliated airways.

2.13 thoracic deposition probability, ψ_T : The sum of the tracheobronchial deposition probability and the alveolar deposition probability

$$\psi_T = \psi_B + \psi_A$$

2.14 rate of mass deposition in the respiratory tract, D_R : The mass of particles deposited in the respiratory tract per unit time.

2.15 rate of mass deposition in sampler, D_s : The mass of particles deposited in a sampler per unit time.

2.16 collection efficiency, E : The ratio of the mass concentration of ambient airborne particles of aerodynamic diameter ϕ measured by a sampler, to the ambient airborne mass concentration of those particles before the air is affected by the presence of the sampler or by the presence of the sampler and exposed individual if he wears the sampler.

2.17 sampling convention factor, K_X : The ratio of the fraction of the ambient airborne mass concentration at an aerodynamic diameter ϕ, measured using a sampler following the sampling convention for the region X of the respiratory tract, to the probability function $\xi(\phi)\ \psi_X(\phi)$ for ambient airborne particles depositing in region X of the respiratory tract.

2.18 deposited mass fraction, F : The ratio of the mass of particles depositing in the respiratory tract per unit volume of air inspired, to the total mass concentration of ambient airborne particles

$$F = \frac{\int_0^\infty M(\phi)\ \xi(\phi)\ \psi(\phi)\ \mathrm{d}\phi}{M_{tot}}$$

2.19 regional deposited mass fraction, F_X : The ratio of the mass of particles depositing in region X of the respiratory tract per unit volume of air inspired to the total mass concentration of ambient airborne particles

$$F_X = \frac{\int_0^\infty M(\phi)\ \xi(\phi)\ \psi_X(\phi)\ \mathrm{d}\phi}{M_{tot}}$$

2.20 ambient air : The air surrounding the human body or sampler, before the air is affected by the presence of the body or sampler.

This applies to both occupational and non-occupational environments.

Table 1 — Symbols

Symbol	Term
D_R	Rate of mass deposition in the respiratory tract (2.14)
D_s	Rate of mass deposition in sampler (2.15)
E	Collection efficiency (2.16)
F	Deposited mass fraction (2.18)
F_X	Regional deposited mass fraction (2.19)
I	Inspirable mass fraction (2.7)
K_X	Sampling convention factor (2.17)
M	Mass distribution function (2.2)
M_{tot}	Total mass concentration (2.3)
q_R	Aspiration rate of the respiratory tract (2.4)
q_s	Aspiration rate of sampling instrument (2.5)
ξ	Inspirability (2.6)
ϕ	Particle aerodynamic diameter (2.1)
ψ	Deposition probability (2.8)
ψ_A	Alveolar deposition probability (2.12)
ψ_B	Tracheobronchial deposition probability (2.11)
ψ_E	Extrathoracic deposition probability (2.10)
ψ_T	Thoracic deposition probability (2.13)
ψ_X	Regional deposition probability (2.9)

3 General expression for deposition

The rate of mass deposition of ambient particles in the respiratory tract is given by the equation

$$D_R = q_R \int_0^\infty M(\phi)\, \xi(\phi)\, \psi(\phi)\, d\phi \quad \ldots (1)$$

which takes into account the probability of ambient airborne particles being inspired by the nose and mouth, the probability of those particles then being deposited, and the air volume inspired per unit time. Then if F is the mass fraction of ambient airborne particles that deposit per unit volume of air inspired, and M_{tot} is the total mass concentration of ambient airborne particles

$$D_R = q_R F M_{tot} \quad \ldots (2)$$

Analogous equations apply for each region X of the respiratory tract, $\psi(\phi)$ in equation (1) then being replaced by $\psi_X(\phi)$, and F in equation (2) being replaced by F_X.

4 The basis of measurement

During measurement, ambient airborne particles are collected by an instrument which has a collection efficiency $E(\phi)$ equal to the inspirability $\xi(\phi)$, i.e. which collects the same mass fraction F of ambient airborne particles as the respiratory tract, but at a rate D_s

$$D_s = q_s F M_{tot} \quad \ldots (3)$$

so that

$$D_R = \frac{D_s\, q_R}{q_s} \quad \ldots (4)$$

The term D_s/q_s is equal to the mass of particles depositing in the respiratory tract per unit volume of air inspired. If q_R is assumed constant over all the exposed population, the rate of mass deposition in the respiratory tract, D_R, is therefore linearly related to mass concentration measured with an instrument which collects the same mass fraction F of ambient airborne particles as the respiratory tract. This is the justification for expressing health risk in terms of mass concentrations. In practice, q_R varies widely, so that the ambient airborne mass concentration is only an imperfect predictor of health risk for an individual. However, the usual practice is to relate the average biological effect in an exposed population directly to the ambient airborne mass concentration, thus effectively averaging for q_R.

An analogous reasoning can be followed for any region of the respiratory tract, using F_X, the mass fraction of the ambient airborne particles that deposits in that region per unit volume of air inspired, instead of F. Hence, hazards to particular regions can be assessed using instruments designed to measure the mass concentration of the appropriate fraction of ambient airborne particles.

It is difficult to design an instrument to operate according to the same function $\xi(\phi)\ \psi_X(\phi)$ as the target region X of the respiratory tract. The main requirement for an instrument is that the fraction of the total airborne mass concentration, of particles of aerodynamic diameter ϕ, that it collects bears a constant ratio K_X to $\xi(\phi)\ \psi_X(\phi)$ at all values of ϕ. In such a case, equation (4) can be rewritten as

$$D_R = \frac{D_s\, q_R}{K_X\, q_s} \qquad \ldots (5)$$

The unknown factor q_R in equation (4) has then become the unknown factor q_R/K_X in equation (5).

NOTE — Where it is necessary to assume a value for the aspiration rate of the respiratory tract, $q_R = 400\ cm^3/s$ is recommended.[1]

5 Quantitative considerations

5.1 Principle and assumptions

Approximations and assumptions are unavoidable in simulating by a practical device the very complex interaction of variables that governs respiratory tract deposition, and a choice has to be made between various alternative approaches.

Tables 2 to 6 give values for the inspirability $\xi(\phi)$ and for the distribution of inspirable particles into mass fractions corresponding to the extrathoracic, tracheobronchial and alveolar fractions. It is envisaged that a sampler will have a collection efficiency $E(\phi)$ equal to the inspirability $\xi(\phi)$, and that the particles thus collected will be divided sequentially, according to the values given, into mass fractions corresponding to the three regions of the respiratory tract just mentioned. If desired, however, samplers could instead be made to collect just one or two of the mass fractions.

The values are necessarily only conventionalized approximations to respiratory tract behaviour, and the following assumptions should be noted.

— Inspirability $\xi(\phi)$ depends on wind speed and wind direction, on inspiration rate, and on whether inspiration is by nose or mouth. The values given in table 2 are for representative values of inspiration rate, and averaged for all wind directions. This is appropriate for an individual uniformly exposed to all wind directions or predominantly to wind from the side or from behind, but the values would underestimate the inspirability of larger particles for an individual who usually faced the wind.

— Particle aerodynamic diameter does not perfectly characterize the probability of deposition of ambient airborne particles, especially for submicrometre particles, whose diffusion is important.

— Total deposition, and its distribution between the regions of the respiratory tract, differ from individual to individual, and recommended values can only correspond approximately to the mean values. However, some provision is made, in the values corresponding to the tracheobronchial and alveolar fractions, for distinction between different target populations (see 5.2).

— Distribution between the different regions of the respiratory tract also depends on inspiration pattern. Distribution between the thoracic region and the extrathoracic region in particular depends on whether inspiration is through the nose or mouth. Where a choice was necessary, the values somewhat overestimate the thoracic deposition at the expense of the extrathoracic deposition, because when a distinction occurs, biological effects are more likely to occur following thoracic deposition than extrathoracic. For operational convenience, the widely used definitions of the American Conference of Governmental Industrial Hygienists (ACGIH) and the British Medical Research Council (BMRC) are retained for alveolar deposition in healthy adults.

— The sampling conventions assume that all inspired particles are deposited, whereas many, especially the smaller particles, are in fact exhaled. In many workplaces, inspired particles that would be exhaled do not contribute much to the aerosol mass, because of their relatively small sizes.

An unavoidable effect of many of these approximations is that the values given are for $K_X\ \xi(\phi)\ \psi_X\ (\phi)$ and not for the actual deposition functions $\xi(\phi)\ \psi_X\ (\phi)$. The values may thus differ from the mass fraction of the ambient airborne particles which deposits in the region of the respiratory tract in question, by a factor K_X which may be different for each region of the respiratory tract, but may be the same for all values of ϕ within each region of the respiratory tract.

In present practice this is not felt to be a serious disadvantage, because the different biological effects following deposition in the different regions of the respiratory tract would in any case normally result in different relations between deposited mass and disease, and K_X would be automatically allowed for in deriving the relationship between disease incidence and mass concentration of ambient airborne particles measured using the values. The values in tables 2 to 6 are therefore referred to as sampling conventions rather than regional depositions.

As knowledge advances, it may be necessary from time to time to revise these values. In some cases, it has been necessary to extrapolate beyond the particle size range in which measurements were made. The most serious case of this is inspirability, $\xi(\phi)$, for which measurements at the time of drawing up the values were only available up to $\phi = 30$ µm; for completeness, inspirability has been extrapolated to zero at $\phi = 185$ µm. However, it is expected that few aerosols will have substantial mass in particles of this size.

5.2 Use

It is envisaged that future International Standards for sampling ambient airborne particles will specify which of the sampling conventions corresponding to regional fractions should be used for measurement, having regard to the biological effects of the chemical substances covered by the International Standard, and in the case of the thoracic fraction, having regard to the population at health risk. For example if a substance is likely to be absorbed by the human body wherever it deposits, then it would be appropriate to specify sampling the inspirable mass fraction, I. If the substance is believed to aggravate chronic bronchitis, then it might be appropriate to specify the sampling convention corresponding to the tracheobronchial fraction, F_B. If the population thought to be most at health risk is the sick or infirm, then the values chosen for the sampling conventions corresponding to the tracheobronchial and alveolar fractions would be the "high health risk" values of tables 5 and 6; but if the population at health risk is the adult working population, one of the "healthy adult" conventions would be chosen. A healthy adult alveolar convention would be chosen if the subject of the International Standard were sampling fibrogenic particles in the workplace.

In the rare case of a chemical substance likely to be a hazard through extrathoracic deposition only, then regard shall be paid to the thoracic bias of these conventions. This could be taken into account with a safety margin by measuring the extrathoracic plus the tracheobronchial conventions as defined, because in nose inspiration many of the particles allocated here to the tracheobronchial region will be deposited extrathoracically. In other rare cases, none of the fractions defined here might be appropriate.

For practical measurements, the values of any particle diameter given in tables 2 to 6 may vary by ± 15 % of the defined values; greater latitude can be permitted if, under the conditions of use and after application of conversion factors, 67 % of results fall within ± 10 % of the result that would be obtained if the specified curve had been followed exactly. Values in tables 2 to 6 are given to one place of decimals, to facilitate plotting. This does not, of course, imply this degree of accuracy in relation to the human biological data.

5.3 Basis of division into fractions

5.3.1 Division of ambient airborne particles into inspired and non-inspired fractions

For ambient airborne particle measurement purposes, inspirability $\xi(\phi)$ shall be taken conventionally as a curve through the points listed in table 2, which therefore specifies the inspirable mass fraction.

Other ambient airborne particles are therefore excluded from measurement; the sampling conventions corresponding to the extrathoracic, tracheobronchial and alveolar fractions are subdivisions of the inspirable mass fraction.

Table 2 — Inspirable mass fraction

Particle aerodynamic diameter, ϕ	Inspirability, $\xi(\phi)$[1]	Particle aerodynamic diameter, ϕ	Inspirability, $\xi(\phi)$[1]	Particle aerodynamic diameter, ϕ	Inspirability, $\xi(\phi)$[1]
µm	%[2]	µm	%[2]	µm	%[2]
0	100	16	65,0	80	26,3
1	95,6	20	60,6	100	19,7
2	91,8	25	55,8	120	14,1
4	85,7	30	51,7	140	9,2
6	80,8	40	44,9	160	4,9
8	76,8	50	39,3	180	1,0
10	73,3	60	34,3	185	0
12	70,3	70	30,1		

1) The values are based on measurements of the average inspirability of a person equally exposed to all wind directions, at wind-speeds between 0 and 8 m/s carried out with particles having an aerodynamic diameter of up to 30 µm,[2] and on extrapolation and interpolation beyond this particle size range. (For later results, see bibliography.[3])

For extrapolation and interpolation the following equation has been used :

$$\xi(\phi) = 100 - 15\,[\log_{10}(\phi + 1)]^2 - 10\log_{10}(\phi + 1)$$

2) The inspirability is expressed as a percentage of ambient airborne mass concentration.

5.3.2 Division into extrathoracic and thoracic fractions

The inspirable mass fraction is divided at the larynx. Inspired particles which pass beyond the larynx form the thoracic fraction; those which do not reach beyond the larynx form the extrathoracic fraction. The curve through the points listed in table 3 defines the corresponding sampling conventions, which are given as percentages of mass concentration of ambient airborne particles in table 6.

As noted in 5.1, it is assumed in these conventionalized fractions that no inspired particles are exhaled.

Table 3 — Conventionalized thoracic fraction

Particle aerodynamic diameter, ϕ	Conventionalized thoracic fraction of inspirable particles, $K_T\,\psi_T(\phi)$[1]	Particle aerodynamic diameter, ϕ	Conventionalized thoracic fraction of inspirable particles, $K_T\,\psi_T(\phi)$[1]
µm	%[2]	µm	%[2]
0	100	11	40,7
4	98,8	12	32,5
5	95,6	13	25,9
6	89,6	14	20,3
7	81,0	16	12,3
8	70,9	20	4,4
9	60,3	24	1,5
10	50,0	30	0

1) The values are based on a review[4] which concluded that, even in mouth inspiration, only a few percent of inspired particles with $\phi = 15$ µm penetrate past the larynx. The above points for $K_T\,\psi_T(\phi)$ lie on a cumulative log-probability curve with a median of 10 µm and a logarithmic standard deviation, σ_g, of 1,5.

2) The points for $K_T\,\psi_T(\phi)$ are percentages of the inspirability $\xi(\phi)$.

5.3.3 Division into tracheobronchial and alveolar fractions

The thoracic fraction is subdivided into the tracheobronchial fraction and the alveolar fraction. Three sampling conventions are permitted.

If the population it is desired to protect are healthy adults, either the ACGIH "respirable fraction" collection or the BMRC "respirable fraction" collection, both listed in table 4, shall be applied.

Table 4 — Conventionalized alveolar fractions

Particle aerodynamic diameter, ϕ	Conventionalized alveolar fractions of inspirable particles, $K_A \psi_A(\phi)$	
	ACGIH	BMRC
µm	%[1]	%[1]
0	90	100
2	90	92,0
2,5	75	87,5
3,5	50	75,5
5	25	50,0
6	—	28,0
7,1	—	0
10	0	—

1) The points for $K_A \psi_A(\phi)$ are percentages of the inspirability $\xi(\phi)$. See also [5] and [6].

Either of these curves may be chosen because extensive practical experience has shown that measurements made using these two curves are similar. The one which is used shall be clearly stated.

Although the alveolar sampling conventions differ from the "respirable fractions" as defined either by ACGIH or BMRC, because they represent percentages of the inspirability $\xi(\phi)$, the permissible error given in 5.2 means that respirable measurements by the ACGIH and BMRC definitions would probably meet these alveolar sampling conventions.

If the population it is desired to protect are children, or the sick and infirm, the selection curve whose points are given in table 5 shall be used. This "high health risk" selection at smaller particle aerodynamic diameters is appropriate because a similar shift is seen in lung deposition in these population groups.[7]

Table 5 — Conventionalized alveolar fraction for groups at high health risk

Particle aerodynamic diameter, ϕ[1]	Conventionalized alveolar fraction of inspirable particles, $K_A \psi_A(\phi)$
µm	%
0	90
1,4	90
1,8	75
2,5	50
3,6	25
7,1	0

1) These values are obtained by multiplying the particle aerodynamic diameters of the ACGIH definition (table 4) by 0,714 to give $K_A \psi_A(\phi) = 50$ % at $\phi = 2{,}5$ µm.

Thus there are three possible sampling conventions defined for the alveolar fraction, and three corresponding tracheobronchial sampling conventions. These are given as percentages of mass concentration of ambient airborne particles in table 6.

5.4 Sampling conventions corresponding to the extrathoracic, tracheobronchial and alveolar fractions as percentages of ambient airborne mass concentration

The values for the sampling conventions corresponding to the extrathoracic, tracheobronchial and alveolar fractions in tables 3 to 5 are percentages of the inspirability $\xi(\phi)$, and are given to show how the divisions were arrived at.

Of more practical interest, however, are the values for these conventions as percentages of the ambient airborne mass concentration. They are specified in table 6 and illustrated in figures 1 to 3.

It will be noted that the inspirable mass fraction is the sum of the extrathoracic and thoracic conventions, and that the thoracic convention is the sum of the alveolar and tracheobronchial conventions.

Table 6 — The inspirability $\xi(\phi)$ and the percentages $K_X\,\xi(\phi)\,\psi_X(\phi)$ of the ambient airborne particles attributed to each region of the respiratory tract to form conventionalized fractions for sampling

Particle aerodynamic diameter, ϕ	Inspirability, $\xi(\phi)$	Conventionalized extrathoracic fraction, $K_E\,\xi(\phi)\,\psi_E(\phi)$	Conventionalized thoracic fraction, $K_T\,\xi(\phi)\,\psi_T(\phi)$	Conventionalized tracheobronchial fraction, $K_B\,\xi(\phi)\,\psi_B(\phi)$			Conventionalized alveolar fraction, $K_A\,\xi(\phi)\,\psi_A(\phi)$		
				ACGIH	BMRC	High health risk	ACGIH	BMRC	High health risk
µm	%	%	%	%	%	%	%	%	%
0	100	0	100	10	0	10	90	100	90
1	95,6	0	95,6	9,6	2,8	9,6	86,0	92,8	86,0
2	91,8	0	91,8	9,2	7,3	30,5	82,6	84,5	61,3
3	88,5	0,1	88,4	33,5	15,4	56,1	54,9	73,0	32,3
4	85,7	1,0	84,7	51,3	27,3	67,5	33,4	57,4	17,2
5	83,1	3,6	79,5	58,7	37,9	69,9	20,8	41,6	9,6
6	80,8	8,6	72,2	59,7	49,6	67,9	12,5	22,6	4,3
7	78,7	15,0	63,7	56,5	62,1	63,5	7,2	1,6	0,2
8	76,8	22,3	54,5	50,6	54,5	54,5	3,9	0	0
10	73,3	36,6	36,7	36,7	36,7	36,7	0		
12	70,3	47,4	22,9	22,9	22,9	22,9			
14	67,5	53,8	13,7	13,7	13,7	13,7			
16	65,0	57,0	8,0	8,0	8,0	8,0			
18	62,7	58,1	4,6	4,6	4,6	4,6			
20	60,6	57,9	2,7	2,7	2,7	2,7			
22	58,6	57,1	1,5	1,5	1,5	1,5			
25	55,8	55,1	0,7	0,7	0,7	0,7			
30	51,7	51,7	0	0	0	0			
35	48,1	48,1							
40	44,9	44,9							
60	34,3	34,3							
80	26,3	26,3							
100	19,7	19,7							
120	14,1	14,1							
140	9,2	9,2							
160	4,9	4,9							
180	1,0	1,0							
185	0	0							